Pilot Study to support Alternatives Analysis: Evaluating Alternatives to Methylene Chloride in Paint Stripper

Prepared for:

California Department of Toxic Substances Control

Prepared by:

Lillian Burns, Kristen Magnuson,
Roland Geyer, Ph.D and Arturo A. Keller, Ph.D

With contributions from:
Jordan Chamberlain, Carolin Meier, Yu Yu

2016

Preface

The California Safer Consumer Products Regulations require the Department of Toxic Substances Control (DTSC) to identify chemical-product combinations of concern to be listed as priority products for alternatives analysis. Responsible entities involved in the manufacture or distribution of these priority products must conduct an alternatives analysis that incorporates life cycle considerations to identify and analyze potentially safer chemical/product alternatives.

DTSC proposed methylene chloride-based paint strippers as a priority product primarily due to human health concerns[1]. Methylene chloride is a commonly used solvent in commercial chemical paint stripping products that has emerged as an effective chemical paint stripper with a low flammability risk. However, there are concerns about the human and ecological risk, including carcinogenicity and neurotoxicity, associated with methylene chloride exposure.

The following document is a case study of alternatives analysis steps for methylene chloride-based paint stripper and three alternatives. The objective of this project was to conduct a pilot study of a quantitative analysis, following the previous study which was a qualitative analysis (Appendix B). These alternatives include two chemical alternatives and one process alternative: benzyl alcohol-based paint stripper; dimethyl adipate-based paint stripper; and sanding. These alternatives were selected to be illustrative of a chemical substitute, a chemical substitute that is marketed as “green,” and a process substitute, in an attempt to cover a range of potential issues that future alternatives analysis practitioners may encounter. These alternatives are not meant to be a comprehensive list of potential alternatives to methylene chloride-based paint stripper. This report aims to capture one approach for quantifying the upstream, use, and end-of-lie impacts of methylene chloride based paint-strippers and alternatives. This report is not intended to be a complete and comprehensive alternative analysis rather it outlines one possible approach using a few example alternatives.

1 CA Department of Toxic Substance Control (2010). *Paint Stripper with Methylene Chloride*. Retrieved from https://www.dtsc.ca.gov/SCP/Paint_Stripper.cfm

2 Chamberlain, J., Magnuson, K., Meier, C., Yu Y. (2015). Safer Consumer Products Alternatives Analysis Development: Developing a framework for the incorporation of

TABLE OF CONTENTS

Preface 1

Executive Summary 5

Introduction 7

Identifying Product Requirements and Alternatives 10
Product Requirements and Functional Unit 10
Product Alternatives 10
Chemical Alternatives and Product Formulations 11
Process Alternative: Sanding and Sandpaper Composition 12
Product Reference Flows 13

Upstream Phase Impact Assessment 16
Economic Input-Output Analysis 17
Process manufacturing approach 23
Comparison: EIO-LCA vs. Process LCA 26

Use Phase 26
Use Phase Hazard 26
Chemical Exposure Model *27*
Sanding Dust Exposure *35*
Chronic Toxicity *39*
Carcinogenicity *45*
Electricity use for a power sander *48*

End-of-Life Fate 49
Chemical Emissions 50
Environmental Fate 51
Level III Model *51*
CliCC Organic Fate Model *55*
Concentration in the air: CLiCC Organic Results 55
Risk Assessment Approach: Aquatic Organisms 57
Risk Assessment: Terrestrial Organisms 61
Results 63

Conclusion 64
Comparing Qualitative and Quantitative Results 65
Lessons Learned 69

Next Steps 70

Appendix 71

TABLES AND FIGURES

Introduction

Figure 1. Example heat maps by impact.....9

Identifying Product Requirements and Alternatives

Table 1. Product formulation.....11
Figure 2. Processes considered for sandpaper.....12
Table 2. Sample sandpaper ingredients.....13
Table 3. Product reference flows.....15

Upstream Life Cycle Assessment

Figure 3. EIO-LCA tool screen-shot.....17
Table 4. Industry classification.....18
Table 5. Chemical prices scaled to 500 functional units.....21
Figure 4. Economic Input-Output TRACI assessment.....22
Figure 5. Process LCA using TRACI 2.1 Impact Assessment.....24
Figure 6. Process LCA using TRACI 2.1 normalization factors.....25

Use Phase

Figure 7. Box model.....28
Table 6. Equation variables and definitions for generation rate.....31
Table 7. Equation variables for partial pressure.....32
Table 8. Equilibrium vapor pressure used to calculate generation rate.....33
Table 9. Experimental generation rates of methylene chloride.....36
Table 10. Wood dust concentrations from electric orbital sanding.....38
Table 11. Acute hazard ratio of paint stripping alternatives.....39
Table 12. Variables and assumptions used to model chronic daily intake.....43
Table 13. Chronic oral reference dose values.....43
Table 14. Uncertainty factors and the modifying factors for the RfD calculations.....44
Table 15. Reference doses for dimethyl adipate.....44
Table 16. Hazard Index.....45
Table 17. Carcinogenicity classifications.....47
Table 18. Carcinogenic Risk for inhalation exposures to methylene chloride.....47
Figure 8. Sanding during use phase.....48

End-of-Life Fate

Table 19. Environmental Parameters for San Francisco Bay.....52
Figure 9. Level III model results when all emissions are released to the air.....53

Figure 10. Level III model results when all emissions are released to the air……..53
Figure 11. Box plot of the distribution of concentration for chemicals in the air.....……..56
Figure 12. Box plot of the distribution of concentration for chemicals in the air.....56
Table 20. Acute risk quotient of fish and invertebrates.....59
Table 21. NOEC and concentration in water for methylene chloride and methanol.....61
Table 22. Reference doses converted to reference concentrations.....62
Table 23. Hazard quotients for concentration in the air.....63
Figure 13.Qualitative and quantitative heat maps……68

Appendix A

Table A1. Low and high emission level from low and high end product formulation.....71
Table A2. Level III fugacity model results when all emissions are released to the air.....71
Table A3. Level III fugacity model results for different release scenarios.....72
Figure A1. Environmental Parameters for CliCC organic fate model……73
Figure A2. Environmental Parameters (continued) for CliCC organic fate model……...74
Figure A3. Environmental Parameters (continued) for CliCC organic fate model…….. 75

Appendix B

Safer Consumer Product Alternative Analysis project…….……76

Executive Summary

While the ultimate goal of an alternatives analysis is to provide the manufacturers of the product with a final alternative selection, the ultimate goal of this report was to provide a possible approach for completing alternative analysis steps and not to provide a specific alternative selection. The report also aims to provide feedback about the challenges that may be faced during assessment. This approach aims to quantify the impacts of each alternative by assessing these impacts individually at three different phases in the product's lifetime; upstream, use, and end-of-life. The results should be valued to those preparing a phase 1 AA report.

Both a process LCA and an Economic Input-Output LCA approaches were used to quantify the upstream (i.e. prior to the consumer use phase) impacts. The results of the process LCA revealed that while one chemical alternative may have less of an impact on human health than other alternatives, it may have a larger impact in other categories. One way to compare impacts across categories is to normalize the data to person equivalents.

A simplified exposure model was used to identify the health risks associated with the use phase of the chemical-based paint strippers and sanding. After modeling exposure and completing multiple sensitivity analyses, it was determined that methylene chloride-based paint strippers pose the highest acute hazard. However, the "green" alternative dimethyl adipate-based paint strippers exceeded DuPont Chemicals' derived Acceptable Exposure Level.

Finally the end of life fate of the chemical paint strippers was analyzed using two models that estimate the concentration of a chemical in each environmental compartment (e.g. water, air, sediment, soil). Based on our estimated environmental releases and their fate, the downstream impacts of the various chemical alternatives appear to pose no adverse environmental or health risks.

Overall, the development of this quantitative analysis was feasible, although data gaps with regards to the upstream phase and chemical toxicity had to be addressed, and resulted in an increase in uncertainty in the comparison of alternatives. While each alternative analysis effort will have its challenges, the steps followed in this pilot study should be helpful to practitioners interested in a realistic case study. As such this report is not intended to fulfill the AA reporting requirements.

Lessons Learned

- The methods outlined in this case study may be applicable to other products containing chemicals of concern, where there can be a significant release of the chemical during the use and end-of-life phases.

- For this case study upstream impacts can be best captured through a process Life Cycle Assessment approach.

- Modeling exposure requires a thorough understanding of the processes taking place during the Use Phase.

- There are ways to fill in data gaps to get reasonable approximations. Practitioners may be able to use similar approaches used in this analysis to fill data gaps.

- Including sensitivity studies is valuable for decision-making. Sensitivity studies are useful for estimating impacts with different degrees of conservativeness. Considering multiple sensitivity studies can help to show what factors are important in the analysis.

Next Steps

By following the alternatives analysis process for other potential priority products, new tools or approaches that were not applicable to this case study may emerge. A larger catalog of case studies may provide greater insight into the challenges and opportunities in conducting alternatives analyses. Additionally, this case study did not address the process for selecting an alternative nor is it complete in regards to the AA requirements. Further guidance on multi-criteria decision analysis and examples would be beneficial.

Introduction

The alternatives analysis process laid out in the California Safer Consumer Products (SCP) Regulations requires manufacturers or other responsible entities to identify and assess potential alternatives to priority products. Many aspects of this process are consistent with other alternatives assessment protocols; but unlike other protocols, which typically focus on product use, this process requires the incorporation of life cycle thinking. That is, assessing impacts that occur throughout the product's lifetime, including such stages as raw material extraction, manufacture, use, waste and end-of-life.

In a previous qualitative case study titled, *The Safer Consumer Products Alternatives Analysis Development* (Appendix B), a framework for incorporating life cycle thinking into the alternatives analysis process was developed and tested using a qualitative case study of methylene chloride-based paint stripper alternatives.[2] From that screening case study, which provides the basis for this analysis, several heat maps (i.e. graphical representations of areas of concern) were used to illustrate the relative differences in impacts from the alternatives studied, and to help in the identification of relevant factors (Figure 1). This report evaluates several aspects of AA and was developed with the goal to inform a responsible entity when writing the AA report.

Among the lessons learned from that qualitative case study were: (1) upstream impacts (i.e. those that occur in life cycle phases prior to the use phase) are difficult to assess from a purely qualitative perspective because of their lack of specificity to the priority product and their consequent high uncertainty levels; and (2) impacts to human health present the greatest concern for the paint stripper alternatives assessed, but the severity of those impacts during use may vary depending upon the unpredictable safety practices of the user.

Here we expand upon the prior paint stripper case study, focusing on quantitative approaches to conducting analysis steps. Learning from the qualitative analysis, this case study examines three general life cycle phases, under which the more specific phases listed in the SCP Regulations fall: upstream; use; and end-of-life fate.

The upstream analysis focuses on traditional life cycle assessment tools that capture impacts associated with all processes leading to manufacture. This aggregated data reduces the data mining burden. Since the primary concern during paint stripper use is the impact to human health, the use phase analysis focuses on human exposure and hazards. To improve understanding and quantify

2 Chamberlain, J., Magnuson, K., Meier, C., Yu Y. (2015). Safer Consumer Products Alternatives Analysis Development: Developing a framework for the incorporation of life cycle considerations into Alternatives Analysis. Retrieved from http://www2.bren.ucsb.edu/~alternatives/

how different conditions of use affect exposures, several sensitivity analyses were performed. Whether through volatilization during product use or at a landfill, or leaching into the soil at a landfill, the paint stripper ingredients ultimately enter the environment. The fate of each chemical ingredient was modeled to estimate the concentration of the chemicals in different environmental compartments (e.g. air, water, etc.). These concentrations were then used in a risk assessment approach for ecotoxicity and public health.

Though this case study builds upon prior work, we begin by introducing the alternatives and reviewing the functional unit for comparison before discussing the quantitative approaches used here

	Raw Material Extraction	Intermediate Material Processes	Manufacture	Use	Reuse and Recycle	EOL and Disposal
Methylene Chloride	H	M	L	L		L
Benzyl Alcohol	M	M	M	L		
Dimethyl Adipate	H	H	H	M		H
Sanding	M	M	H	H		H

Public Health

	Raw Material Extraction	Intermediate Material Processes	Manufacture	Use	Reuse and Recycle	EOL and Disposal
Methylene Chloride	H	M	M	L		L
Benzyl Alcohol	L	H	L	L		M
Dimethyl Adipate		M	M	L		L
Sanding	M	M		M		M

Air Quality

Methylene Chloride	H		H	H		H
Benzyl Alcohol	L		M			L
Dimethyl Adipate	M		M	H		H
Sanding	M	M		M		M

Soil Quality

Methylene Chloride	M	H	H	H		H
Benzyl Alcohol		L	M	L	M	L
Dimethyl Adipate	M		M	H	H	H
Sanding	M	M		M		M

Water Quality

Methylene Chloride	H	L	L	L		L
Benzyl Alcohol	M			L		
Dimethyl Adipate	M		H	H	H	
Sanding	M	M		M		M

Ecological Impact

	L	M	M		M
	M		M	M	L
M			H	H	H
M	M		L		M

Waste/End-of-Life

High Impact	Medium Impact	Low Impact	Minimal to No Impact	No Data	**N/A**

H	High Uncertainty
M	Medium Uncertainty
L	Low Uncertainty

Figure 1. Qualitative heat maps by impact. Screening of impacts associated with four paint-stripping products (Appendix B). The six heat maps are separated by impact category; columns indicate life cycle phases; rows indicate products/alternatives; colors indicate the impact severity; L-M-H indicate uncertainty level associated with the evaluation. Life cycle segments colored grey indicate a lack of data upon which to evaluate, and life cycle phases colored black do not apply to that product.

Identifying Product Requirements and Alternatives

Product Requirements and Functional Unit

Paint stripping products aid in the removal of paint or varnish from a substrate such a wood or metal. Desirable qualities may include efficacy on a variety of paint types and painted surfaces, time to work, and/or number of applications to work.

For simplicity, this case study assumes only one layer of a single paint type and painted surface type.

To compare the performance of alternatives, a functional unit must be established. The functional unit used in this case study is:

$$Functional\ Unit\ = \frac{1\ m^2\ painted\ hard\ wood, 95\%\ stripped\ of\ 1\ layer\ of\ acrylic\ paint}{3\ hour\ time\ period}$$

This functional unit reflects that it is difficult to remove all paint from a painted surface and that most consumers are satisfied with 95% paint removal. Other studies of methylene chloride alternatives have used 3 hours as a threshold time period, so this functional unit also considers a time span of 3 hours to be acceptable to most consumers for removing paint.[3] This time includes application and removal time and the chemical paint stripper dwell time.

Product Alternatives

Methylene chloride constitutes more than 50% of the product formulation assessed in this case study (based on concentrations for products in the marketplace). It is a strong solvent and serves to dissolve the previously applied paint on the surface of interest. As the primary active ingredient, removal of this ingredient in the paint stripper formulation would result in a product that would not meet performance requirements. Therefore, a simple removal of the chemical of concern from the product is not feasible, and alternative formulations and/or processes must be identified.

For the purpose of this case study, all alternatives identified are existing formulations or processes already available on the market:

Benzyl alcohol based paint stripper – Smart Strip Pro (link to Safety Data Sheet: http://www.dumondchemicals.com/pdf/MSDS/Smart_Strip_Pro.pdf)

3 Morris, M., & Wolf, K. (2006). Methylene chloride consumer product paint strippers: low-VOC, low toxicity alternatives. *Institute for Research and Technical Assistance*.

Dimethyl Adipate based paint stripper – 3M Safest Stripper Paint and Varnish Remover (link to Safety Data Sheet: https://www.janilink.com/pdf/3M%20Safest%20Stripper%20Paint%20and%20Varnish%20Remover%20MSDS.pdf)

Chemical Alternatives and Product Formulations

In addition to a methylene chloride-based paint stripper formulation, two chemical based paint strippers were assessed: benzyl alcohol- and dimethyl adipate. These alternatives were selected to represent a chemical alternative and a chemical alternative marketed as "green" (dimethyl adipate). The complete formulations of the chemical products assessed in this document are listed in Table 1.

Table 1. Product formulation for methylene chloride paint stripper and two chemical alternatives.

Methylene Chloride Paint Stripper		
Ingredient	CAS #	% Product Composition
methylene chloride	75-09-2	70-75%
methanol	67-56-1	20-22%
Stoddard solvent	8052-41-3	3-5%
Benzyl Alcohol Paint Stripper		
Ingredient	CAS #	% Product Composition
water	7732-18-5	40-60%
benzyl alcohol	100-51-6 30-50	30-50%
titanium dioxide	13463-67-7 1-5	1-5%
Dimethyl Adipate Paint Stripper		
Ingredient	CAS #	% Product Composition
water	7732-18-5	65-75%
dimethyl adipate	627-93-0	20-30%
dimethyl glutarate	1119-40-0	1-5%
smectite	12199-37-0	1-5%

Process Alternative: Sanding and Sandpaper Composition

There are process alternatives to chemical paint stripping as well. One such alternative is sanding. Sanding can be performed using electric sanders or may be performed manually. There are numerous types of electric sanders and sandpapers that can be used. Sandpaper typically consists of an abrasive grit bound to a flexible backing by a resin (often urea formaldehyde or phenol-formaldehyde resin). Sandpaper may be comprised of a variety of grits and can have a film, cloth, or paper backing. While the most common abrasive used in sandpaper is aluminum oxide, a variety of different abrasives may be used depending on the purpose or desired finish. Common sandpaper components are listed in Table 2.

For the purposes of this case study, a single sandpaper type was assessed. The sandpaper components and the electricity consumption during the use phase of sanding were assessed. The upstream Impacts associated with manufacturing an electric sander were not included in this analysis. Therefore, the assessment here likely underestimates the impacts associated with this alternative.

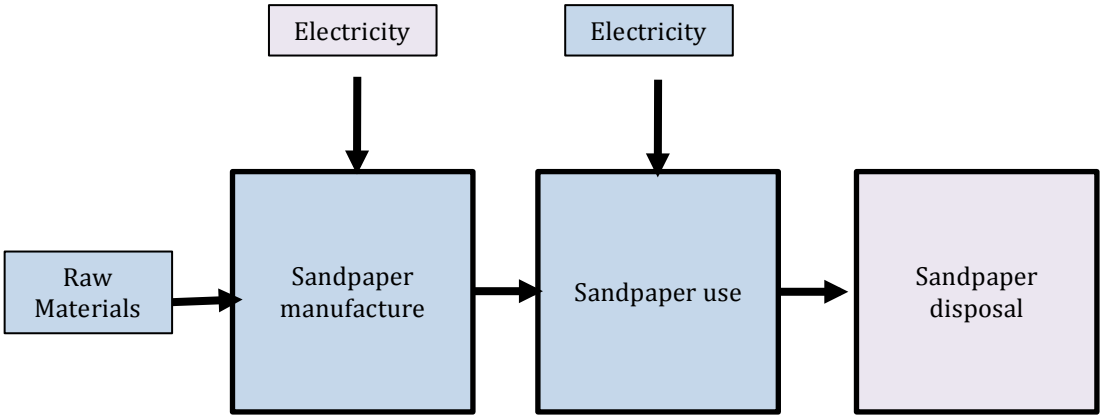

Figure 2. Processes considered for sandpaper. In blue are the processes within the scope of the analysis, in purple the ones that are outside the scope.

Additionally, the exposure risks from sanding are different than the exposure risks from chemical paint strippers. Sandpaper particles are released during the sanding process but most of the particles consist primarily of wood and paint dust. Consequently, there may be various exposures depending on the specific formulation of the paint being removed (e.g. lead-based paint, paints containing nanomaterials, etc.). Exposures from various paint formulations were not assessed in this study, but warrant additional study.

Table 2. Sample sandpaper ingredients for paper, film, or cloth backing sandpaper.

Ingredient	CAS #	Max Weight %
Aluminum oxide	1344-28-1	0-65
Silicon Carbide	409-21-2	0-65
Zirconium Oxide	1314-13-2	0-65
Garnet Abrasive	1302-62-1	0-65
Emery Abrasive	12415-34-8	0-65
Cured Binding Resin	n/a	1-25
Calcium Carbonate	1317-65-3	5-10
Kaolin	1332-58-7	5-10
Cryolite	15096-52-3	1-15
Inorganic Fluoride	14075-53-7	1-15
Paper Backing	Mixture	45-60
Film Backing	Mixture	20-50
Cloth Backing	Mixture	5-60

Product Reference Flows

Since all the alternatives examined in this analysis are products that exist on the market, reference flows[I] were determined for all alternatives (Table 3). These reference flows for the chemical paint strippers were determined based upon information from product instructions and MSDSs. The reference flow for sandpaper was determined based upon experimental and literature values.[4] A sample reference flow calculation is provided for methylene chloride-based paint stripper.

Sample calculation:

mass of 1 gallon of product:

I A reference flow is a quantified amount of the product(s), including product parts, necessary for a specific product system to deliver the performance described by the functional unit. (definition from: Udo de Haus, H., Heijungs, R. (2007). Life Cycle Assessment, A Problem Orientate Approach, Introduction and Resources, Trainer's Manual. (Draft) Retrieved from http://www.lca-center.dk/resources/777.pdf)

4 O'Doherty, G. A. (1968). Experimental Painting Studies: Central Mortgage and Housing Corporation Rental Projects Cornwall, Ontario: First Progress Report.

9.5 lbs = 4.3E+03 g

<u>area</u> that 1 gallon of product can cover:

80 ft^2 = 7.4 m^2

suggested <u>time</u> for product to remain on surface:

15 minutes

product reference flow $= \frac{mass}{area}$

$= \frac{4.3E{+}03\ g}{7.4\ m^2} = 580\ \frac{g}{m^2}$

★ Note that the time for the product to work does not factor into the reference flow calculation. The functional unit includes a general acceptable time frame, which this product meets. The time-to-work value does play a role in use-phase exposure calculations, though.

ingredient reference flow $= \frac{mass\ of\ product \times ingredient\ mass\ percent\ composition}{area} = \frac{ingredient\ mass}{area}$

methylene chloride $= \frac{4.3E{+}03\ g \times 0.75}{7.4\ m^2} = \frac{3.2E{+}03\ g}{7.4\ m} = 435\ \frac{g}{m^2}$

The reference flow values in table 3 were used throughout this case study to ensure that all results were based upon the common functional unit.

Table 3. Product Reference Flows

Methylene Chloride Paint Stripper	
Ingredient	**Reference Flow (g/m^2)**
Overall product	580 g/m^2
methylene chloride	435 g/m^2
methanol	116 g/m^2
Stoddard solvent	17 g/m^2
time to work	15 min
Benzyl Alcohol Paint Stripper	
Ingredient	**Reference Flow (g/m^2)**
Overall product	976 g/m^2
water	391-586 g/m^2
benzyl alcohol	293-488 g/m^2
titanium dioxide	10-49 g/m^2
time to work	30 min
Dimethyl Adipate Paint Stripper	
Ingredient	**Reference Flow (g/m^2)**
Overall product	1042 g/m^2
water	677-781 g/m^2
dimethyl adipate	208-312 g/m^2
dimethyl glutarate	10-52 g/m^2
smectite	10-52 g/m^2
time to work	45 min
Sanding	

Ingredient	Reference Flow (m^2 sandpaper/m^2 wood)
Sandpaper sheet	1.2 E-02 m^2/m^2 (2-3 five-inch circular sanding discs)
Required sanding time (electricity)	<60 min

Upstream Phase Impact Assessment

The process flows and study scope boundaries for the life-cycle of paint strippers were the same as in the qualitative case study (Appendix B). In summary, three phases were considered: upstream (production), use, and end-of-life. The study considered a generic non-lead based paint consistently across all alternatives.

Upstream life cycle or fabrication of a product can be modeled using both economic input-output[5] (EIO-LCA) and process life cycle assessments[6]. Process LCA and EIO_LCA are the two major methods used for performing a LCA[7]. These approaches rely on using different datasets to model the impacts and since both models are used in the LCA community both were explored in this analysis. To assess the upstream impacts we explored using both of these approaches. The first approach utilizes industry economic data and pricing information to estimate impacts, while the second approach uses data that has been collected for specific processes for the product being assessed. We first walk through the steps of each method and the results from this case study, followed by a comparison of the utility of these approaches.

While the EIO-LCA approach is simple, free, and presents few data input challenges, the underlying model does not provide granular enough information to see nuances between alternatives within the same industry classification[8]. If all alternatives fall within the same industry classification, this approach is of little value, as seen in this case study. However, if alternatives fall under separate industry classifications, the EIO-LCA approach can be a more useful screening-level tool.

---

5 Carnegie Mellon University Green Design Institute. (2008) Economic Input-Output Life Cycle Assessment (EIO-LCA), US 1997 Industry Benchmark model [Internet],Available from:<http://www.eiolca.net> Accessed 1 January, 2008.

6 Hendrickson, C., Horvath, A., Joshi, S., & Lave, L. (1998). Peer reviewed: economic input–output models for environmental life-cycle assessment. *Environmental science & technology*, *32*(7), 184A-191A.

7 Geyer, R., Kuczenski, B., & Trujillo, M. (2015). Assessing the Greenhouse Gas Savings Potential of Extended Producer Responsibility for Mattresses and Boxsprings in the United States. *Journal of Industrial Ecology*.

8 Hendrickson, C., Horvath, A., Joshi, S., & Lave, L. (1998). Peer reviewed: economic input–output models for environmental life-cycle assessment. *Environmental science & technology*, *32*(7), 184A-191A.

A process LCA can provide more robust and informative results for comparing alternatives. This approach presents more opportunities for data gaps to emerge. However, there may also be opportunities to fill some of these data gaps with reasonable substitutions (e.g. in this case study, data for dimethyl adipate production was used as a proxy for the similar chemical, dimethyl glutarate).

The data and tools used in a process LCA may not be free. And understandably, the degree of difficulty in completing a process LCA increases with the complexity of the product (e.g. an assembled product with many components and subcomponents is likely more difficult to model than a formulated product with three ingredients). But the results of a process LCA are specific to the product being modeled, likely presenting less uncertainty than the EIO-LCA approach.

Economic Input-Output Analysis

Carnegie Mellon's online US 2002 Benchmark Model was used to conduct an input-output LCA (Figure 3).

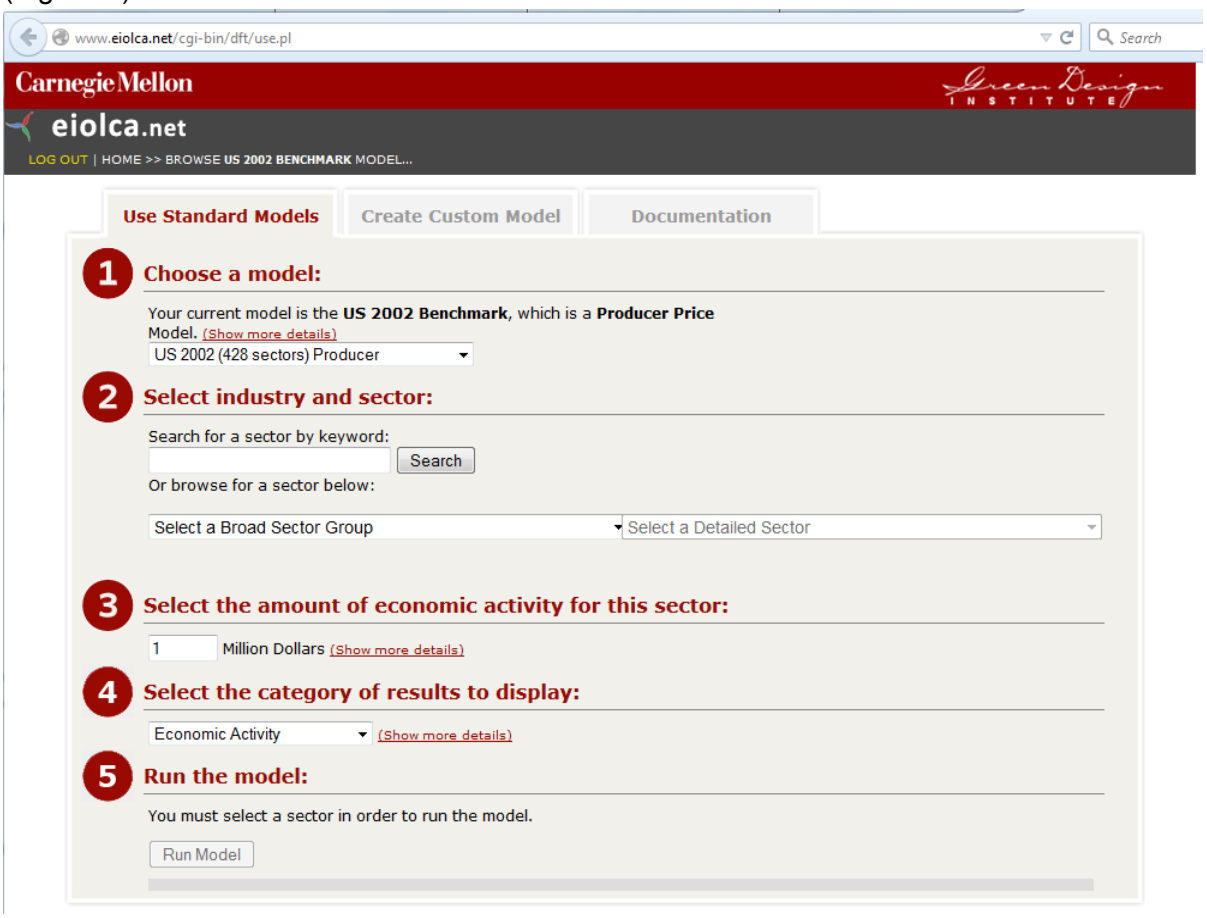

Figure 3. EIO-LCA tool screen-shot

It is important to note that since these results are only based upon product manufacture, they capture impacts associated with upstream activities, but do not capture impacts associated with use phase or downstream impacts.

Since the EIO-LCA tool is based upon industry-wide data, the North American Industry Classification System (NAICS) codes for each ingredient in the various alternatives was determined (Table 4). With the exception of titanium dioxide, all chemical ingredients were classified as basic organic chemical manufacturing. Sandpaper was classified as an abrasive product.

Table 4. Industry classification of chemicals for ECO_LCA Tool.

Ingredient	Classification
methylene chloride	All other basic organic chemical manufacturing
methanol	All other basic organic chemical manufacturing
Stoddard solvent	All other basic organic chemical manufacturing
benzyl alcohol	All other basic organic chemical manufacturing
titanium dioxide	Other Basic Inorganic Chemical Manufacturing
dimethyl adipate	All other basic organic chemical manufacturing
dimethyl glutarate	All other basic organic chemical manufacturing
smectite	All other basic inorganic chemical manufacturing
sandpaper	Abrasive product manufacturing

This analysis was conducted using estimates of wholesale prices in 2002 dollars.

Industrial chemical distributors were contacted to obtain estimates of chemical prices. However, only the bulk price of benzyl alcohol was available to us. There was, however, market pricing information available for all chemicals from scientific chemical suppliers. We compared the bulk price (wholesale price) of benzyl alcohol with the market price listed from the scientific chemical supplier to determine a markup rate. Based on the markup of benzyl alcohol, we then assumed an approximate 15,000% markup on all chemicals. A manufacturer conducting an alternatives assessment may be able to obtain bulk rate prices for the chemicals they are considering in their formulations. To be compatible

with the EIO-LCA tool, these prices were then deflated to 2002 dollars using the Bureau of Labor Statistics' wholesale price index for industry classifications.

The cost of all chemical ingredients was then scaled to the ingredient's presence in the product formulation (Table 5). This economic value was scaled to the equivalent of 500,000 functional units to ensure manageable numbers from the tool's output (note: the EIO-LCA tool assumes a linear relationship between the amount of product and impacts). The TRACI Impact Assessment option was used for the output of this analysis.

Sample calculation for chemical formulation:

1. *determine the wholesale price (bulk rate) of ingredient in 2015$*

   wholesale price of benzyl alcohol:

   $1.00/lb = $0.0022/g

   market price of benzyl alcohol:[9]

   $173.49/500mL = $0.332/g

   markup rate[II]:

   $$100 \times \frac{market\ price - producer\ price}{producer\ price} = \frac{\$0.3324/g - \$0.0022/g}{\$0.0022/g} = 1.50E04\%$$

   market price of 500 mL of methylene chloride:

   $118

   mass of 500 mL of methylene chloride:

   $$volume \times density = 500\ mL \times 1.3\ \frac{g}{mL} = 663\ g$$

   unit market price of methylene chloride:

   $$\frac{ingredient\ market\ price}{ingredient\ mass} = \frac{\$118}{663\ g} = \$0.178/g$$

   wholesale price of methylene chloride:

   $$\frac{ingredient\ unit\ market\ price}{1 + markup\ rate} = \frac{\$0.178/g}{15{,}000\%} = \$0.00118/g$$

2. *determine the wholesale price of ingredient in $2002*

   deflation rate to 2002$ from 2015$:

   $$\frac{2002\ annual\ producer\ price\ index\ for\ all\ other\ basic\ organic\ chemical\ manufacturing\ industry\ data}{2015\ annual\ producer\ price\ index\ for\ all\ other\ basic\ organic\ chemical\ manufacturing\ industry\ data}$$
   $$= \frac{150.2}{296.9} = 0.5 = 50\%$$

   2002$ wholesale price of methylene chloride:

9 Benzyl Alcohol (Certified), Fisher Chemical:Chemicals:Other Organics A-Z. (n.d.). Retrieved July 17, 2015, from https://www.fishersci.com/shop/products/benzyl-alcohol-certified-fisher-chemical-3/p-64404

II For additional examples of how to calculate markup rates, visit such resources as: https://purplemath.com/modules/percntof2.htm

$= producer\ price\ of\ methylene\ chloride \times 50\% = \$0.0012/g \times 50\%$
$= \$0.00060/g$

3. determine the ingredient/product reference flow cost

ingredient reference flow cost of methylene chloride:

= $\$2002\ ingredient\ producer\ price \times ingredient\ reference\ flow$
$= \$0.00060/g \times 435\ \frac{g}{m^2} = \$0.26/m^2$

★ Since all the classified ingredients in the methylene chloride-based paint stripper fall under the same industry classification, the entire product can be modeled at one time by determining the overall product reference flow cost. If ingredients fall under separate classifications, as with the benzyl alcohol-based paint stripper, then the ingredients must be modeled separately and their output combined at the end to determine overall impacts.

product reference flow cost of methylene chloride-based paint stripper:

$= \Sigma\ ingredient\ reference\ flow\ costs$

$= methylene\ chloride\ reference\ flow\ cost\ +\ methanol\ reference\ flow\ cost$
$+ stoddard\ solvent\ reference\ flow$
$= \$0.26/m^2 + \$.003/m^2 + \$.0034/m^2 = \$0.29/m^2$

4. scale the cost to multiple units for the purpose of the EIO-LCA tool

scaled cost to achieve 500,000 functional units

$= \$0.29/m^2 \times 500{,}000\ m^2 =$ 0.14 million dollars

Sample calculation for sanding:

<u>wholesale unit market price</u> for 5-inch circular sandpaper disc:

$= \frac{\$40}{100\ discs} = \$0.4/disc$

<u>deflation rate</u> to 2002$ from 2015$:

$$= \frac{2002\ annual\ producer\ price\ index\ for\ abrasive\ product\ manufacturing\ industry\ data}{2015\ annual\ producer\ price\ index\ for\ abrasive\ product\ manufacturing\ industry\ data}$$

$= \frac{166.4}{218.3} = 0.76 = 76\%$

<u>$2002 wholesale price</u> of sanding disc:

$= wholesale\ unit\ market\ price\ of\ sanding\ disc \times 76\%$
$= \$0.4/disc \times 76\% = \$0.304/disc$

sanding disc reference flow cost:

= $\$2002\ ingredient\ producer\ price \times ingredient\ reference\ flow$
$= \$0.304/disc \times 2.5\ \frac{discs}{m^2} = \$0.76/m^2$

scaled cost to achieve 500,000 functional units

$= \$0.76/m^2 \times 500{,}000\ m^2 = \$0.38$ million dollar

Table 5. Chemical costs scaled to 500,000 functional units.

Chemical	Scaled to 500,000 functional units (2002$)
methylene chloride	130,000
methanol	15,000
Stoddard solvent	1,700
benzyl alcohol	160,000– 270,000
titanium dioxide	3,100 – 15,000
dimethyl adipate	80,000 – 120,000
dimethyl glutarate	6,800 - 34,000
smectite	22 - 111
sand paper	380,000

Note: Chemicals with two prices indicate the price for low end and high end product formulation.

Based upon the results of this impact assessment, all impact categories show the same relationship among the chemical alternatives, with benzyl alcohol-based paint strippers having the highest impacts and dimethyl adipate-based paint strippers having the lowest (Figure 3). This result is unsurprising, given the nature of this approach. The EIO-LCA is based upon industry-wide data and individual ingredient pricing information; since the chemical alternatives fell within the same industry, pricing information became the determinant of the results. Because the reference flow cost for benzyl alcohol-based paint stripper is the highest, it yielded the highest impact results among the chemical alternatives. A 15,000% markup was assumed based on the available pricing of benzyl alcohol, leading to potential over/under estimates of the overall impacts of the chemicals. This assumed markup introduces significant uncertainty, but would require an in-depth study of markups to determine the uncertainty introduced. It is consistent across all alternatives, so the uncertainty is similar for all.

Sanding, however, falls under a different industry classification. It is not universally better or worse than the chemical alternatives; there are tradeoffs, particularly with regard to human health and ecotoxicity.

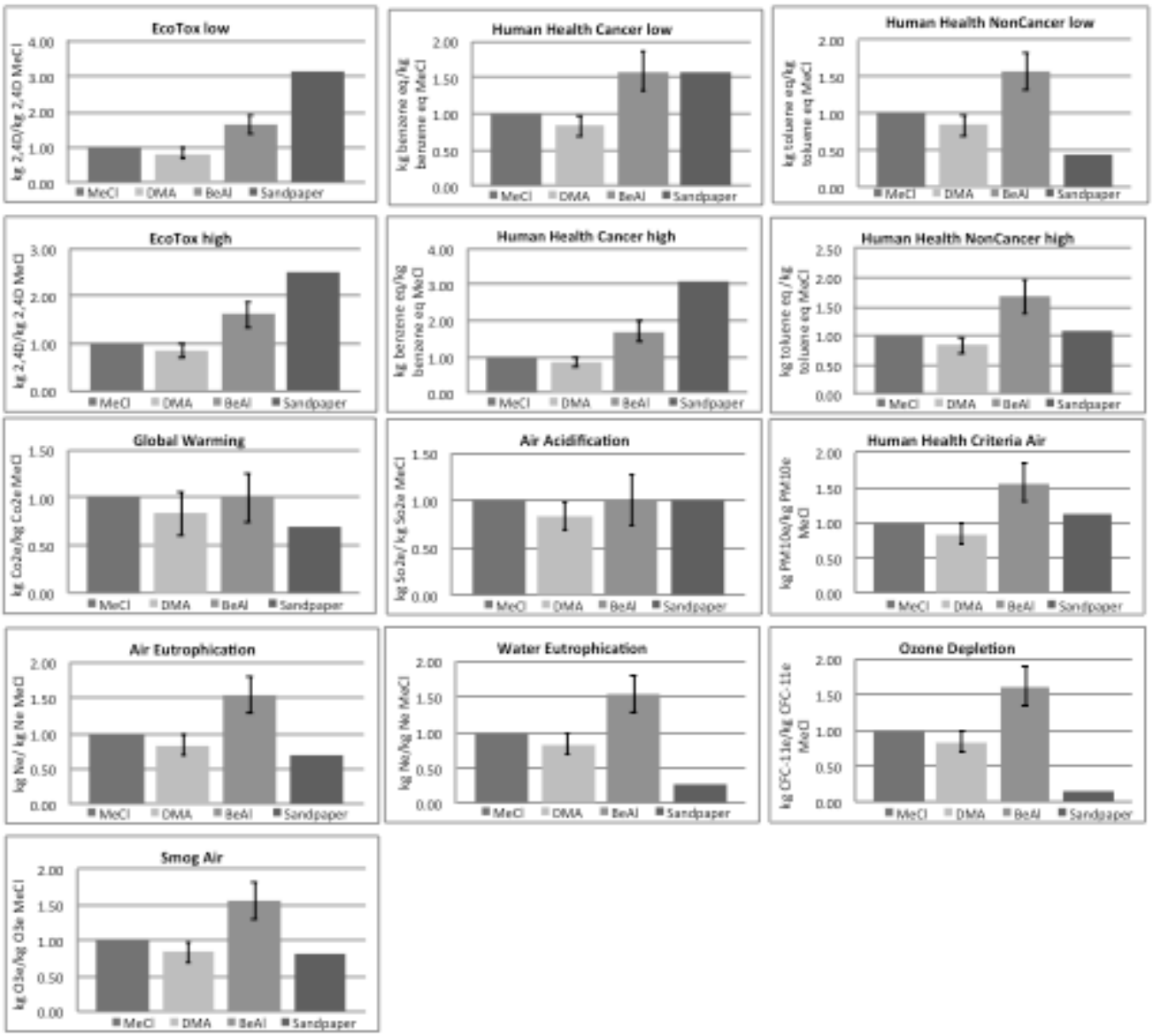

Figure 4. Economic Input-Output TRACI Impact Assessment. Results are normalized to the methylene chloride based paint stripper. Dimethyl adipate and benzyl alcohol-based paint strippers are average results with error bars to indicate the range of impacts based upon possible ranges of the chemicals present within the product (e.g. low end of 20% dimethyl adipate and 1% dimethyl glutarate; high-end of 30% dimethyl adipate and 5% dimethyl glutarate). Impacts were not assessed for ingredients for which there was no available industry classification.

Process manufacturing approach

Ecoinvent data[III] for methylene chloride, methanol, water, benzyl alcohol, and titanium dioxide was used with GaBi software[IV] to create processes for methylene chloride-based paint stripper and benzyl alcohol-based paint stripper manufacturing.

Data for dimethyl adipate production in the Netherlands was purchased[V]. Data for dimethyl glutarate was not available. Since the production processes of dibasic esters are similar, it was assumed that the dimethyl adipate data was also representative of dimethyl glutarate.

Aggregated Ecoinvent data for aluminum oxide, zirconium oxide, kaolin, cryolite, and urea formaldehyde (a commonly used resin in sandpapers), were used to create the process for manufacturing sand paper, and later on for considering the impact of electricity during the use phase of a sander.

All processes were modeled for their reference flows, with ranges modeled for the benzyl alcohol- and dimethyl adipate-based paint strippers. The impact assessment used TRACI 2.1[VI] characterization factors from GaBi (Figure 4).

Sanding and dimethyl adipate-based paint strippers have overall lower impacts than methylene chloride, with dimethyl adipate exceeding methylene chloride only in its global warming impacts.

There are tradeoffs between the impacts from methylene chloride-based paint stripper and benzyl-alcohol based paint stripper. For many impacts, there is less than an order of magnitude difference between the alternatives. The clear exception is ozone depletion, which is several orders of magnitude larger for methylene chloride-based paint stripper than for any other alternative.

III EcoInvent data can be accessed here: http://www.gabi-software.com/america/databases/gabi-databases/ecoinvent-integrated/

IV Gabi software can be accessed here : http://www.gabi-software.com/america/index/)

V Information on thinkstep databases can be found here: http://www.gabi-software.com/databases/

VI Information of the TRACI 2.1 normalization factors are built into the Gabi Software .

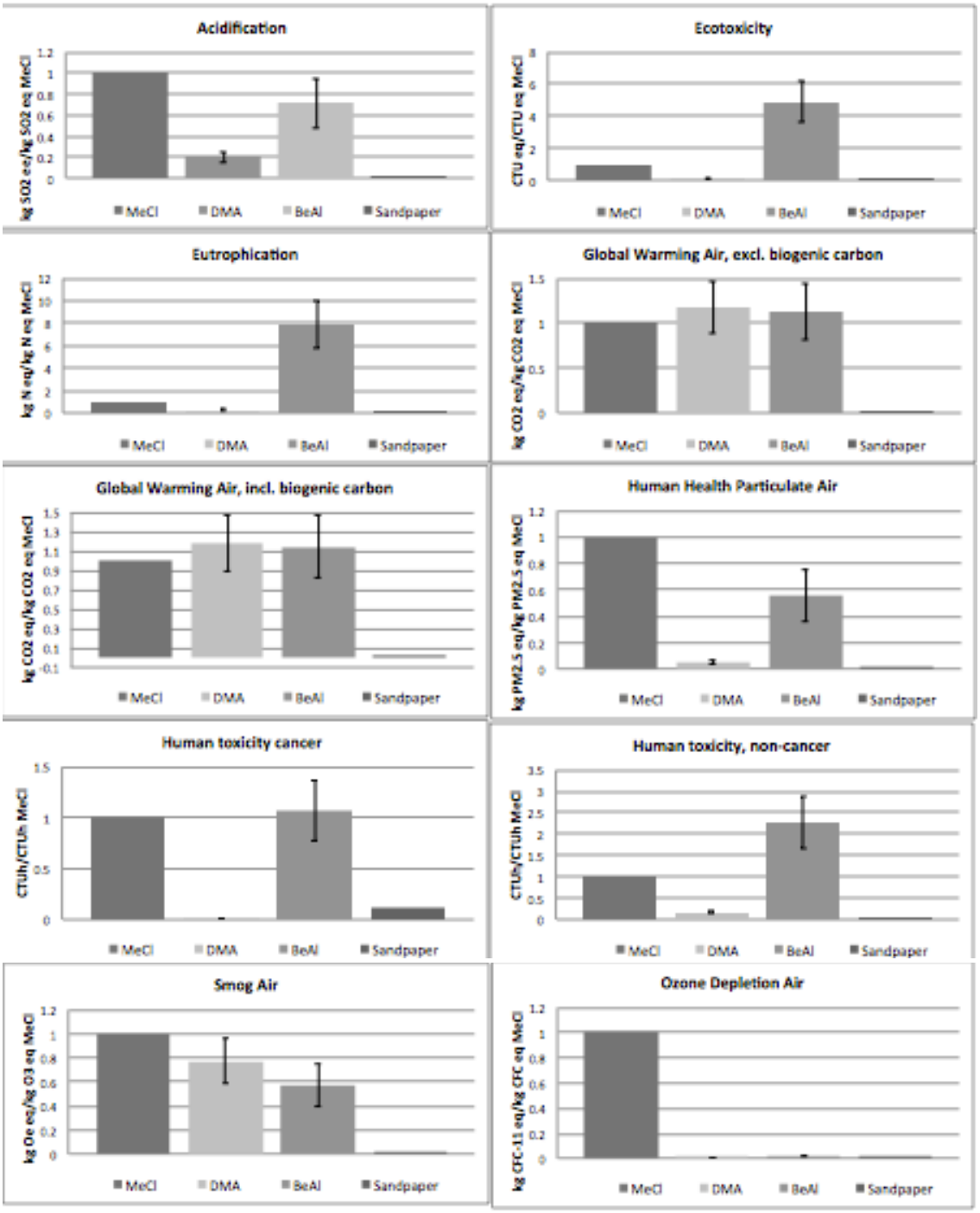

Figure 5. Manufacturing Process Impacts using TRACI 2.1 Impact Assessment. Results are normalized to methylene chloride-based paint stripper. For dimethyl adipate- and benzyl alcohol-based paint stripper we present average results with error bars to indicate the range of impacts based upon possible ranges of the chemicals present within the product (e.g. low end of 20% dimethyl adipate, 1% dimethyl glutarate, and 65% water; high-end of 30% dimethyl adipate and 5% dimethyl glutarate, and 75% water). Impacts were not assessed for ingredients for which there was no available data and no process could be modeled (e.g. smectite).

While it is important to understand how alternatives compare to one another within impact categories, it is also helpful be able to compare impact categories themselves.

To better understand which impacts are most relevant in this analysis, TRACI 2.1 normalization factors for California were used to translate results into “person equivalents” as a way to estimate relative impact importance (Figure 5).

From these normalized results, human toxicity and ecotoxicity emerge as being the most relevant impact categories for comparison. Note that for the production phase of these paint strippers the additional human toxicity represents less than 0.2% of the toxicity one may encounter from other activities.

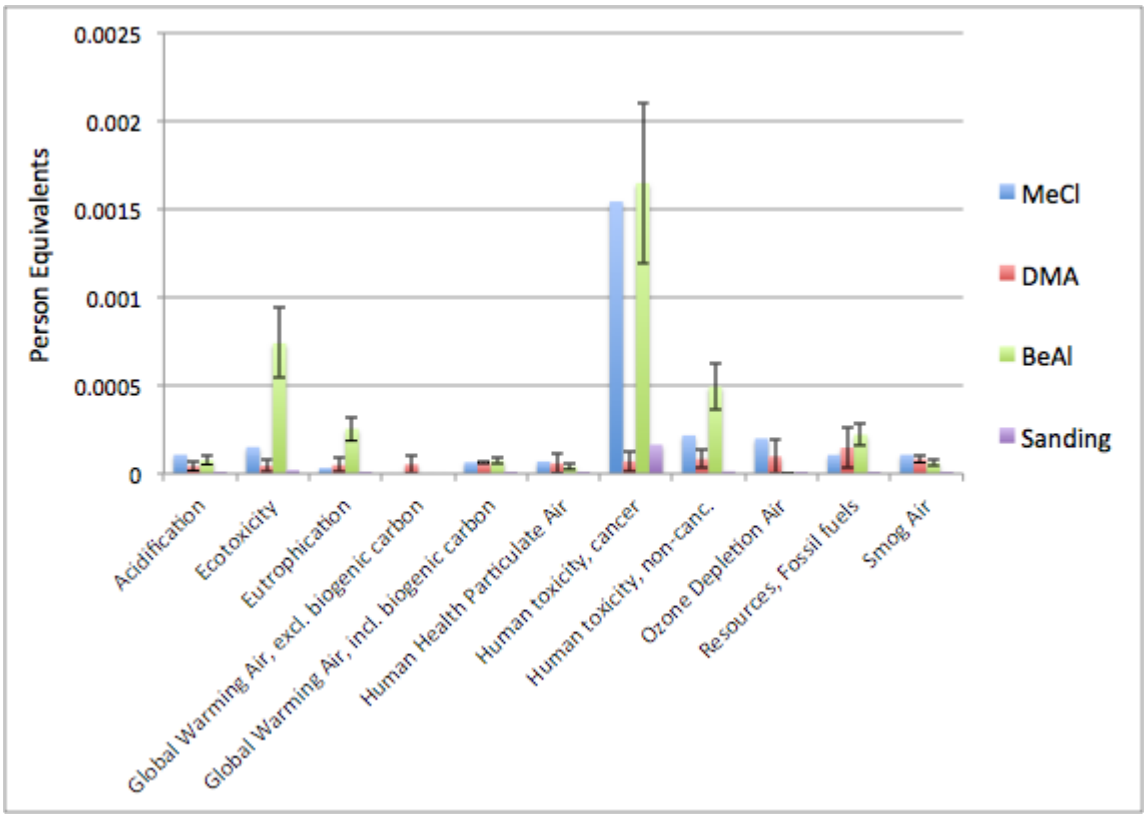

Figure 6. Manufacturing Process results in person equivalents, using TRACI 2.1 normalization factors and EIO_LCA outputs.

Comparison: EIO-LCA vs. Process LCA

The EIO-LCA and process LCA approaches yield results that are inconsistent with one another, but they may each serve a purpose in the alternatives analysis process. For example, the results of the two models yield inconsistent results for ozone depletion. The results of the EIO-LCA model reveal that benzyl alcohol has the greatest ozone deletion factor whereas the Process LCA results indicates that methylene chloride has the greatest ozone depletion factor. The EIO–LCA approach results show that Benzyl Alcohol and sandpaper have the greatest impacts in most categories. The results for process LCA reveal that sandpaper has a much lower impact than the alternative chemicals which is inconsistent with the EIO-LCA results.

The quantitative nature of these LCA approaches provide clear comparisons of alternatives, though decision-making may not necessarily be clear due to tradeoffs. Additionally, the use of normalization factors helps to illustrate which impacts are most relevant to focus on when comparing alternatives.

Use Phase

The use phase portion of this analysis focuses on human health impacts, which present the greatest concern during the actual use of paint stripping products. Exposure can occur during the application period as well as the time needed for the product to effectively strip the paint. Since chemical paint strippers do volatilize during use, they will eventually enter the environment and potentially have such impacts as ecotoxicity. Those impacts are not captured in the use phase portion of this analysis, but are captured in the end-of-life fate section considering the fate and transport of formulation components.

Additionally, the electricity use associated with a power sander was assessed during the use phase.

Use Phase Hazard

The first step to assess use phase impacts is to model exposure. Exposure to chemicals during the use phase can occur via inhalation, ingestion of contaminated water or food, or via the skin (dermal exposure). For a particular consumer product, some of these pathways may not be significant if the product is used as intended. In this case study, we focus on the intended use of paint strippers or sanding, although it is possible that if a consumer does not wash her/his hands, there is the potential for exposure via ingestion of contamination food. In this case study, the predominant exposure route is assumed to be inhalation.

Exposure to a chemical depends upon the reference flows--the amount of chemical applied or amount of sandpaper required to fulfill the functional unit. Again the functional unit is:

$$\frac{1\ m^2\ of\ hard\ wood,\ 95\%\ stripped\ of\ \ 1\ layer\ of\ acrylic\ paint}{3\ hour\ time\ period}$$

Product reference flows can be found in Table 3. For the exposure assessment, the time required to achieve the functional unit is also important.

Inhalation of chemical paint stripper alternatives is not likely, but there is a possibility of ingesting dust particles from sanding. Here we model chemical exposure through inhalation.

Chemical Exposure Model

The concentrations of chemical ingredients in the air following application of paint stripper to a 1 m^2 piece of wood were determined using a simplified box model based on the methods and equations outlined by Jayjock (1994) and Van Veen, et al. (1999).[10,11] Equations noted in these studies were used to determine the generation rates (g/min), or release to the air, of paint stripper ingredients. A room, with a volume of 54 m^3 was used to represent a typical room area in the US, determined by survey data.[12] A ventilation rate of 68 m^3/hr (54 m^3 * 1.64 hr^{-1}) was used as the expected ventilation rate, or air exchange rate, for a room with multiple windows open.[13] In this model, the concentration in the air is a function of the generation rate, the saturation vapor pressure of the chemical ingredient, molecular weight of the paint stripper compound, ventilation rate, and size of room. Several sensitivities were also performed.

Due to the small volume of chemical applied, it is assumed that a simplified box model (Figure 6) can be used to determine the concentration in the air, where back pressure does not affect the evaporation rate of the chemical.

10 Jayjock, Michael A. "Back pressure modeling of indoor air concentrations from volatilizing sources." *American Industrial Hygiene Association* 55.3 (1994): 230-235.

11 Van Veen, M. P., Fortezza, F., Bloemen, H. J. T. H., & Kliest, J. J. (1999). Indoor air exposure to volatile compounds emitted by paints: experiment and model. *Journal of exposure analysis and environmental epidemiology*, *9*(6), 569-574.

12 Environmental Protection Agency. (2014). TSCA Work Plan, Chemical Risk Assessment: Methylene Chloride Paint Stripping Use (EPA Document No. 740-R1-4003).

13 Environmental Protection Agency. (2014). TSCA Work Plan, Chemical Risk Assessment: Methylene Chloride Paint Stripping Use (EPA Document No. 740-R1-4003).

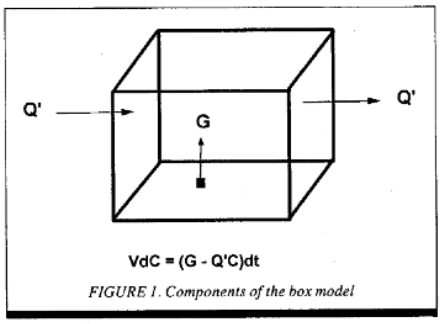

Figure 7. Image of Comparison of the box model from JayJock et al. (1994).

A simple box model considers the amount of chemical already present in the air ($C_{airborne}$; initially assumed to be zero), the amount of chemical evaporating (G) and the amount of chemical leaving the room as a result of ventilation (Q) at any given time:

(eq 1)

$$C_{room,t} = C_{airborne,t-1} + \frac{G_t \times t}{room\ volume} - C_{leaving,t}$$

$$\left[\ \frac{g}{m^3} = \frac{g}{m^3} + \frac{\frac{g}{min} \times min}{m^3} - \frac{g}{m^3}\ \right]$$

where

(eq 2)

$$C_{leaving} = \frac{Q \times t}{room\ volume} \times C_{room}$$

$$\left[\ \frac{g}{m^3} = \frac{\frac{m^3}{min} \times min}{m^3} \times \frac{g}{m^3}\ \right]$$

and

(eq 3)[14,15]

$$G = \frac{Kt \times MW \times Area}{R \times T} \times (P_{partial} - P_{actual})$$

$$\left[\frac{g}{min} = \frac{\frac{m}{min} \times \frac{g}{mole} \times m^2}{\frac{atm - m^3}{mole - K} \times K} \times atm - atm)\ \right]$$

14 Jayjock, M. A. (1994). Back pressure modeling of indoor air concentrations from volatilizing sources. *American Industrial Hygiene Association*, *55*(3), 230-235.

15 Van Veen, M. P., Fortezza, F., Bloemen, H. J. T. H., & Kliest, J. J. (1999). Indoor air exposure to volatile compounds emitted by paints: experiment and model. *Journal of exposure analysis and environmental epidemiology*, *9*(6), 569-574.

(eq 4) [16]

$$P_{partial} = \frac{\frac{C_{volatile\ compound}}{MW_{volatile\ compounds}}}{\frac{C_{volatile\ compound}}{MW_{volatile\ compounds}} + \frac{C_{other}}{MW_{other}}} \times P_{eq}$$

$$[\ atm \quad = \quad \frac{\frac{g/g}{g/mol}}{\frac{g/g}{g/mol} + \frac{g/g}{g/mol}} \quad \times atm]$$

To calculate the amount of chemical released to the air (G), several parameters are required (Table 5). Standard temperature and pressure were assumed for these calculations.

16 Van Veen, M. P., Fortezza, F., Bloemen, H. J. T. H., & Kliest, J. J. (1999). Indoor air exposure to volatile compounds emitted by paints: experiment and model. *Journal of exposure analysis and environmental epidemiology*, *9*(6), 569-574.

Table 6. Equation variables and definitions for generation rate equation.

Variable	Definition (Units)
G	Generation Rate (g/minute) of the volatile compound in the mixture
Kt✣	Mass Transfer Rate (m/minute)
MW	Molecular weight (g/mol) of the compound for which the generation rate was calculated
Area	(1 m^2)
P_{actual}	"the time dependent actual vapor pressure exerted by the compound under local conditions of ventilation i.e., back pressure" (atm)"[17]
$P_{partial}$	Refer to table 6 for calculation
R	gas constant $(\frac{atm-m^3}{mole-K})$
T	Temperature of the volatilizing liquid (°K)

Note: Equation Variables and Definitions from Jayjock (1994) and Van Veen, et al. (1999)

17 Jayjock, M. A. (1994). Back pressure modeling of indoor air concentrations from volatilizing sources. *American Industrial Hygiene Association*, *55*(3), 230-235.

Table 7. Equation Variables for the partial pressure

Variable	Definition (Units)
$P_{partial}$	Partial vapor pressure (atm)
$C_{volatile}$	Concentration of the volatile compound
$MW_{volatile}$	Molecular weight (g/mol) of the volatile compound in the mixture
C_{other}	Concentration of the other compounds used in the mixture
MW_{other}	Molecular weight of the other compounds in the mixture that correspond with the C_{other}
P_{eq}	The equilibrium vapor pressure (atm) of the volatile chemical in the mixture

Table 8. Equilibrium vapor pressure (P_{eq}) used to calculate the generation rate.

Compound	Equilibrium Vapor Pressure (atm)
Methylene Chloride	0.459[18]
Methanol	0.128[19]
Benzyl Alcohol	0.0001[20]
Dimethyl Adipate✳	0.000079[21]
	0.00026[22]
Dimethyl Glutarate	0.004[23]

✳There are several reported equilibrium vapor pressures for dimethyl adipate. The lower vapor pressure (0.0000789 atm) was used to calculate the generation rate used in a baseline scenario because it is similar to the approximate vapor pressure range that the California Air Resources Board reports for dimethyl adipate (<0.05 torr).[24] An additional scenario was modeled for sensitivity using the higher vapor pressure value.

✣*Note that K_t was calculated using the equation from Watts 1998,[25] where $K_t = K_1$ in the following equation:*

$$K_1 = K_2 \times \left(\frac{M_2}{M_{volatile\ compund}}\right)^{1/3}$$

18 Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological Profile for Methylene Chloride (Update). Draft for Public Comment. Public Health Service, U.S. Department of Health and Human Services, Atlanta, GA. 1998.

19 Watts, R. J. (1998). Hazardous wastes: sources, pathways, receptors.

20 ICSC 0833 - BENZYL ALCOHOL. *IPCS INCHEM.* Retrieved July 17, 2015, from http://www.inchem.org/documents/icsc/icsc/eics0833.htm

21 Dimethyl adipate ≥99%. *Signma Aldrich.* Retrieved July 17, 2015, from http://www.sigmaaldrich.com/catalog/product/aldrich/186252?lang=en®ion=US

22 Dimethyl Adipate. *Chemical Book. Retrieved July 30, 2015, from* http://www.chemicalbook.com/ChemicalProductProperty_EN_CB1412954.htm

23 Dimethyl Succinate. *Chemical Book.* Retrieved July 30,2015, rom http://www.chemicalbook.com/ChemicalProductProperty_EN_CB9230712.htm

24 627390 Dimethyl Adipate. *CA.gov.* Retrieved July 20, 2015, from http://www.arb.ca.gov/db/solvents/solvent_pages/esters-HTML/dimethyl_adipate.htm

25 Watts, R. J. (1998). Hazardous wastes: sources, pathways, receptors.

- *Water is used as the reference chemical, where K_2 = 0.83 cm/sec and M_2 is equal to the molecular weight of water. $M_{volatile}$ is equal to the molecular weight of the volatile compound in the mixture for which the generation rate was calculated.*[26]

Methylene chloride-based paint strippers contain paraffin wax to slow the release of the methylene chloride to the air. Consequently, the equation used to estimate generation rate (eq 3) may not be accurate for this product.

Since solid paraffin wax is not considered hazardous, it is not required to be listed on the paint stripper MSDS.[27] Therefore, the exact percentage of paraffin present in the methylene chloride-based paint stripper formulation used in this study is unknown. As such, the generation rate for methylene chloride is also unknown.

To estimate methylene chloride generation rates from paint stripper, experimental values from a study by Vulcan Chemicals were used.[28] A baseline of 1% wax was assumed.

Table 9. Experimental Results from "An Investigation of the reduction of Methylene Chloride"

Composition	Wax Weight %	Generation Rate (mg/min/in^2)	Generation rate converted to m^2 and multiplied by an area of 1 m^2 (mg/min)
Methylene Chloride	-	29	4.5E+04
Methylene Chloride + Wax	1.0 %	2.2	3.4E+03
Methylene Chloride + Wax	1.5%	0.4	6.2E+02

Note: Here the evaporation rate is not the evaporation rate of methylene chloride relative to a reference compound. The generation rate was measured experimentally. Values in table reflect the recorded results.

Assuming no paraffin wax in the benzyl alcohol or dimethyl adipate product formulations, generation rates were derived using Equation 3.

The concentration in the air was then determined using the equation for the simple box model:

26 Matthiessen, 1986 R.C Matthiessen Estimating chemical exposure levels in the workplace. Chemical Engineering Progress, April (1986), pp. 30–34

27 U.S. Department of Labor, Occupational Safety and Health Administration. *Guidance for Hazard Determination.* Retrieved from https://www.osha.gov/dsg/hazcom/ghd053107.html

28. Vulcan Chemicals). An Investigation of the Reduction of Methylene Chloride Volatility in Paint Strippers. Wichita, KS: Mainz, E.L.

(eq 1) $$C_{room,t} = C_{airborne,t-1} + \frac{G_t \times t}{room\ volume} - C_{leaving,t}$$

where $C_{room,\ t}$ represents the chemical concentration in the air to which the user may be exposed at a given time. The concentration was modeled until $C_{room,\ t}$ reached zero.

The 8-hour time weighted average (TWA) concentration was then calculated for each chemical using a time-interval of 15 minutes.

(eq 5) $$TWA = \frac{t_1 c_1 + t_2 c_2 + \ldots + t_n c_n}{t_1 + t_2 + \ldots + t_n}$$

(eq 6) $$TWA_{8-hour} = \frac{0.25c_1 + 0.25c_2 + \ldots + 0.25c_n}{8-hour}$$

$$\left[\ \frac{g}{m^3} = \frac{hr \cdot \frac{g}{m^3} + hr \cdot \frac{g}{m^3} + \ldots + hr \cdot \frac{g}{m^3}}{hr}\ \right]$$

where t_n represents a 15 minute, or 0.25 hour, time interval until 480 minutes, or 8 hours; and c_n is equivalent to $C_{room,\ t}$ at time t_n.

Sensitivities were performed for:

- Room size
  - small room: 9 m^3, the approximate volume of a small bathroom
  - baseline, mid-size room: 54 m^3
  - large room: 91 m^3, the approximate volume of a 2-car garage
- Ventilation rate
  - low ventilation: 10th percentile ventilation rate
  - mid ventilation: mean ventilation rate[29]
  - baseline, high ventilation: 90th percentile ventilation rate
- Formulation ranges
  - low chemical: lowest amount of chemical, highest amount of water
  - baseline, mid chemical: middle amount of chemical
  - high chemical: highest amount of chemical, lowest amount of water
- Time

29 U.S. Environmental Protection Agency. (2014). *TSCA Work Plan, Chemical Risk Assessment: Methylene Chloride Paint Stripping Use* (EPA Document No. 740-R1-4003).

    - low: time of chemical indoors equivalent to the time to achieve the functional unit plus 5 minutes to remove scrapings outside
- Percent volatilization
    - low: 90% of chemical available to volatilize
    - mid: 95% of chemical available to volatilize
    - baseline, high: 100% of chemical available to volatilize
- Partial pressure to calculate G (for dimethyl adipate-based paint stripper)
    - baseline, low: partial pressure calculated from DMA vapor pressure of 7.89E-05 atm
    - high: partial pressure calculated from DMA vapor pressure of 2.6E-04 atm
- Wax % (for methylene chloride-based paint stripper)
    - low: 0.5% wax
    - baseline, mid: 1% wax
    - high: 1.5% wax

Sanding Dust Exposure

Unlike chemical paint strippers, which present inhalation exposures to vapors, sanding presents inhalation exposures to particles. The diameter of particles generated when sanding can be equal to or smaller than 10 µm, classified as PM10, and are therefore inhalable.[30] The smaller particles can have a diameter of 0.5 to 5µm, making them easily respirable (i.e. they can enter into the lower airways of the body).[31]

Since the sanding process does not fit the exposure model used for the chemical paint strippers, a separate exposure assessment was completed for sanding dust.

There are multiple studies that have measured the concentration of dust generated from sanding. Experimental values of total and respirable dust concentrations from sanding wood with an electric orbital sander, published by the National Toxicology Program, were used instead of modeling dust concentrations (Table 10).[32] Scenarios with and without a vacuum collector were explored.

30 U.S. Environmental Protection Agency (2015, September) *Particulate Matter (PM).* Retrieved from http://www.epa.gov/pm/.

31 NTP (National Toxicology Program). 2014. *Report on Carcinogens, Thirteenth Edition.* Research Triangle Park, NC: U.S. Department of Health and Human Services, Public Health Service. Retrieved from http://ntp.niehs.nih.gov/pubhealth/roc/roc13/

32 NTP (National Toxicology Program). 2014. *Report on Carcinogens, Thirteenth Edition.* Research Triangle Park, NC: U.S. Department of Health and Human Services, Public Health Service. Retrieved from http://ntp.niehs.nih.gov/pubhealth/roc/roc13/

Table 10. Wood dust concentrations from electric orbital sanding with and without a vacuum attached to the sander. (Reported by the National Toxicology Program in the *Thirteenth Carcinogens*' section on Wood Dust)

	Total Dust Concentration	**Respirable Dust Concentration**
Sander with Vacuum	0.002 mg/m^3	0.001 mg/m^3
Sander without Vacuum	0.70 mg/m^3	0.008 mg/m^3

Note: Values in table represent results recorded in report.

Exposure information was then coupled with hazard/toxicity information to compare alternatives for their acute toxicity, chronic toxicity, and carcinogenicity.

Acute Toxicity

The 8-hour TWA concentration was compared with a standard acute exposure limit. The only standard that existed for all three chemicals of interest was DuPont's acceptable exposure level (AEL). The relative acute hazard of each chemical was calculated by taking the ratio of the TWA to the AEL:

(eq 7)

$$Acute\ Hazard\ Ratio = \frac{TWA_{8-hour}}{AEL_{8-hour}}$$

$$\left[\ dimensionless = \frac{mg/m^3}{mg/m^3}\right]$$

An Acute Hazard Ratio greater than 1 indicates a concern. Multiple Acute Hazard ratios for sanding were calculated, using a permissible exposure level (PEL) or a recommended exposure level (REL), reported in Table 10.[33]

The methylene chloride-based paint stripper presents the greatest acute hazard, even with the higher 1.5% paraffin wax formulation to reduce exposure. Though its acute hazard is lower than that of methylene chloride, exposure to dimethyl adipate-based paint strippers may also exceed the AEL under the high generation rate scenario (i.e. if the vapor pressure is actually higher than estimated by the California Air Resources Board). It should be noted, though, that DuPont's AEL is currently the

33 NTP (National Toxicology Program). 2014. *Report on Carcinogens, Thirteenth Edition.* Research Triangle Park, NC: U.S. Department of Health and Human Services, Public Health Service. Retrieved from http://ntp.niehs.nih.gov/pubhealth/roc/roc13/

only standard for dimethyl adipate, and it is unclear whether the exposure limit set for this chemical is more or less conservative than it is for other chemicals. While these acute hazard results are meaningful, additional standards, such as the industry standards for wood dust exposure set forth by the Centers for Disease Control, would help reduce uncertainty in the risk estimates[34].

34 Centers for Disease Control and Prevention (CDC). (2009). NIOSH pocket guide to chemical hazards. *Cincinnati: US Department of Health and Human Services (NIOSH) publication*, 90-11.

Table 11. Acute Hazard Ratio of Paint Stripping Alternatives. Generation Rate, 8-hour AEL, and modeled 8-hour TWA for paint strippers using mid product formulation are provided. PEL and REL, and experimental air concentrations for total dust and respirable dust are provided for sanding.

Paint Stripper	**Generation Rate ($g/min\ m^2$)**	**8-hour TWA (mg/m^3)**	**8-hour AEL (mg/m^3)**	**Acute Hazard Ratio**
Methylene Chloride - 1.0% Paraffin Wax	3.4	996	174	5.7
Methylene Chloride - 1.5 % Paraffin Wax	0.62	468	174	2.7
Benzyl Alcohol	0.024	1.88	44.2	0.043
Dimethyl Adipate [baseline G (high G)]	0.008 (0.026)	6.15 (20.3)	10	0.62 (2.0)
Sanding Dust Type	**Vacuum Attachment**	**Measured Concentration in the Air (mg/m^3)**	**OSHA PEL (mg/m^3)**	**Acute Hazard Ratio**
Total Dust	with vacuum	0.002	15	0.00013
Respirable Dust	with vacuum	0.001	5	0.0002
Total Dust	without vacuum	0.70	15	0.047
Respirable Dust	without vacuum	0.008	5	0.0016
Sanding Dust Type	-	**Measured Concentration in the Air (mg/m^3)**	**NIOSH REL (mg/m^3)**	**Acute Hazard Ratio**
Total Dust	with vacuum	0.002	1	0.002
Total Dust	without vacuum	0.70	1	0.70

Chronic Toxicity

To model the chronic hazard for exposure to the alternatives, the chronic daily intake (CDI) was calculated:[35]

(eq 8)

$$CDI = \frac{CA \times IR \times ET \times ED \times EF}{BW \times AT}$$

$$\left[\frac{mg}{kg \cdot day} = \frac{\frac{mg}{m^3} \times \frac{m^3}{hr} \times \frac{hr}{day} \times years \times \frac{days}{year}}{kg \times days}\right]$$

The equation terms and any assumptions made regarding those terms are described in Table 11.

Table 12. Variables and assumptions used to model chronic daily intake (mg/kg-day).

Variable	Description *(units)*	Assumption
CDI	Chronic daily intake by inhalation *(mg/kg-day)*	
CA	Concentration of pollutant in in the air *(mg/m^3)*	The 8-hr time weighted average air concentration calculated using equations 1-4 Sensitivity was included for room size and how long the paint stripper remained indoors (the scenarios found to have the greatest sensitivity in the exposure model)
ET	Exposure time *(hr/day)*	The time for the product to achieve the functional unit (e.g. 15 minutes for methylene chloride-based paint stripper = 0.25 hr/day) Sensitivity was included for a continuous 8-hour exposure
EF	Exposure Frequency *(days/year)*	Based on the reported average number of paint stripper uses per year of 3.5-3.7 uses.[36, 37]

35 Watts, R. J. (1998). Hazardous wastes: sources, pathways, receptors.

		Assumed EF = 3.6 days/year Sensitivity: 0.5 × EF = 1.8 days/year 2 × EF = 7.2 days/year
ED	Exposure Duration (*years*)	1 year
IR	Inhalation Rate *(m^3/hr)*	Average inhalation rate for 21 to 61 years old based on EPA's 2011 long-term exposure inhalation rates.[38] Assumed IR = 15.85 m^3/hr
AT	Averaging Time (period over which exposure is averaged - *days*)	For non-carcinogenic effects, AT = ED*365 days/ year = 365 days
BW	Body Weight (*kg*)	The average body weight for combined male and female adults (age 20+), based on 1994-1996, 1998 USDA CSFII.[39] Assumed BW = 76 kg Sensitivity: 10th percentile BW = 54 kg 95th percentile BW = 107 kg

A similar calculation can be performed for sensitive subpopulations such as children or adults with breathing difficulties. Since this is meant to be demonstrative, we did not perform calculations for sensitive subpopulations, which may be specific for a given case.

Sensitivities were performed for:

- Concentration of pollutant in the air, from the exposure model
    - low: based on a shorter amount of time that the chemical remains indoors
    - low: based on a large room size
    - baseline, mid: based on the baseline exposure model
    - high: based on a small room size
    - three scenarios were modeled for dimethyl adipate based on three different dimethyl adipate vapor pressures used in the exposure model

36 Abt Associates. "Methylene Chloride Consumer Products Use Survey Findings." Prepared for the U.S. Consumer Products Safety Commission, Bethesda, Maryland. 1992. http://hero.epa.gov/index.cfm?action=reference.details&reference_id=1005947

37 Westat. 1987. "Household solvent prodcts – A national usage survey." Prepared for U.S. Environmental Protection Agency, Washington, D.C. PB88-132881. http://www.ntis.gov/search/product.aspx?ABBR=PB88132881

38 U.S. EPA. Exposure Factors Handbook 2011 Edition (Final). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-09/052F, 2011

39U.S. EPA. Exposure Factors Handbook 2011 Edition (Final). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-09/052F, 2011.

- Exposure time
  - baseline, mid: time needed to strip 1m^2 of painted wood
  - high: 8-hour work time
- Body weight[40]
  - low: 10th percentile body weight of American adults, 54 kg
  - baseline, mid: average body weight of American adults, 76 kg
  - high: 95th percentile body weight of American adults, 107 kg
- Exposure frequency[41, 42]
  - low: half the number of annual uses of chemical paint stripper, 1.8 days
  - baseline, mid: average annual uses of chemical paint stripper, 3.6 uses = 3.6 days
  - high: twice the number of annual uses of chemical paint stripper, 7.2 days

The chronic daily intake was then used to calculate the hazard index (HI):[43]

(eq 9)

$$HI = \frac{CDI}{RfD}$$

$$[\, dimensionless = \frac{mg/kg \cdot day}{mg/kg \cdot day} \,]$$

where RfD is equal to the chronic inhalation reference dose.

Inhalation reference doses, or reference concentrations, are generally provided in units of mg/m^3 (Table 13). The following unit conversion from Washington State can be used to convert inhalation concentrations to doses:[44]

(eq 10)

$$Dose = Concentration \times \frac{20}{70}$$

$$[\, \frac{mg}{kg \cdot day} = \frac{mg}{m^3 air} \times \frac{m^3 air/day}{kg\ body\ weight} \,]$$

Where the assumption is that a typical human breathes 20 m^3 of air/day and weighs 70 kg. These values can be adjusted for sensitive subpopulations.

40 U.S. EPA. Exposure Factors Handbook 2011 Edition (Final). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-09/052F, 2011.

41 Abt Associates. "Methylene Chloride Consumer Products Use Survey Findings." Prepared for the U.S. Consumer Products Safety Commission, Bethesda, Maryland. 1992. http://hero.epa.gov/index.cfm?action=reference.details&reference_id=1005947

42 Westat. 1987. "Household solvent products – A national usage survey." Prepared for U.S. Environmental Protection Agency, Washington, D.C. PB88-132881. http://www.ntis.gov/search/product.aspx?ABBR=PB88132881

43 Watts, R. J. (1998). Hazardous wastes: sources, pathways, receptors.

44 Notes on Chemical-Specific Parameters –Toxilogical Prpoerties. Retrieved October 12 2015, from https://fortress.wa.gov/ecy/clarc/FocusSheets/ToxicologicalParameters.htm#RFDi

As far as we could determine, reference doses for dimethyl adipate or dimethyl glutarate have not been developed. There is, however, a study providing a NOEC (no observable effect concentration) for inhalation of dimethyl glutarate.[45] The 8-hour AEL for dimethyl adipate and dimethyl glutarate are both 10 mg/m^3. In the absence of experimental data for dimethyl adipate, it was assumed that the NOEC for dimethyl glutarate (50 mg/m^3) is a reasonable approximation of what the NOEC for dimethyl adipate would be. For the purposes of this study, a reference dose was derived:

(eq 11)

$$RfD = \frac{NOEC}{UF \times MF}$$

$$\left[\frac{mg}{kg \cdot day} = \frac{mg/kg \cdot day}{unitless\ factors}\right]$$

The reference dose takes into account uncertainty and professional judgment with an uncertainty factor (UF) and a modifying factor (MF). The UF is the product of four factors; H, A, S, and L. While a reference dose is meant to be conservative, one that is too conservative may be misleading as to possible hazards. Two potential reference doses are presented here, with one more conservative than the other.

The uncertainty level used to calculate the dimethyl adipate RfD is explained in Table 14.

45 Copyrighted source : http://echa.europa.eu/web/guest/legal-notice European Chemicals Agency. Dimethyl Glutarate. Retrieved 13 July 2015 from http://apps.echa.europa.eu/registered/data/dossiers/DISS-b6b5bc9c-d510-2a57-e044-00144f67d031/AGGR-ed96668e-e44d-449a-b1cc-07d07373b55a_DISS-b6b5bc9c-d510-2a57-e044-00144f67d031.html#AGGR-ed96668e-e44d-449a-b1cc-07d07373b55a

Table 13. Chronic oral reference dose values for chemicals found in chemical paint stripper alternatives.

Chemical	**Chronic Oral Rfd mg/ kg day *(Uncertainty Factor)***	**Inhalation Rfd mg/ kg day *(Uncertainty Factor)***
Methylene Chloride	6.0E-03 *(30)*[46]	0.6 mg/m^3 *(30)* [47] = 0.17 mg/kg day
Methanol	2.0 *(100)* [48]	20 mg/ hr L *(100)*[49]
Stoddard Solvent	NA	NA
Dimethyl Adipate	NA	NA
Dimethyl Glutarate	NA	NA
Smectite	NA	NA
Benzyl Alcohol	0.3 *(NA)*[50]	NA
Titanium Dioxide	1.0 *(NA)*	NA

Note: NA = data not available. Reported are literature values.

46 U.S. Environmental Protection Agency(2015, February). *Dichloromethane (CASRN 75-09-2)*. Retrieved from US EPA website http://www.epa.gov/IRIS/subst/0070.htm

47 U.S. Environmental Protection Agency(2015, February). *Dichloromethane (CASRN 75-09-2)*. Retrieved from US EPA website http://www.epa.gov/IRIS/subst/0070.htm

48 U.S. Environmental Protection Agency(2014, October). Methanol (CASRN 67-56-1). Retrieved from US website www.epa.gov/iris/subst/0305.htm.

49 U.S. Environmental Protection Agency(2014, October). Methanol (CASRN 67-56-1). Retrieved from US website www.epa.gov/iris/subst/0305.htm.

50 European Medicines Agency (2014) Question and Answers on Benzyl Alcohol in the context of the revision of the guideline 'Excipients and the label and package leaflet of medicinal products for human use (CPMP/463/00) (Draft) Canary Warf, United Kingdom: Committee for Human Medicinal Products (CMHP).

Table 14. Uncertainty factors and the modifying factors for the RfD calculations.

Uncertainty Factors and Modifying Factor	Value	Reasoning
Intraspecies variability (H)	10	Empirical data from animal study
Interspecies uncertainty (A)	10	Empirical data from animal study
Sub-chronic to chronic extrapolation (S)	10	Empirical data from sub-chronic study
Use of LOEL in absence of NOEL (L)	1	NOEC value was used, so no uncertainty associated with using LOEC value
Modifying factor	1 or 10	Professional judgment may vary. Potential reasons for increasing how conservative the estimate is could include: somewhat small population size of study (n=120); dimethyl glutarate instead of dimethyl adipate
UF x MF	*1,000 or 10,000*	*product of all uncertainty factors and modifying factor*

Table 15. Reference doses for dimethyl adipate using two different levels of conservativeness.

Dimethyl Adipate	NOEC	UF x MF	RfD ($\frac{NOEC}{UF \times MF}$)
RfD	50 mg/m^3	1,000	0.05 mg/m^3 =0.014 mg/kg day
more conservative RfD	50 mg/m^3	10,000	0.005 mg/m^3 =0.0014 mg/kg day

No reference dose exists for sanding dust, and one could not be derived. Therefore, chronic toxicity was only assessed for chemical alternatives, not for sanding.

The CDI was calculated with sensitivities for air concentration based on room size and exposure time, as well as sensitivities for body weight and exposure frequency. Variations in the air concentration were found to have the greatest effect on CDI.

The hazard index was calculated for all scenarios (Table 16). In all scenarios, benzyl alcohol was found to have a lower HI than methylene chloride. Two potential dimethyl adipate reference doses were used to calculate a hazard index. Dimethyl adipate was found to have a lower HI than methylene chloride when using the first reference does, and was found to have a higher HI than methylene chloride when a more conservative reference dose was used.

To more accurately assess chronic hazard, better inhalation reference doses should be derived.

Table 16. Hazard Index for methylene chloride, benzyl alcohol, and dimethyl adipate for three air concentration scenarios. A hazard index was calculated for dimethyl adipate using two reference doses with different levels of conservativeness; in parentheses are the range of values calculated from the generation rate sensitivity to dimethyl adipate vapor pressure.

	Hazard Index from Baseline Scenario	**Hazard Index from High Concentration Scenario**	**Hazard Index from Low Concentration Scenario**
Methylene Chloride	3.0	18.0	0.37
Benzyl Alcohol	0.006	0.04	0.00005
Dimethyl Adipate, RfD [baseline G (high G)]	0.66 (2.2)	4.0 (13.14)	0.08 (0.25)
Dimethyl Adipate, more conservative RfD [baseline G (high G)]	6.6 (22)	40 (131.4)	0.77 (2.5)

Carcinogenicity

Methylene chloride is classified as a category 2B carcinogen[51], meaning that it is possibly carcinogenic to humans.

51 IARC (International Agency for Research on Cancer), 1987. IARC monograph on the Evaluation of Carcinogenic Risk to Humans. Lyon, France, pp. 82-87.

Carcinogenic risk is calculated using chronic daily intake,

(eq 8) $$CDI = \frac{CA \times IR \times ET \times ED \times EF}{BW \times AT}$$

where averaging time (AT) is the only distinction between the chronic daily intake value used to calculate hazard index and that used to calculate carcinogenic risk. Since carcinogenic risk is a lifetime risk, the averaging time is calculated for an average lifetime of 70 years (AT = 70 * 365 days/ year = 25,550 days).

The probability of carcinogenic risk is calculated as:

(eq 12) $$Carcinogenic\ Risk = CDI \times SF$$

$$[\ dimensionless = \frac{mg}{kg \cdot day} \times \frac{kg \cdot day}{mg}\ ]$$

where SF is a carcinogenic slope factor derived by the EPA from dose-response relationships. Since the primary route of exposure to paint stripper ingredients is through inhalation, an inhalation slope factor is used in this case.

The OECD QSAR Toolbox[VII] was used to predict whether any alternative ingredients are likely carcinogenic. Based on experimental and predictive results from this toolbox, all chemical alternatives are non-carcinogenic.

Some wood dust, however, is classified as carcinogenic (Table 1).[52]

[VII] OECD QSAR Toolbox can be accessed here: http://www.qsartoolbox.org/

52 United States Department of Labor, Occupational Safety and Health Administration. *NIOSH Pocket Guide to Chemical Hazards, Wood Dust.* Retrieved from https://www.osha.gov/dts/chemicalsampling/data/CH_276185.html

Table 17. Carcinogenicity Classifications for Paint Stripper Ingredients and Sanding Wood Dust

Ingredient	**Carcinogen Classification**
Methylene Chloride	Possibly Carcinogenic
Benzyl Alcohol	Inconclusive*
Titanium Dioxide	Not Likely Carcinogenic
Dimethyl Adipate	Not Likely Carcinogenic
Dimethyl Glutarate	Not Likely Carcinogenic
Wood Dust Type	**Carcinogen Classification**
Oak and Beech	Confirmed Human Carcinogen
Birch, Mahogany, Teak, and Walnut	Suspected Human Carcinogen
All Other Wood Dusts	Not Classifiable as a Human Carcinogen

*The OECD QSAR Toolbox provides results from multiple carcinogenicity/genetic toxicity tests, both experimental and predictive. The majority of results for benzyl alcohol were negative, but there were some tests that were inconclusive or positive.

A slope factor has been derived for methylene chloride (inhalation SF = 0.00165 mg/kg-day),[53] but not for any other alternative. Consequently, carcinogenic risk was only calculated for methylene chloride exposure (Table 18). The same sensitivities assessed in the hazard index calculation were also assessed here. As with the hazard index, the greatest sensitivity in carcinogenic risk is the concentration of the pollutant in the air. The carcinogenic risk calculated for methylene chloride exceeds the typical level considered by US EPA of 1 in a million increase in cancer risk.

Table 18. Carcinogenic Risk for inhalation exposures to methylene chloride from paint stripper at varying air concentrations.

	Inhalation Carcinogenic Risk from Baseline Scenario	**Inhalation Carcinogenic Risk from High Concentration Scenario**	**Inhalation Carcinogenic Risk from Low Concentration Scenario**
Methylene Chloride	0.0008	0.005	0.0001

53POPS Toolkit. Slope Factors (SF) for Carcinogens from US EPA (Toolkit) Retrieved from http://www.popstoolkit.com/tools/HHRA/SF_USEPA.aspx

Electricity use for a power sander

Electricity from a power sander was measured using an electricity usage monitor. The power sander required 1634 watts of power over a time period of 60 minutes which was then be converted to MJ. The impacts from the use phase were assessed using a process LCA approach which requires a flow in the form of MJ. The results were then normalized using Traci 2.1 normalization factors for California.

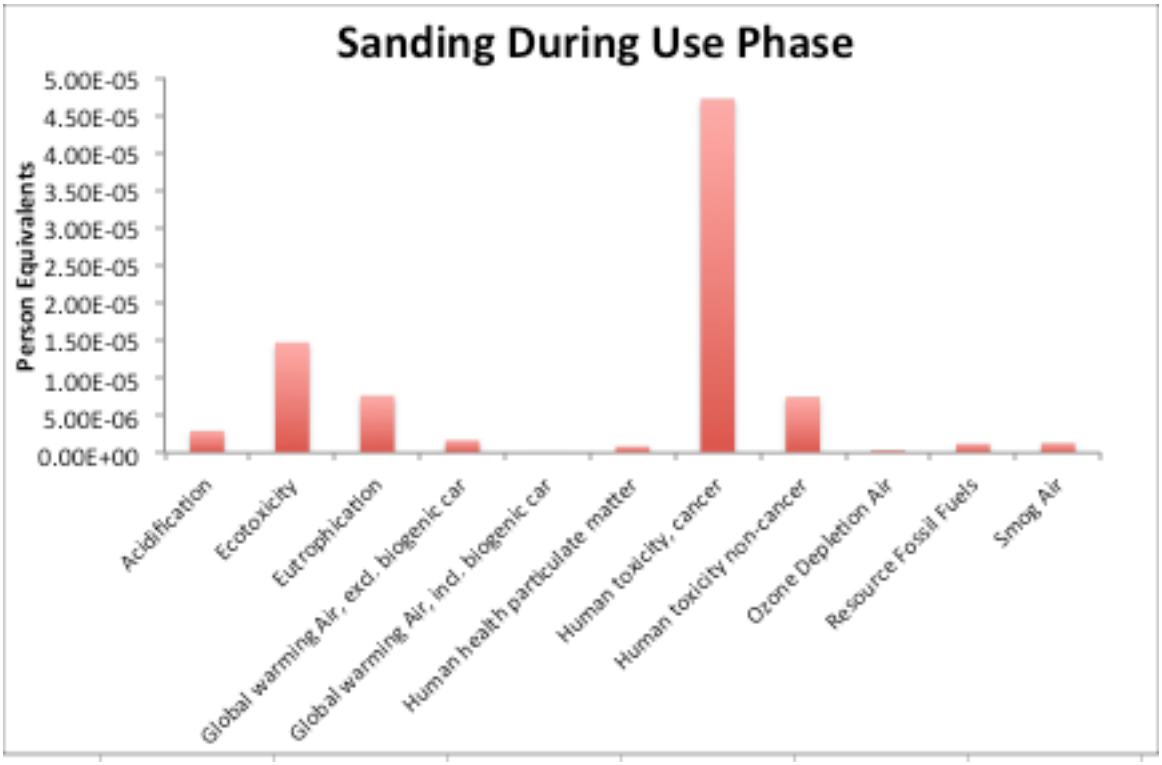

Figure 8. Use phase sanding electricity Process results in person equivalents, normalized using Traci 2.1 normalization factors for California.

The impacts generated for power consumption during sanding are greatest for human toxicity, cancer. When compared with the upstream person equivalent value for human toxicity, cancer is two orders of magnitude smaller than the human toxicity, cancer person equivalents for methylene chloride and benzyl alcohol. This suggests that the non-inhalation impacts generated during the use phase of sanding are most likely not relevant. While the time to sand one square meter of wood varies based on a variety of factors (e.g. age and type of paint) the expected time is less than 60 minutes. A 60-minute time period provided a worst-case scenario for the impacts generated during the use phase.

End-of-Life Fate

After use, the consumer product can be disposed of in a landfill or discarded in the environment. . In the case of paint strippers, releases are mostly to the atmosphere from the use phase, although it is possible that a user could dispose of the waste in the drain, directly into soil or a water body. Since the likelihood of improper disposal is nowadays much smaller, the analysis here focuses on the complete release of chemicals to the environment.

The downstream impacts of chemical-based paint strippers were assessed by first modeling the end-of-life fate of the volatile chemicals in each paint stripper. Two different models of a pollutant fate were considered: the "Level III fugacity model" developed by the Canadian Centre for Environmental Modelling and Chemistry at the University of Toronto[VII], and the CLiCC organic fate model developed at the University of California, Santa Barbara (UCSB). The two models were used for comparison since the CLiCC model is more sophisticated. Both models were run to determine how each chemical partitions in the environment based on the chemical's physicochemical properties.

A Level III model represents an open system in steady state that considers mass transfer limitations and large-scale advective transport. MacKay and Paterson (1991) use a four-compartment model to simulate the end of life transport of chemicals. The model estimates the concentrations of the organic within the same order of magnitude as observed values, crediting its precision in modeling the end of life fate and transport of chemicals in the environment.[54] The CLiCC organic fate model represents a transient open system, also with advective transport. Initial emission rates (kg/hr) for each chemical are required to run either model. The Level III model estimates a single concentration value for different environmental compartments, while the CLiCC organic fate model estimates daily concentrations in 27 environmental compartments over the simulated time period. The CLiCC organic fate model requires more environmental parameters than a Level III model.

After running a series of sensitivity analyses for a Level III model, the results of the Level III and CLiCC organic models were used to estimate risk to living organisms, presented as hazard and acute risk quotients. Since the focus of environmental and public health revolves around concentrations in air and (fresh) water, the comparison of the models was performed based on these environmental compartments. The models are expected to be used in a specific geographic location, so that parameter values for the environmental compartments can be adjusted. For this case study we considered the San Francisco (CA) Bay area as the geographical region to be modeled.

VII The Centre for Environmental Modeling can be accessed here: (http://www.trentu.ca/academic/aminss/envmodel/models/VBL3.html)

54 Mackay, D., & Paterson, S. (1991). Evaluating the multimedia fate of organic chemicals: a level III fugacity model. *Environmental Science & Technology*, *25*(3), 427-436.

Assuming that most of the chemicals in the paint stripper eventually volatilize, the ultimate fate of the chemicals were first modeled as emissions to the air. A sensitivity analysis was also performed to examine the fate if 90% of the compound by mass volatilizes and 10% of the product ends up as emissions to soil; this scenario simulates the event that 10% of the product ends up in a landfill as scrapings and migrates into the soil rather than volatilizing to the air. The risks associated with pollutants in the water and air were then analyzed using toxicological data.

A combination of methylene chloride market data and population data were used to determine the emission rates of the chemicals.

Chemical Emissions

In 2010 approximately 181 million pounds of methylene chloride were used in the United States annually, 25% of which were used for chemical paint stripping purposes[55]. The number of square meters that could be stripped with this mass of methylene chloride was determined using the annual consumption mass of methylene chloride in paint stripper and its reference flow. This square meter value was then used to determine the mass of benzyl alcohol or dimethyl adipate that would be required to replace methylene chloride, using the reference flows of the respective chemicals. For the purposes of this study, complete substitution of alternatives was assumed.

Sample Calculation

Annual US Consumption

$$181\ \frac{million\ pounds\ of\ methylene\ chloride}{year} \times 25\%\ for\ paint\ stripping\ purposes$$

$$= 45.3\ \frac{million\ pounds\ of\ methylene\ chloride\ for\ paint\ stripping}{year}$$

Number of functional units (m^2 stripped) that can be achieved

$$Annual\ consumption\ \div\ methylene\ chloride\ reference\ flow$$

$$45{,}250{,}000\ \frac{pounds\ of\ methylene\ chloride}{year} \div 0.96\ \frac{pounds\ of\ methylene\ chloride}{m^2}$$

$$= 47{,}300{,}000\ \frac{m^2}{year}$$

Calculated annual US consumption of alternative chemical replacement

55 Environmental Protection Agency. (2014). TSCA Work Plan, Chemical Risk Assessment: Methylene Chloride Paint Stripping Use (EPA Document No. 740-R1-4003).

$$number\ of\ functional\ units\ that\ can\ be\ achieved$$
$$\times alternative\ chemical\ reference\ flow$$
$$low\ end\ =\ 47{,}300{,}000\ \frac{m^2}{year} \times 0.64\ \frac{pounds\ of\ benzyl\ alcohol}{m^2}$$
$$=\ 30{,}500{,}000\ \frac{pounds\ of\ benzyl\ alcohol}{year}$$
$$high\ end\ =\ 47{,}300{,}000\ \frac{m^2}{year} \times 1.07\ \frac{pounds\ of\ benzyl\ alcohol}{m^2}$$
$$=\ 50{,}800{,}000\ \frac{pounds\ of\ benzyl\ alcohol}{year}$$

Annual United States consumption was then scaled to consumption in the San Francisco Bay area using 2010 US Census data. Population data was combined with annual consumption data to determine the mass of paint stripping chemicals consumed and consequently emitted in the San Francisco Bay area.

These calculations assume that chemical paint strippers are used on a regular basis throughout the year and that there are no sharp increases or decreases in emissions. We also did not consider seasonality in emissions, given limited data on consumer use of these products.

Environmental Fate

Level III Model

First, the Level III multimedia fugacity model was used to simulate the fate of methylene chloride, methanol, benzyl alcohol, and dimethyl adipate from paint stripper releases in the San Francisco Bay. Environmental parameters for the San Francisco Bay were found in the San Francisco Bay PCBs TMDL Staff Report (Table 19).[56] When literature values were not available, default values in the model were used and tested for sensitivity. Default values were used for transport velocities (m/h) since these values were not available from the collected data.

56 California Regional Water Quality Control Board, San Franciso Bay Region. (2008, February). Total Maximum Daily Loads for Propsed Basin Plan Management. Retrieved from http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/sfbaypcbs/Staff_Report.pdf

Table 19. Environmental Parameters for San Francisco Bay for Level III Fugacity Model

Total Surface Area	**m**	**Organic Carbons**		**g/g**
Air Height	300	Suspended particles		0.2
Average water depth	6	Soil		0.01
Average soil depth	0.25	Sediment		0.04
Average Sediment Depth	0.5 to 1	Lipid fraction (fish)		0.05
Bulk/Sub Compartments	**m^3**	**Density (kg/m^3)**	**Transport Velocities**	**m/h**
Air	3.30E+12	1.19	*air side air-water MTC*	*5*
Water	6.60E+09	1000	*water side air-water MTC*	*0.05*
Soil	2.48E+09	2400	*Rain rate*	*0.001*
Sediment	5.50E+07	**2400**	*aerosol dry deposition*	*10*
Fish	6600	1100		
Air aerosols	220	2000	*soil-air phase diffusion MTC*	*0.02*
	Volume Fractions	**Density (kg/m^3)**	*soil-water phase diffusion MTC*	*0.00001*
Air aerosols	6.67E-11		*soil-air boundary layer MTC*	*5*
Suspended particles in water	0.000005	1500	*sediment-water diffusion MTC*	*0.0001*
Fish	0.000001	1100	*sediment deposition*	*0.0000005*
Air in soil	*0.2*	1.206	*sediment resuspension*	*0.0000002*
Water in soil	*0.3*	1000	*soil-water runoff rate*	*0.00005*
Soil solids	*0.5*	2400	*soil-solids runoff rate*	*1.00E-08*
Water in sediment	*0.8*	1000	*scavenging ratio (unitless)*	*200000*
Sediment Solids	*0.2*	*2400*		

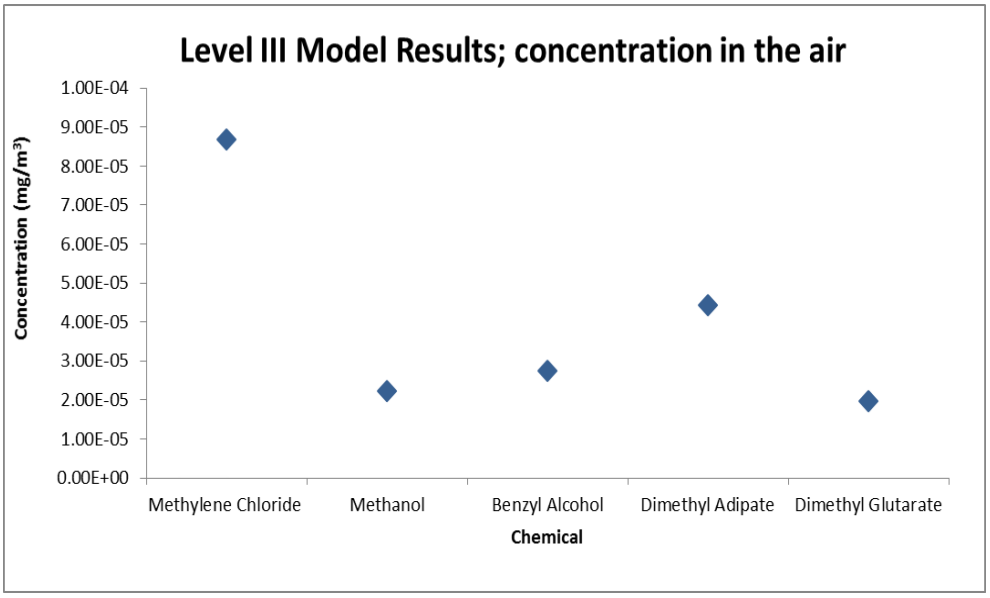

Figure 9. Level III model results; concentration in the air when all emissions are initially released to the air. Results are for high release scenarios.

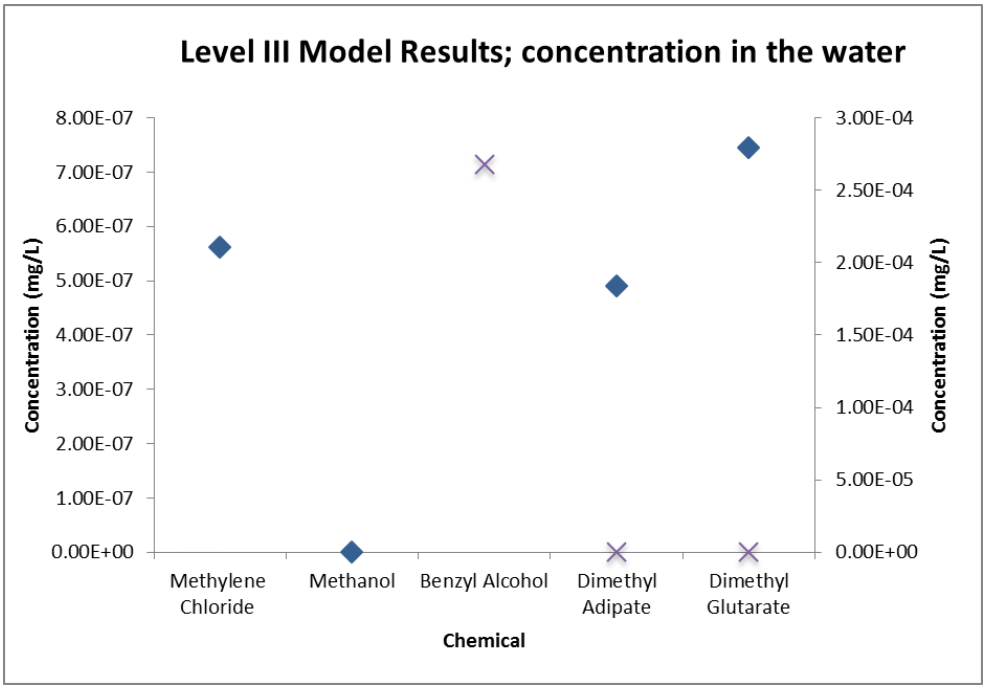

Figure 10. Level III model results; concentration in water when all emissions are initially released to the air. Methylene Chloride, Methanol, Dimethyl Adipate, and Dimethyl Glutarate on the left y-axis, Benzyl Alcohol on the right y-axis. Results are for high release scenarios.

Level III model results predict that methylene chloride would have the highest concentration in the air when all emissions are initially released to the air (Figure 9). The concentration of benzyl alcohol would be predicted to be two orders of magnitude greater than the concentration of the other chemicals in water (Figure 10). The concentration of methanol in water would be the lowest of all the chemicals.

After running the Level III model results under the baseline scenario (Table 19) the following sensitivity analyses were completed:

- The mass transfer coefficients were multiplied by a factor of 0.5 and 1.5. A separate sensitivity analysis was also run to examine the effect that individually altering each mass transfer coefficient value by 1.5 times the default value has on the model results. This sensitivity analysis showed that the final results are not greatly affected by altering the mass transfer coefficients and thus the default values can be used as an approximation.

- The Level III model was run under two different emission levels (kg/hr); low and high end formulation for each chemical. This sensitivity was performed using default mass transfer coefficients, assuming that all emissions are released into the air. (Table A1 and Table A2)
    - The results reveal that the mass of the chemical under study in each environmental compartment is proportional to the emission level (Table A2). The percentage of an individual chemical in each environmental compartment is independent of the emission level and is a factor of the chemical's physicochemical properties. Taking a conservative approach, the final sensitivities were performed using the high emissions level to reveal the highest potential concentration of chemical in each environmental compartment.

- Emissions) to air and soil were altered. The model was run for two scenarios; 100% of emissions were released into air, and 90% of emissions were released into air and 10% were released into the soil, assuming disposal of excess or spent product to soils. 100% of emissions released to the air assumes that all the product used volatilizes, even after the paint has been removed.
    - The results reveal that when 90% of the emissions are considered to be released to the air and 10% of emissions released to the soil a larger percentage of chemical ends up in the soil, for all the chemicals (Table A3). For a chemical such as benzyl alcohol a large percentage of the chemical is predicted to be in the soil (91%) when all emissions are released to the air. The percentage change when emissions are released to soil is only 1.4%. For a chemical such as dimethyl glutarate a small percentage is in the soil (2.7%) when all emissions are released to air. The percentage change when emissions are released to soil is 71%.

CliCC Organic Fate Model

The CLiCC organic fate model was used to simulate the fate of methylene chloride, methanol, benzyl alcohol, and dimethyl adipate from paint stripper releases in the San Francisco Bay. Environmental parameters for the San Francisco Bay were collected and provided by the CLiCC project (Figure A1 – Figure A3). The model was run under two scenarios; when all emissions (kg/day) are released to the air and when 90% of the emissions are released to the air and 10% to the soil for the high end product formulations. The same emission levels used to model emissions in the Level III model were used to model releases for the CLiCC organic fate model (Table A3).

Concentration in the air: CLiCC Organic Results

Figure 11 shows the distribution of concentration of each chemical in the air for methylene chloride, methanol, benzyl alcohol, dimethyl adipate, and dimethyl glutarate for the CLiCC organic model when all emissions are released to the air. The results of the CLiCC organic fate model are presented in a box plot to indicate the range of concentrations expected. Methylene chloride has the highest maximum concentration followed by methanol. A box plot with the same data, excluding methylene chloride, was created in order to visualize the distribution of methanol, benzyl alcohol, dimethyl adipate, and dimethyl glutarate more clearly (Figure 12). While methanol has the second highest maximum concentration, 50% of the mean concentration values lie below benzyl alcohol and dimethyl adipate indicating that the maximum concentration in the air may not be the most valid for estimating risk (Figure 12).

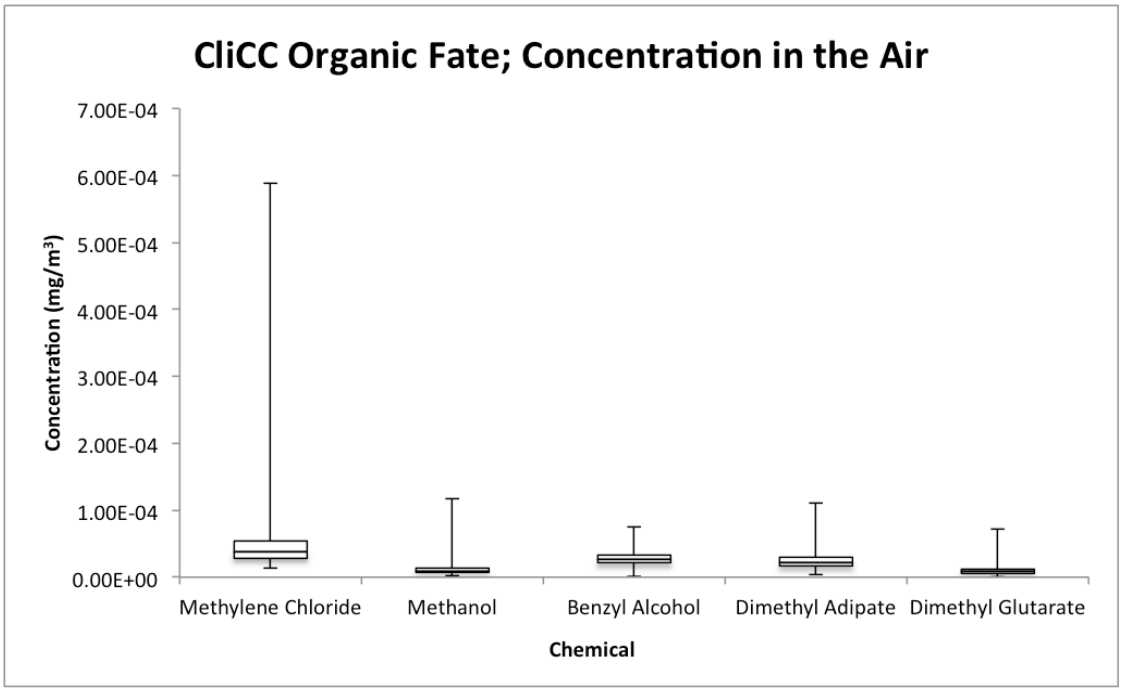

Figure 11. Box plot of the distribution of concentration for chemicals in the air. The bars are the maximum and minimum concentration. The boxes are the 25th and 75th percentile, the median is a solid line.

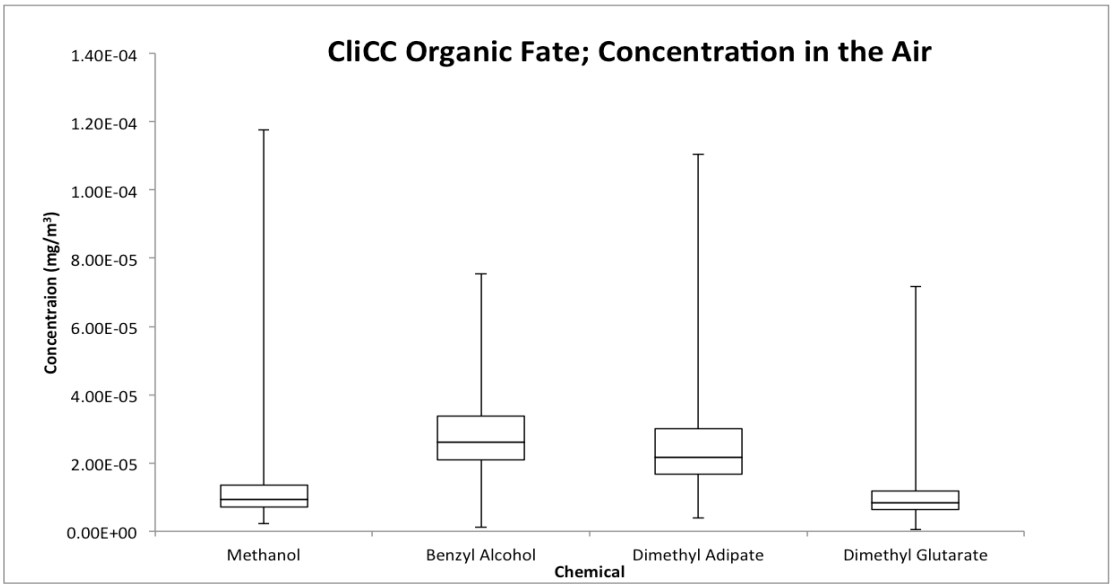

Figure 12. Box plot of the distribution of concentration for chemicals in the air. The bars are the maximum and minimum concentration. The boxes are the 25th and 75th percentile, the median is a solid line.

Since the CliCC Organic fate model considers the dynamic meteorological conditions in the study area, it generates a distribution of values for each chemical based on the predicted daily concentrations, while the Level III model generates a single concentration value since it assumes steady state conditions. The Level III values fall within the range of the results of the CliCC Organic fate model for all of the chemicals. All of the concentration values for the Level III model are greater than the median value for the CliCC Organic Fate Model. While the CliCC organic fate model estimates a range of values and the distribution of concentration, both models yield results that fall within the same order of magnitude suggesting that both tools are useful for estimating the end-of-life fate of methylene chloride and the alternatives. While the Level III model is easy to use and provides an estimate for the chemical concentration in the environment, a single concentration value may not be representative of a chemical's true behavior in the environment.

Risk Assessment Approach: Aquatic Organisms

The conceptual model for the pathways of exposure of aquatic organisms is that the "end-of-life" release of the chemicals used in the various alternative formulations of paint strippers, essentially via volatilization to the atmosphere as explained in detail in the Use Phase section, are then transported to the various environmental compartments (soils, freshwater, seawater) where other processes (e.g. transformation, adsorption) may occur. The Level III and CLiCC organic fate models perform the calculations to estimate the concentrations in the various environmental compartments. These exposure concentrations can then be used in a very general manner to estimate the risk to aquatic organisms.

Acute Risk Quotient for Aquatic Organisms

The concentration of chemicals in water were analyzed to consider their potential impacts on aquatic and terrestrial organisms. Acute risk and hazard quotients were calculated based on the concentrations estimated from the Level III and CLiCC organic fate models when all emissions are released to air. For the Level III model when all emissions are released to air, the concentration in the air is higher than when 10% of emissions are released to soil, indicating the worst case scenario for all the chemicals. For a chemical such as dimethyl glutarate, 95.1% of the chemical is in the air compartment when all emissions are released to the air. The percentage of dimethyl glutarate in the air compartment when emissions are released to the air (90%) and soil (10%) is only 24.6%. For benzyl alcohol, the percentage of the chemical in the air compartment is 1.33% when all emissions are initially released to the air. The percentage of benzyl alcohol in the air compartment when emissions are initially released to the air (90%) and soil (10%) is 1.02%. These two chemicals show the greatest and smallest change in percentage in the air compartment when emissions are released

to the air and when emissions are released to the air and soil. For the CLiCC Organic Fate Model the average concentration of dimethyl glutarate in the air when all emissions are initially released to the air is 115 kg/m^3 and the concentration of dimethyl glutarate in the air when emissions are released the air (90%) and soil (10%) is 9.46E-12 kg/m$^{3.}$ The average concentration of benzyl alcohol in the air when all emissions are released to the air is 305 kg/m^3 and the average concentration in the air when emissions are released to the air (90%) and soil (10%) is 276 kg/m^3.

An acute Risk Quotient (RQ) was calculated for each chemical using the following equation:

(eq 13)[57] $$RQ_{fish\ and\ invertebrates} = \frac{peak\ water\ concentration}{most\ sensitive\ organism\ LC_{50}\ or\ EC_{50}}$$

The risk quotient was calculated using the results generated when all chemical emissions are released to the air (Table 19). For all of the chemicals, the most sensitive LC_{50} values were from 96-hour exposure studies. In this equation, LC_{50} refers to the lethal concentration of chemical in air water that kill 50% of the test subjects; EC_{50} refers to the effective concentration at 50% (i.e. the concentration at which 50% of test subjects suffer adverse effects).[58] These values were compared across multiple sources to find the lowest (i.e. most conservative) LC_{50} value and ultimately cited from material data safety sheets and peer-reviewed studies. While the risk quotient requires the peak concentration, the range of environmental concentration data for the CLiCC organic fate model was provided to show the range of risk quotients.

57 US Environmetnal Protection Agency (2015, Septeber 30).Technical Overview of Ecological Risk Assesment: Risk Characterization Retrieved from http://www2.epa.gov/pesticide-science-and-assessing-pesticide-risks/technical-overview-ecological-risk-assessment-risk

58 Canadian Centre for Occupational Health and Safety (2015) OSH Answers Fact Sheets. Retrieved from www.ccohs.ca/oshanswers/chemicals/ld50.html

Table 20. Acute risk quotient of fish and invertebrates for methylene chloride, methanol, benzyl alcohol, dimethyl adipate, and dimethyl glutarate.

Chemical	Species	LC_{50}- 96 hour (mg/L)	Level III concentration in water (mg/L)	Acute $RQ_{fish\ and\ invertebrates}$ (based on Level III concentration estimates)	Minimum -- Maximum CLiCC concentration in water (mg/L)	Acute $RQ_{fish\ and\ invertebrates}$ (based on CLiCC concentration estimates)
Methylene Chloride	rainbow trout (flow through conditions)	10.95 [59]	5.6E-7	5.1E-8	2.0E-6 - 3.9E-6	1.9E-7 - 3.6E-7
Methanol	Fathead Minnow	100 [60]	3.5E-13	3.5E-15	2.0E-6 - 2.4E-4	2.0E-8 - 2.4E-6
Benzyl Alcohol	Bluegill (static conditions)	10 [61]	2.7E-4	2.8E-5	1.1E-3 - 6.9E-2	1.1E-4 - 6.9E-3
Dimethyl Adipate	Fathead Minnow	18-24[62]	4.9E-7	2.7E-8 - 2.1E-8	6.0E-6 - 1.1E-3	3.3E-7 - 2.5E-7, 5.9E-5 - 8.5E-6
Dimethyl Glutarate	Fathead Minnow	18 -24[63]	7.5E-7	4.1E-8 - 3.1E-8	3.6E-6 - 4.5E-4	1.9E-7 - 1.5E-7, 2.5E-5 - 1.9E-5

*For dimethyl adipate and dimethyl glutarate the CLiCC organic risk quotients are low concentration/low LC_{50}– low concentration/high LC_{50}, high concentration/low LC_{50} – high concentration/high LC_{50}. Where the LC_{50} value for dimethyl glutarate and dimethyl adipate was given as a range of values.

59 Material Safety Data Sheet Dichloromethane. BDH. Retrieved 30 September 2015, from http://feql.wsu.edu/MSDS/Dichloromethane.pdf

60 Ewell, W. S., Gorsuch, J. W., Kringle, R. O., Robillard, K. A., & Spiegel, R. C. (1986). Simultaneous evaluation of the acute effects of chemicals on seven aquatic species. *Environmental Toxicology and Chemistry*, *5*(9), 831-840.

61 Dawson, G.W. Jennings, A.L .,Drozdowsk, D., & Rider E. (1976) The acute toxicity of 47 industrial chemicals to fresh and saltwater fishes. *Journal of hazardous materials*, 1(4), 303-318.

62 Material Data Safety Sheet (MSDS) Kelly Solutions. Retrieved 30 September 2015, from .http://www.kellysolutions.com/erenewals/documentsubmit/KellyData%5CVA%5Cpesticide%5CMSDS%5C5383%5C5383-112%5C5383-112_POLYPHASE_641_11_5_2012_1_53_47_PM.pdf

63 Material Data Safety Sheet (MSDS). Kelly Solutions. Retrieved 30 July 2015, from .http://www.kellysolutions.com/erenewals/documentsubmit/KellyData%5CVA%5Cpesticide%5CMSDS%5C5383%5C5383-112%5C5383-112_POLYPHASE_641_11_5_2012_1_53_47_PM.pdf

The Level III and CLiCC organic fate model results reveal that the risk is very low for all chemicals. Although well below a threshold of 1, benzyl alcohol has the highest acute risk quotient in water when comparing all the chemicals. The acute risk quotient for benzyl alcohol for low emissions level, considering Level III results, is 1.6E-05 and the acute risk quotient for dimethyl adipate for the low emission level is 1.82E-07. The range of concentration values for each chemical in the CLiCC organic fate model is higher than the concentration of each chemical in the Level III model resulting in higher risk quotients, and for methanol there were considerable differences across the models.

All of the acute risk quotients are much less than one, indicating that at the calculated emission rates, these chemicals will most likely not have a damaging effect on the surrounding fish and invertebrates. The acute risk quotient serves to compare impacts across chemicals by determining how close the environmental concentration is to a particular toxicological measure for sensitive species. These results are distinctly different from those obtained during the original qualitative alternatives assessment, which did not perform the rigorous calculations presented here.

Chronic Risk Quotient for Aquatic Organisms
The EPA has also derived an equation to calculate a chronic risk quotient:

(eq 14) Chronic RQ_{fish} = 56-day or 60-day average water concentration / Fish early life-stage or full life-cycle toxicity NOAEC. [64]

The concentration in the water estimated by the Level III and CLiCC organic fate models was compared to the NOEC for methylene chloride and methanol. The estimated concentration of each chemical in water, by either model, is much less than the NOEC for each chemical (Table 21).

64 US Environmetnal Protection Agency (2015, Septeber 30).Technical Overview of Ecological Risk Assesment: Risk Characterization Retrieved from http://www2.epa.gov/pesticide-science-and-assessing-pesticide-risks/technical-overview-ecological-risk-assessment-risk

Table 21. NOEC and concentration in water for methylene chloride and methanol.

Chemical	Species	NOEC Concentration (mg/L)	Estimated concentration in water (mg/L) Level III	Estimated maximum concentration in water (mg/L) CLiCC organic
Methylene Chloride	Sheepshead Minnow	1.30E+01	5.62E-07	3.89E-06
Methylene Chloride	Zebra Danio	6.55E+01	5.62E-07	2.38E-04
Methanol	Water Flea	3.20E+03	3.47E-13	6.89E-02
Dimethyl Adipate	NA	NA	4.91E-07	1.06E-03
Dimethyl Glutarate	NA	NA	7.46E-07	4.52E-04

Risk Assessment: Terrestrial Organisms

A hazard quotient was used to assess the downstream impacts of the chemicals in the air. The hazard quotient for each non-carcinogenic chemical can be calculated using the following equation:

(eq 15)[65] Hazard Quotient = C/RfC

Where C is the maximum ambient air concentration (μg/m^3) and RfC is the pollutant-specific reference concentration (μg/m^3). The oral reference doses were the test standard used to calculate the Hazard Quotient, where the concentration was calculated using equation 16 from the previous section.

65 New Jersey Department of Environmental Protection 92009). *Guidance on Risk Assesment for Air Contaminant Emissions* (Technical Manual 1003). Retrieved from http://www.nj.gov/dep/aqpp/downloads/techman/1003.pdf,

(eq 16) $$Dose = Concentration \times \frac{20}{70}$$

$$\left[\frac{mg}{kg \cdot day} = \frac{mg}{m^3} \times \frac{m^3/day}{kg}\right]$$

Although methylene chloride is classified as possibly carcinogenic, the hazard quotient was calculated in order to compare the same quotient across all the chemicals. If needed, a separate equation can be used to quantify human health risks from carcinogenic chemicals.

The resulting concentrations are for high product formulations for the scenario in which all chemicals are initially released as emissions to the air.

Table 22. Reference doses converted to reference concentrations for methylene chloride, methanol, benzyl alcohol, dimethyl adipate, and dimethyl glutarate. Reference doses (mg/kg-day) were converted to concentrations (mg/m^3) using equation 10.

Chemical	Toxicity measure	Reference Dose (mg/kg-day)	Converted concentration (mg/m^3)
Methylene Chloride	Chronic oral Rfd	6.00E-03	0.021
Methanol	Chronic Oral Rfd	2	7
Benzyl Alcohol	Chronic Oral Rfd	0.3	1.05
Dimethyl Adipate	Derived Rfd	0.014 - 0.0014	0.049 - 0.0049
Dimethyl Glutarate	Derived Rfd	0.014 - .0014	0.049 - 49

Table 23. Hazard quotient for Level III and CLiCC organic fate model for concentration in the air.

Chemical	Level III concentration in air ($mg/m^{3)}$	Hazard Quotient based on Level III model estimates	Average and maximum CLiCC organic concentration in air (mg/m^3)	Hazard Quotient based on CLiCC organic (mg/m^3) (average – maximum)
Methylene Chloride	8.68E-05	4.1E-03	5.02E-05 – 5.88E-04	2.39E-03 – 9.82E-03
Methanol	2.2E-05	3.14E-06	1.23E-05 - 1.18E-04	1.76E-06 – 5.88E-05
Benzyl Alcohol	2.74E-05	2.61E-05	2.78E-05 – 7.53E-04	2.64E-05 – 2.51E-04
Dimethyl Adipate	4.44E-05	9.06E-04 - 9.06E-03	2.57E-05 – 1.10E-04	5.24 E-04 -7.89E-03
Dimethyl Glutarate	1.97E-05	4.02E-04 - 4.02E-03	1.05E-05 – 1.18E-04	2.13E-04 – 8.4E-03-03

Note: There are four calculated values for the hazard quotient CLiCC organic for dimethyl adipate and dimethyl glutarate. Shown are the range of values.

Results

The results of both models reveal that the risk of each chemical in the air and water is very low because the hazard and risk quotients are much less than one. While the qualitative analysis used in the first stage to generate the heat maps indicated that some of the chemicals, such as benzyl alcohol and methylene chloride, may have a high risk, the overall impact of a chemical in an environmental compartment is a function of both the emission releases and the environment in which they are released. The more rigorous quantitative analysis, with two levels of modeling, indicates that in reality there is very little risk at EOL since the concentrations are well below toxicity thresholds (e.g. RfC). It should be noted that the reference dose for dimethyl adipate and dimethyl glutarate were derived. Two separate values were considered in order to account for uncertainty in the calculation.

Conclusion

This paint stripper case study has been used to evaluate the issues encountered when performing several alternatives analysis steps.

The case study consisted of three general life cycle stages to capture upstream, use phase, and end-of-life impacts. The analysis for each of these stages utilized different methods and tools to best estimate the relevance and magnitude of several impacts.

The upstream analysis utilized economic input-output and process life cycle assessment approaches. While the EIO-LCA tool is free, easy to use, and requires limited data inputs, the results are not specific to individual chemicals. This approach may be useful for initial screening of alternatives, particularly when alternatives are classified in different industries, but provides little or no differentiation if the alternative chemicals are from the same industrial class. The process LCA, using GaBi software, was also a relatively simple process. While it requires more inputs, data gaps were filled and results were more reliable and robust. Additionally, the use of normalization factors in the process LCA helped to clearly identify the most relevant factors to consider. It should be noted that several endpoints were assessed in both of these processes, and these endpoints capture many of the categories listed in the Safer Consumer Products Regulations.

The analysis of impacts during use focused on human health impacts. A combination of data and models were used to estimate user exposure under multiple scenarios. Exposure concentrations were then combined with hazard information to estimate human risk with an acute hazard ratio, a chronic hazard quotient, and carcinogenic risk. This assessment found that, overall, methylene chloride-based paint stripper presents greater risk to human health than other alternatives assessed.

Impacts associated with electricity use for power sanding were also assessed during the use phase. These impacts were found to be low, and are likely not relevant.

End-of-life assessments were performed to estimate human health and ecological impacts. Two fate models were used to estimate pollutant concentrations in different environmental media in San Francisco Bay. Both models provided similar estimates for air and water. The CLiCC organic fate model provided dynamic results (i.e. daily concentrations over the modeled period).This assessment found that none of the chemical alternatives present high risks to human or ecological health at their end of life, even when considering the maximum daily concentrations as a worst-case scenario. However, it should be noted that these assessments were performed assuming minimal background concentration of the chemicals in the environment. Additionally, we were unable to model the fate of dust particles from sanding at the time of this study. There are, however, emerging tools and models that will help to fill this gap in the future and allow for a more comprehensive assessment.

This case study did not go through the decision-making process of selecting an alternative. However, the results of this case study do provide a foundation of information with which alternatives could be compared. For a responsible entity, the results lead to the identification of key factors to consider in the second phase AA study.

Comparing Qualitative and Quantitative Results

After completing this study the qualitative heat maps generated during the prior case study were updated. Since the economic input-output and process life cycle assessments did not provide specific information on raw material extraction or intermediate material process, the information presented in the updated heat map is exactly the same as for the qualitative analysis. Clearly these methods have to advance to be able to provide more quantitative information for these two life-cycle stages. The reuse and recycle stage is not clearly applicable to paint stripping products, since the chemical components are rather volatile and thus practically impossible to recover after use, and the abrasive material after sanding is also very difficult to recover. Thus, this stage was colored black in all cases. The other stages were modified as discussed below.

Public Health Impact during the Manufacturing Phase
Using Traci 2.1 normalization factors to quantify the impacts associated with public health during the manufacturing phase using the process life cycle assessment we estimate that methylene chloride and benzyl alcohol have a medium impact with low to medium uncertainty. Sanding and dimethyl adipate have low impacts with a medium uncertainty due to their noticeable standard deviations. Compared to the qualitative analysis, there was a decrease in the expected public health impact for all alternatives, once the risks were normalized in the quantitative analysis.

Public Health Impact during the Use Phase
The hazard Index and the carcinogenic risk were used to assess the public health impact during the use phase of the chemical based paint strippers and sanding. While the carcinogenic risk for methylene chloride is small, the hazard index for both the high concentration scenario and baseline concentration scenario exceed one and therefore it was assigned a high impact. The impact associated with use of the benzyl alcohol based paint stripper was categorized as low. Taking a more conservative approach, dimethyl adipate has a medium public health impact, but with a high uncertainty due to the calculation of the reference dose. Thus, it could fall into a high or low impact depending on the value used. Sanding has a low public health impact with a medium uncertainty during the use phase. However, the health impacts of sanding may be higher if it is done without a vacuum, indicating medium uncertainty associated with the human health impacts. Overall the uncertainty on the public health impacts during the use phase decreased significantly by performing a more qualitative analysis

Public Health Impact during the End of Life Phase
Overall the results of the fate modeling indicated low ambient concentrations for the chemicals of interest in each alternative, which substantially decreased the predicted impact to public health. All the estimated hazard quotients were substantially below 1.

Air Quality during the Manufacturing Phase
Potential for urban smog formation and stratospheric ozone depletion (Figure 5) were used to determine the impact of each chemical-based paint stripper and sanding on air quality during the manufacturing phase. Methylene chloride was assigned a high impact with a low uncertainty since it has the highest impact for both smog and ozone depletion, respectively. Methylene chloride and dimethyl adipate have a medium impact and were assigned medium uncertainty due to their noticeable standard deviation. Sanding has a low impact with a low uncertainty. The results were similar to the qualitative analysis.

Air Quality during the Use Phase
Although locally (point of use) the paint strippers and sanding process may have public health impacts, the broader air quality is not likely to be significantly influenced by the use of methylene chloride or its alternatives. The predicted concentrations are quite low. The emissions during the use phase quickly become “end-of-life” as these products dissipate into the atmosphere.

Air Quality during the End-of-Life Disposal
Once released to the environment, the concentration in the air for all chemicals is expected to be quite low with a hazard quotient for all the chemicals less than one. Sanding is also not expected to contribute significantly to particulate matter, although this was not modeled, therefore the uncertainty is medium. Overall there was a significant decrease in predicted impact going from a qualitative to a quantitative analysis.

Water quality during the Manufacturing Phase
Acidification and eutrophication (Figure 5) were used to determine the impact of each chemical based paint stripper and sand paper on water quality during the manufacturing phase. Both benzyl alcohol and dimethyl adipate based paint strippers may contribute to water acidification and benzyl alcohol can contribute to acidification.

Soil and Water Quality during Use and End-of-Life Phases
In general the use of these chemicals in this application are not likely to have significant impacts on soil or water quality during the use or end-of-life phases, since during use there is likely very low release to either soil or water, and the fate calculations predict very low concentrations in these media. Given the low concentrations, the uncertainty in the predicted impact is low. These results were significantly different from those from the qualitative analysis, which could not consider concentrations to put the risk into perspective.

Ecological Impact during the Manufacturing Phase
The normalized results of the process manufacturing assessment method indicate that only dimethyl adipate represents a medium impact, with a medium uncertainty based on the standard deviation.

Ecological Impact during the Use and End-of-Life Phases
All chemicals are expected to have a low ecological impact during use and end-of life phases due to the low concentrations. Both the hazard quotient and risk quotient for all the chemicals are low suggesting that the impacts associated with the end-of-life and disposal are low. The end-of-life fate of sanding was not assessed and therefore no impact was assigned to this category.

Waste/End-of-life during the Use and End-of-Life Phases
Overall the impacts associated with the waste and end-of-life all the chemical based paint strippers is low. The end-of-life fate of sanding was not assessed and therefore no impact was assigned to this category.

It is useful to compare the quantitative results of this analysis with the qualitative results of the previous paint stripper screening case study (Appendix B).

The overall trends regarding relevant impacts are reasonably consistent between the studies. Public health impacts remain of great relevance during the use phase, and probably dominate the overall concern with the use of methylene chloride and dimethyl adipate. Normalization factors in the quantitative analysis are of great use in determining relevancy.

However, there are differences in how the alternatives compare between the qualitative and quantitative approaches. For example, qualitatively it appeared that at EOL there would be concerns with air and water quality, but the quantitative analysis indicated that impacts on air and water quality during the end-of-life phase are likely well below risk thresholds. We observed the largest discrepancy between qualitative and quantitative approaches results in the upstream phases.

The qualitative upstream analysis underestimated water quality impacts of benzyl alcohol, assessing it as being one of the alternatives with the lowest impact. However, the uncertainty in the original quantitative analysis was designated as high, indicating the unknown impacts associated with benzyl alcohol. Yet the process LCA results show that, of the alternatives, benzyl alcohol has the greatest contribution to eutrophication. Upstream ecotoxicity for benzyl alcohol was also underestimated compared with the alternatives.

The level of uncertainty associated with the results was also evaluated in the quantitative analysis. Including sensitivities allowed for comparisons across multiple scenarios; trends among the scenarios indicated whether one alternative was consistently better or worse than another for a given impact. Overall, for those impacts that were evaluated quantitatively, the uncertainty in the prediction of impact was reduced. This is particularly the case for the use and end-of-life phases.

Public Health	Raw material extraction	Intermediate material processes	Manufacture	Use	Reuse and recycling	EOL disposal
Methylene Chloride	H	M	L	L		L
Benzyl Alcohol	M	M	M	L		
Dimethyl Adipate	H	H	M	M		L
Sanding	M	H	M	M		L

Air Quality	Raw material extraction	Intermediate material processes	Manufacture	Use	Reuse and recycling	EOL disposal
Methylene Chloride	H	M	L	L		L
Benzyl Alcohol	L	H	M	L		L
Dimethyl Adipate		M	M	L		L
Sanding	M	M	L	L		M

Soil Quality	Raw material extraction	Intermediate material processes	Manufacture	Use	Reuse and recycling	EOL disposal
Methylene Chloride	H		M	L		L
Benzyl Alcohol	L		M	L		L
Dimethyl Adipate	M		M	L		L
Sanding	M	M		L		L

Water Quality	Raw material extraction	Intermediate material processes	Manufacture	Use	Reuse and recycling	EOL disposal
Methylene Chloride	M	H	L	L		L
Benzyl Alcohol		L	M	L		L
Dimethyl Adipate	M		M	L		L
Sanding	M	M		L		L

Ecolo-gical Impact	Raw material extraction	Intermediate material processes	Manufacture	Use	Reuse and recycling	EOL disposal
Methylene Chloride	H	L	L	L		L
Benzyl Alcohol	H		M	L		L
Dimethyl Adipate	M		L	L		L
Sanding	M	M	L	L		

Waste/ End-of-life	Raw material extraction	Intermediate material processes	Manufacture	Use	Reuse and recycling	EOL disposal
Methylene Chloride		L	M	L		L
Benzyl Alcohol		M		L		L
Dimethyl Adipate	M			L		L
Sanding	M	M		L		

High Impact	Medium Impact	Low Impact	Minimal to No Impact	No Data	Not Applicable

H = High uncertainty	M = Medium uncertainty	L = Low uncertainty

Figure 13. Quantitative-based heat maps by impact. L-M-H indicate the level of uncertainty associated with the evaluation. Life cycle segments colored grey indicate a lack of data upon which to evaluate, and life- cycle phases colored black do not apply to that product.

Lessons Learned

From this case study, several lessons were learned about the alternatives analysis process.

Each alternatives analysis will require a unique approach.

While the methods outlined in this case study provide an example of how practitioners might approach alternatives analysis steps, it may not be directly applicable to all products. A critical aspect of the alternatives analysis process is to thoroughly think about what is involved in in each life cycle phase. By doing a qualitative screening study, practitioners can choose tools and approaches that are most helpful to their analysis.

Upstream impacts are best captured through a process LCA.

Gathering qualitative data for upstream processes can be time-consuming, and the quality of the information is often poor. The data tends to be general and results in high levels of uncertainty. Using tools, such as GaBi software, to conduct a process LCA provides higher quality results and minimizes the amount of time devoted to data-gathering.

Modeling exposure for all alternatives requires a thorough understanding of the processes taking place during use.

This case study explored alternatives that present inhalation exposures during use. However, the types of exposures are not all the same; chemical alternatives present exposure to vapors, while sanding presents exposure to particles. These different types of exposures cannot all be estimated with a single model. Different models or data must be used for processes that are not the same.

While not perfect, there are ways to fill in data gaps to get reasonable approximations.

Data gaps are a near inevitability. However, this case study demonstrated that there are opportunities to get reasonable approximations of impacts despite these gaps. In this study, there were multiple data gaps for the dimethyl adipate-based paint stripper. In some cases, we used data on dimethyl adipate to fill gaps for dimethyl glutarate, or vice versa. We assumed that these related compounds were reasonably representative of one another, and could serve as proxies. In other cases, QSAR data or other modeled data provided good estimates when experimental values were not available. Future practitioners may be able to use similar approaches to fill data gaps.

Including sensitivity is valuable.

Sensitivity evaluation is useful for estimating impacts with different degrees of conservativeness. Considering multiple sensitivity studies can help to show what is important in the analysis. For

example, of the numerous sensitivities performed during the use phase hazard analysis, concentration in the air as a consequence of room size proved to have the greatest difference from the baseline results. By including analyses for small-, mid-, and large-sized rooms, we can compare alternatives under different conditions of use rather than assuming that all users follow the same procedures.

Next Steps

While this case study has not thoroughly addressed all aspects of an alternatives analysis (e.g. limited number of alternatives assessed; economic considerations, etc.), it has demonstrated the feasibility of the alternatives analysis process and has provided a basic understanding of relevant factors for alternatives to methylene chloride-based paint strippers.

By following the alternatives analysis process for other potential priority products, new tools or approaches that were not applicable to this case study may emerge. Furthermore, a larger catalog of case studies may provide greater insight into the challenges and opportunities in conducting alternatives analyses.

Additionally, this case study did not address the process for selecting an alternative. Further guidance on multi-criteria decision analysis and examples would be beneficial.

Appendix A

Table A1. Low and high emission level generated from low and high end product formulation

Compound	Low Emission Level (kg/hr) from low end product formulation	High Emission Level (kg/hr) from high end product formulation
Benzyl Alcohol	58.9	35.1
Dimethyl Adipate	37.8	25.1
Dimethyl Glutarate	13. 8	2.65

Note: Methylene Chloride paint stripper has only one product formulation.

Table A2. Level III fugacity model results for chemicals in paint strippers when all emissions are released to the air

Chemical	Air Mass (kg)	Water Mass (kg)	Soil Mass (kg)	Sediment Mass (kg)
Benzyl Alcohol (High)	301	1471	21416	9.78E-02
Benzyl Alcohol (Low)	179	878	12773	5.82E-02
Dimethyl Adipate (High)	488	3.23	7.73	2.15E-04
Dimethyl Adipate (Low)	325	2.154	5.14	1.43E-04
DImethyl Glutarate (High)	41.6	0.947	1.2	6.29E-05
Dimethyl Glutarate (Low)	217	4.92	6.22	3.27E-04

Note: Low and High indicate low and high emission level. These are results for all emission levels.

Table A3. Level III model results for 100% of releases to air and 90% release to air 10% release to soil for high emission levels

Chemical - Emissions	Emissions to air, Emissions to soil (kg/hr)	concentration in Air (ng/m^3)	concentration in water (ng/L)	concentration in soil (ng/g)	concentration in sediment (ng/g)
Methylene Chloride - all to air	52.40, 0	8.68E+01	5.62E-01	5.73E-04	1.31E-07
Methylene Chloride - 90/10	47.16, 5.24	8.27E+00	1.37E+00	1.32E-01	3.19E-07
Methanol - all to air	13.98, 0	2.22E+01	3.47E-07	1.67E-18	6.22E-11
Methanol- 90/ 10	12.58, 1.40	2.22E+01	3.47E-07	5.24E-16	9.53 E-16
Benzyl Alcohol- all to air	58.85,0	2.74E+01	2.68E+02	2.80E+00	4.47E-05
Benzyl Alcohol- 90/10	52.97, 5.89	2.47E+01	2.67E+02	3.29E+00	4.45E-05
Dimethyl Adipate - all to air	37.76,0	4.44E+01	4.91E-01	5.73E-04	6.99E-08
Dimethyl Adipate- 90/10	33.984, 3.776	4.30E+01	1.87E+00	1.32E-01	2.66E-07
Dimethyl Glutarate - all to air	13.78, 0	1.97E+01	7.46E-01	6.02E-04	1.44E-04
Dimethyl Glutarate- 90/10	12.40, 1.38	1.88E+01	2.40E+00	5.98E-02	1.35E-07

Note: “All to air” indicates all emissions to air. 90/10 indicates 90% release to air and 10% release to soil.

Create your environment:

Compartment Characteristics	Matlab Code	Value	Units
Area of Environment	area	11000000000	m^2
Air Height	airH	1000	m
Air Density	airP	1.185	kg/m^3
Density of Aerosols	aerP	2000	kg/m^3
Concentration of Aerosols	aerC	0.000000035	kg/m^3
Percent of Environment Water	waterPerc	0.1	%
Depth of Seawater	seawD	6	m
Depth of Freshwater	freshwD	6	m
Density of Water	waterP	1000	kg/m^3
Percent of Water Seawater	seawPerc	0.4	%
Density of Seawater	seawP	1027	kg/m^3
pH of Seawater	seawpH	8.4	
Density of Freshwater	freshwP	1000	kg/m^3
pH of Freshwater	freshwpH	7	
Coastal Area Perc	coastalAP	0.0025	%
Seawater Suspended Sediment Density	seassP	1500	kg/m^3
Seawater Suspended Sediment Concentration	seassC	0.005	kg/m^3
Freshwater Suspended Sediment Density	freshssP	1500	kg/m^3
Freshwater Suspended Sediment Concentration	freshssC	0.01	kg/m^3
Soil Compartment 1, % of total soil area	soilPerc1	0.1	%
Soil Compartment 2, % of total soil area	soilPerc2	0.3	%
Soil Compartment 3, % of total soil area	soilPerc3	0.6	%
Depth Surface Soil 1	soilD1	0.2	m
Depth Surface Soil 2	soilD2	0.2	m
Depth Surface Soil 3	soilD3	0.2	m
Depth Deep Soil 1	deepsD1	1	m
Depth Deep Soil 2	deepsD2	1	m
Depth Deep Soil 3	deepsD3	1	m
Initial Soil Water Content 1	soilWC1	0.3	%
Initial Soil Water Content 2	soilWC2	0.3	%
Initial Soil Water Content 3	soilWC3	0.3	%
Initial Soil Air Content 1	soilAC1	0.2	%
Initial Soil Air Content 2	soilAC2	0.2	%
Initial Soil Air Content 3	soilAC3	0.2	%
Initial Deep Soil Water Content 1	deepsWC1	0.5	%
Initial Deep Soil Water Content 2	deepsWC2	0.5	%
Initial Deep Soil Water Content 3	deepsWC3	0.5	%
Initial Deep Soil Air Content 1	deepsAC1	0.1	%

Calculations:

Compartment Characteristics	Matlab Code	Value	Units
Air Volume	airV	11000000000000.00	m^3
Volume Fraction of Aerosols	aerVf	0.00	
Aerosols Volume	aerV	220.00	m^3
Area of Water	waterA	1100000000.00	m^2
Volume of Water	waterV	6600000000.00	m^3
Area of Seawater	seawA	440000000.00	m^2
Volume of Seawater	seawV	3960000000.00	m^3
Percent of Water Freshwater	freshwPerc	0.60	%
Area of Freshwater	freshwA	660000000.00	m^2
Volume of Freshwater	freshwV	2640000000.00	m^3
Coastal A	coastalA	1100000.00	m^2
Seawater Suspended Sediment Volume	seassV	13200.00	m^3
Freshwater Suspended Sediment Volume	freshssV	19800.00	m^3
Area of Soil	soilA	9900000000.00	m^2
Area Soil 1	soilA1	990000000.00	m^2
Area Soil 2	soilA2	2970000000.00	m^2
Area Soil 3	soilA3	5940000000.00	m^2
Volume Soil 1	soilV1	198000000.00	m^3
Volume Soil 2	soilV2	594000000.00	m^3
Volume Soil 3	soilV3	1188000000.00	m^3
Volume Deep Soil 1	deepsV1	396000000.00	m^3
Volume Deep Soil 2	deepsV2	1188000000.00	m^3
Volume Deep Soil 3	deepsV3	2376000000.00	m^3
Volume Soil Water 1	soilwV1	59400000.00	m^3
Volume Soil Water 2	soilwV2	178200000.00	m^3
Volume Soil Water 3	soilwV3	356400000.00	m^3
Volume Deep Soil Water 1	deepswV1	495000000.00	m^3
Volume Deep Soil Water 2	deepswV2	1485000000.00	m^3
Volume Deep Soil Water 3	deepswV3	2970000000.00	m^3
Volume Soil Air 1	soilaV1	39600000.00	m^3
Volume Soil Air 2	soilaV2	118800000.00	m^3
Volume Soil Air 3	soilaV3	237600000.00	m^3
Volume Deep Soil Air 1	deepsaV1	99000000.00	m^3
Volume Deep Soil Air 2	deepsaV2	297000000.00	m^3
Volume Deep Soil Air 3	deepsaV3	594000000.00	m^3
Area of FW Sediment	sedFWA	660000000.00	m^2
Volume of FW Sediment	sedFWV	33000000.00	m^3
Area of SW Sediment	sedSWA	440000000.00	m^2
Volume of SW Sediment	sedSWV	22000000.00	m^3
Volume Freshwater Biota	biotaFWv	5.00	m^3
Volume Seawater Biota	biotaSWv	5.00	m^3
Volume Sediment Biota	biotaSedv	4.85	m^3
Volume Soil Biota	biotaSv	4.85	m^3

Figure A1. San Francisco Bay environmental parameters and calculations for the CLiCC organic fate model.

Create your environment:					Calculations:			
Compartment Characteristics	Matlab Code	Value	Units		Compartment Characteristics	Matlab Code	Value	Units
Organic Carbon Content Soil 1	soilOC1	0.02	%		Freshwater Percent Biota	FWbiotaPerc	0.00	
Organic Carbon Content Soil 2	soilOC2	0.02	%		Volume Soil	soilV	198000000.00	m^3
Organic Carbon Content Soil 3	soilOC3	0.02	%					
Soil Water pH 1	soilWpH1	8.2						
Soil Water pH 2	soilWpH2	7.5						
Soil Water pH 3	soilWpH3	7						
Runoff Curve Number Soil 1 (30-100)	CN1	60						
Runoff Curve Number Soil 2 (30-100)	CN2	75						
Runoff Curve Number Soil 3	CN3	90						
Organic Carbon Content Deep Soil	dsoilOC1	0.01	%					
	dsoilP1	1650.00	kg/m3					
Organic Carbon Content Suspended Particles	spOC	0.2	%					
Density of Soil Air 1	dSA1	1188	kg/m3					
Density of Soil Air 2	dSA2	1188	kg/m3					
Density of Soil Air 3	dSA3	1188	kg/m3					
Density of Soil Solid 1	dSS1	2400	kg/m3					
Density of Soil Solid 2	dSS2	2400	kg/m3					
Density of Soil Solid 3	dSS3	2400	kg/m3					
Depth Freshwater Sediment	sedFWD	0.05	m					
Depth of Seawater Sediment	sedSWD	0.05	m					
Density of Freshwater Sediment	sedFWP	1280	kg/m^3					
Density of Seawater Sediment	sedSWP	1280	kg/m^3					
Organic Carbon Content of Freshwater Sediment	sedFWOC	0.04	%					
Organic Carbon Content of Seawater Sediment	sedSWOC	0.04	%					
pH Freshwater Sediment	sedFWpH	7						
pH Seawater Sediment	sedSWpH	8.4						
Mass Freshwater Biota	biotaFWm	5000	kg					
Density Freshwater Biota	biotaFWp	1000	kg/m^3					
Lipid Content Freshwater Biota	biotaFWlc	0.05	%					
Mass Seawater Biota	biotaSWm	5000	kg					
Density Seawater Biota	biotaSWp	1000	kg/m^3					
Lipid Content Seawater Biota	biotaSWlc	0.05	%					
Mass Sediment Biota	biotaSedm	5000	kg					
Density Sediment Biota	biotaSedp	1030	kg/m^3					
Lipid Content Sediment Biota	biotaSedlc	0.02	%	some of these values are made up for testing purposes				
Mass Soil Biota	biotaSm	5000	kg					
Density Soil Biota	biotaSp	1030	kg/m^3					
Lipid Content Soil Biota	biotaSlc	0.02	%					
Mass Terrestrial Biota	biotaTm	5000	kg					
Density Terrestrial Biota	biotaTp	900	kg/m^3					
Lipid Content Terrestrial Biota	biotaTlc	0.02	%					
Lipid Content Freshwater Sediment Biota	biotaFSedlc	0.05	%					
Lipid Content Seawater Sediment Biota	biotaSSedlc	0.05	%					
Organic Carbon Content Soil	soilOC	0.02	%					
Density of Soil	soilP	1500	kg/m^3					

Figure A2. San Francisco Bay environmental parameters and calculations (continued) for the CLiCC Organic fate model.

Create your environment:					Calculations:			
Compartment Characteristics	Matlab Code	Value	Units		Compartment Characteristics	Matlab Code	Value	Units
Air-Water Mass Transfer Coefficient (water side)	awMTCwater	0.05	m/h					
Air-Soil Mass Transfer Coefficient	asMTC	5	m/h					
Diffusion path length in soil	soilpathlen	0.05	m					
Molecular diffusivity in air	airMD	0.001	m^2/h					
Molecular diffusivity in water	waterMD	5.00E-07	m^2/h					
Sediment-Freshwater Mass Transfer Coefficeint	sedfwMTC	0.0001	m/h					
Sediment-Seawater Mass Transfer Coefficient	sedswMTC	0.0001	m/h					
Soil Water Content	soilWC	0.3	%					
Soil Air Content	soilAC	0.2	%					
Freshwater Sediment Percent Solid	fsedpercSolid	0.2	%					
Seawater Sediment Percent Solid	ssedpercSolid	0.2	%					
Aerosol Deposition Rate	aerDepR	10	m/h					
Leaching Rate in Soil	leachR	6.25E-05	m^3/m^2h					
Freshwater Sediment Deposition Rate	freshssDepR	5.00E-07	m^3/m^2h					
Seawater Sediment Deposition Rate	seassDepR	5.00E-07	m^3/m^2h					
Freshwater Sediment Resuspension Rate	freshssSusR	2.00E-07	m^3/m^2h					
Seawater Sediment Resuspension Rate	seassSusR	2.00E-07	m^3/m^2h					
Freshwater Sediment Burial Rate	freshssBurR	4.19E-08	m^3/m^2h					
Seawater Sediment Burial Rate	seassBurR	4.19E-08	m^3/m^2h					
Precipition Scavenging Ratio	precipScavR	200000						
Soil Solid Runoff Rate	soilRunS	1.00E-08	m^3/m^2h					
Soil Water Runoff Rate	soilRunW	5.00E-05	m/h					
Density of Fresh Sediment Solid	dFWSedS	2400	kg/m3					
Density of Sea Sediment Solid	dSWSedS	2400	kg/m3					
Density of Deep Soil 1	dsoilP1	1650.00	kg/m3					
Density of Deep Soil 2	dsoilP2	1650.00	kg/m3					
Density of Deep Soil 3	dsoilP3	1650.00	kg/m3					
Organic Carbon Content Deep Soil 1	dsoilOC1	0.01	%					
Organic Carbon Content Deep Soil 2	dsoilOC2	0.01	%					
Organic Carbon Content Deep Soil 3	dsoilOC3	0.01	%					
Air Advection Residence Time	airrestime	20						
Water Advection Residence Time	waterrestime	4400						
Sediment Advection Residence Time	sedrestime	4400000						
Density of Soil Water 1	dSW1	1000	kg/m3					
Density of Soil Water 2	dSW2	1000	kg/m3					
Density of Soil Water 3	dSW3	1000	kg/m3					

Figure A3. San Francisco Bay environmental parameters (continued) for the CliCC Organic Fate model

.

Appendix B

SAFER CONSUMER PRODUCTS ALTERNATIVES ANALYSIS DEVELOPMENT

Developing a framework for the incorporation of life cycle considerations into Alternatives Analysis

Group Members
Jordan Chamberlain | Kristen Magnuson | Carolin Meier | Yu Yu

Advisor
Dr. Arturo Keller

20 March 2015

A Group Project submitted in partial satisfaction of the requirements for the degree of Master of Environmental Science and Management for the Bren School of Environmental Science & Management at the University of California, Santa Barbara.

California Department of Toxic Substances Control

Bren School of Environmental Science & Management
UNIVERSITY OF CALIFORNIA, SANTA BARBARA

Signature Page

Safer Consumer Products Alternatives Analysis Development

As authors of this Group Project report, we are proud to archive this report on the Bren School's website such that the results of our research are available for all to read. Our signatures on the document signify our joint responsibility to fulfill the archiving standards set by the Bren School of Environmental Science & Management.

Jordan Chamberlain	Kristen Magnuson
Carolin Meier	Yu Yu

The mission of the Bren School of Environmental Science & Management is to produce professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a three-quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

Arturo Keller	Date

Acknowledgements

We would like to extend our gratitude to the individuals and organizations that have advised and supported us throughout the thesis process.

Thank you to the **Bren School of Environmental Science & Management** of the University of California, Santa Barbara, and to the **Department of Toxic Substances Control** of the California Environmental Protection Agency for providing the opportunity to pursue this project.

We would like to thank the following people for sharing knowledge and expertise that was instrumental to the completion of this project:

Advisors
Primary advisor, Dr. **Arturo Keller**
Internal Bren advisor, Dr. **Sangwon Suh**
External advisor and client contact, **Bob Boughton**

Consultants
Primary PhD consultant, **Anastasiya Lazareva**
Economic assessment PhD consultant, **Jessica Perkins**

Acronyms

CoC—Chemical of Concern
DfE—Design for the Environment
DMA—Dimethyl adipate
DTSC—Department of Toxic Substances Control
LCA—Life Cycle Assessment
SCP—Safer Consumer Products

Definitions

Alternatives Analysis—Systematic comparison of alternative chemicals and/or products; distinguished from an Alternatives Assessment by the inclusion of life cycle considerations.

Chemical of Concern—A chemical that has a hazard trait that can harm people and the environment.

First Stage—The screening stage of an Alternatives Analysis with a focus on: (1) identifying potential alternatives; (2) screening alternatives; and (3) identifying factors relevant for further consideration.

Responsible Entity—A manufacturer, importer, assembler or retailer for a listed Priority Product (note: only one company along a particular Priority Product's supply chain must conduct an Alternatives Analysis).

Relevant Factor—An impact that makes a significant contribution to the overall impact of the Priority Product and/or one or more alternatives or an impact for which there is a significant difference between alternatives.

Second Stage—The investigation stage of an Alternatives Analysis with a focus on: (1) thorough investigation of relevant factors; (2) final comparison; and (3) final selection decision.

Priority Product—A consumer product containing one or more chemicals that have a hazard trait that can harm people and the environment.

Abstract

The California Safer Consumer Products Regulations, passed in 2013, require manufacturers of products containing Chemicals of Concern to identify and assess potential alternatives through an Alternatives Analysis. The Regulations require the incorporation of life cycle thinking into this Analysis. Typical life cycle assessments are data-intensive; gathering data under the time constraints of these Regulations requires a screening approach to identify those areas that most contribute to a product's impacts.

This project: (1) developed a framework for incorporating life cycle thinking into a screening level Alternatives Analysis; (2) tested this framework with a case study of methylene chloride-based paint strippers and three alternatives; and (3) developed an approach for visually communicating results. The steps of the developed framework include: (1) determining the function of the product and Chemical of Concern; (2) identifying potential alternatives; (3) defining a functional unit; (4) brainstorming questions to consider; (5) conducting research; and (6) evaluating data.

While this framework is only one of many potential methods for bringing life cycle considerations into an Alternatives Analysis, it will provide guidance for practitioners unsure of how to conduct such an assessment.

TABLE OF CONTENTS

Signature Page ii
Acknowledgements iii
Acronyms iv
Definitions iv
Abstract v
Executive Summary 2
Project Objectives 6
Significance 7
Background & Literature Review 8
General Background 8
1. *DTSC* *8*
2. *AB 1879* *8*
3. *Safer Consumer Products Regulations* *8*
Existing Methodologies Background 9
1. *Life Cycle Assessment* *9*
2. *Alternatives Assessment* *12*
3. *Hotspot Analysis* *14*
Paint Stripper Chemical of Concern & Alternatives Background 14
1. *Methylene Chloride (Current Chemical)* *15*
2. *Chemical Substitutes* *15*
3. *Process Substitute* *17*
Methods & Data 18
Framework Development 18
Case Study 18
Economic Considerations 21
Results 25
Framework/Approach for Initial Life Cycle Screening in Alternatives Analysis 25
Results of Economic Considerations Assessment 60
Discussion & Conclusion 62
Framework 62
Case Study 63
Economic Considerations 64
Conclusion 66

Appendices **67**
Appendix A. Paint stripper chemical alternatives 67
Appendix B. Generalized Worksheet 69

References **78**

List of Figures and Tables

Figure 1. Generic life cycle flow diagram 9
Table 1. Example of how to display life cycle screening results 20
Table 2. Human health and environmental impact categories for TRACI 2.1 23
Figure A. Primary steps for incorporating life cycle screening 25
Figure B. Generic life cycle flow diagram 29
Table A. Example of how to display life cycle screening results 30
Table B. Potential Sources for finding quantitative data 43
Table C. Sample impact evaluation criteria, borrowed from TURI 45
Figure C. Example heat map 48
Figure D. Example heat maps by alternative 52
Figure E. Example heat maps by impact 54
Figure F. Framework primary steps and secondary details 55
Table 3. Net Present Value for paint stripper alternatives 60
Table 4. Benefit Cost Ratios of revenue for paint stripper alternatives 60

Executive Summary

Many consumer products contain chemicals that are known to be detrimental to human health and the environment. However, due to the current lack of regulation, and the lack of chemical content disclosure and consumer awareness, most manufacturers have little incentive to replace Chemicals of Concern (CoCs) with safer alternatives. AB 1879, signed into law by Governor Schwarzenegger in 2008, required the California Department of Toxic Substances Control (DTSC) to develop the Safer Consumer Products (SCP) Regulations. These Regulations established a process for identifying Priority Products—products that pose high risk to human health and the environment. The Regulations also require manufacturers to evaluate safer alternatives to these Priority Products by following an Alternatives Analysis protocol that incorporates a life cycle perspective to account for impacts throughout the production, use, and disposal of a product.

By integrating life cycle thinking into the Alternatives Analysis, manufacturers can avoid shifting environmental burdens and making environmentally unfavorable substitutions. Although well-developed guidelines exist for conducting appraisals for chemical substitutes (e.g. GreenScreen and EPA's Design for the Environment (DfE) program), and multiple case studies are available for those protocols, little guidance exists for fully incorporating life cycle considerations into a comprehensive Alternatives Analysis.

The focus of this group master's thesis project was to determine the best available methods for incorporating life cycle considerations into the Alternatives Analysis process required by the SCP Regulations. A framework for incorporating life cycle considerations was developed and tested using a case study of methylene chloride-based paint strippers and three alternatives. This report provides the objectives and significance of this project, describes the methods, results, discussion and conclusions for developing a life cycle screening approach, and provides a supplementary analysis of economic considerations. A review of relevant literature is included to provide a background on both Alternatives Assessment and Life Cycle Assessment (LCA) as they pertain to this project's development of the life cycle screening framework.

Incorporating life cycle considerations into the Alternatives Analysis involved a comprehensive assessment of available data, methods, and case studies regarding CoCs identified under the SCP Regulations. For the case study, the following actions were taken:

- Identification of methylene chloride in paint stripper as an appropriate example for the life cycle considerations case study;
- Obtainment and analysis of data and LCA methods relevant to the chosen product and potential alternatives; and

- Development of guidelines and suggestions for the incorporation of life cycle considerations into a First Stage Alternatives Analysis.

Our team researched industry, state, and international case studies of Alternatives Assessments pertaining to hazardous chemicals in products. Instances of life cycle thinking incorporated into these assessments were noted for further analysis. The team researched and assessed available methods for life cycle screening and their potential for incorporation into the DTSC Alternatives Analysis guidelines. Externalities not incorporated into companies' analysis processes were also identified and are reported in this document. Considerations for economic valuation of these externalities were explored through a cost benefit analysis and a comparison of net present value for several alternatives.

After reviewing relevant literature, the group developed a life cycle screening case study using methylene chloride in paint strippers and three potential alternatives: (1) benzyl alcohol, to represent a chemical substitution; (2) dimethyl adipate, to represent a 'green' chemical substitution; and (3) sanding, to represent a process substitution. These three diverse alternatives allowed the case study to incorporate a breadth of factors that must be considered in an Alternatives Analysis. Through the case study, key elements of life cycle consideration were identified. Important aspects of conducting an effective assessment were also identified, including:

- Ensuring that methods for research and ranking of impacts are standardized across the working group.
- Developing a systematic way to manage data gaps and uncertainty.
- Devising a system for documenting sources and specific data points.

Heat maps, modeled after examples in hazard assessments, were used to display the results of the methylene chloride case study. A heat map provides a condensed, easy to understand visualization of results from a life cycle screening. Comparing the maps by product allows for screening of alternatives that appear worse than the CoC. Alternatively, the maps can be compared by impact category (e.g. air quality) to help identify which impact categories are of the greatest concern for the product, chemical and alternatives.

To conduct the case study, a framework for life cycle screening was developed. The framework includes six primary steps:

1) Determine the function of the product and CoC
2) Identify potential alternatives
3) Define the functional unit
4) Brainstorm questions to consider
5) Research

6) Evaluate

These steps capture the need for an assessment to consider a breadth of alternatives and potentially relevant factors by requiring practitioners to assess functionality of both the product and the CoC prior to identifying potential alternatives. Defining a set quantity of a service to be delivered by a product or product system (i.e. functional unit) provides a standard for comparing impacts and exposure across alternatives. Brainstorming questions to consider prior to researching provides direction for the research and ensures that the scope of consideration includes all potentially relevant factors.

The research step of the framework contains two parts: (1) qualitative research and (2) quantitative research. Qualitative data is often more readily available and can be more easily understood by individuals new to life cycle concepts. Starting with qualitative data allows for relatively rapid data acquisition of life cycle impacts as they pertain to the product, CoC and alternatives. Quantitative data, when available, can improve the robustness of results by providing numerical data that are easier to compare directly across alternatives. When researching, it is encouraged to acquire as much quantitative information as possible, supplemented with qualitative data, and when necessary, to cycle between the two types of research to ensure that enough information is available for comparison.

The final stage of the framework requires practitioners to evaluate the compiled information and synthesize it into communicable results that allow for comparison of impacts across products. Two key aspects of the evaluation phase addressed at the end of the framework were not incorporated into the methylene chloride case study due to time and resource limitations:

1. Standardization of results by the functional unit, meaning the quantity of a chemical or product used to compare data points.
2. Normalization of results across impact categories to compare the different types of impacts.

From the case study, several key data gaps were identified, including: lack of human health data for less-studied alternatives; and lack of upstream, or pre-use phase, data (i.e. raw material extraction and production). To address lack of human health data, information from animal studies (e.g. lethal dose for rats) can be extrapolated to inform human health hazards; ideally, comparable studies should be used for all alternatives. To address the lack of data for upstream impacts, it is helpful to trace the compounds used to produce a given chemical or product and search for the impacts of these compounds. In the methylene chloride case study, data gaps in raw material extraction and production were a weakness in the results, and further research should be conducted to address these data gaps.

To complete the methylene chloride case study, additional quantitative information should be gathered to allow for standardization of results and a normalization technique should be selected to allow for comparison of results across impact categories. It is recommended that an existing normalization method, such as the US Environmental Protection Agency's (EPA's) Tool for the Reduction of Chemical and other environmental Impacts (TRACI), be adapted to fit the SCP requirements for consideration and be used to improve the comparison of methylene chloride paint strippers and alternatives. Additionally, for the methylene chloride case study to serve as a comprehensive example, all of the alternatives identified should be included in the First Stage analysis.

The Safer Consumer Products Alternatives Analysis Development master's thesis project ultimately furthered the potential for incorporation of life cycle considerations in the analysis of hazardous chemicals in products and their potential alternatives.

Project Objectives

The Bren Group Project team worked with the Department of Toxic Substances Control (DTSC) to develop guidelines for considering life cycle impacts in Alternatives Analyses and to prepare a framework document and visualization surrounding one of the three initial Priority Products and Candidate Chemicals covered under the Safer Consumer Products Regulations.[1] Paint stripper containing methylene chloride was chosen as the ideal Priority Product for developing a life cycle consideration framework due to the availability of alternatives that include chemical substitutes and full process substitutes (e.g. power sander). Assessment of the life cycle implications for the chosen product and chemical combination helped differentiate the steps and procedures outlined in the guidance.

Specific objectives included:

1. Developing a life cycle screening framework and testing that framework with a case study of methylene chloride in paint strippers and alternatives.
2. Designing a document explaining the steps for the developed life cycle screening framework and a visual presentation to communicate evaluations to public and corporate audiences.

Significance

The results of this project are expected to play a role in supporting the implementation of the Safer Consumer Products Regulations. Given the limited practical experience conducting an Alternatives Analysis, the completed case study and the findings of the Group Project will help the Department of Toxic Substances Control (DTSC) develop guidance documents for industry.

The creative approaches that Group Project members provided, with advice from experts including Dr. Arturo Keller and Dr. Sangwon Suh, will be valuable for DTSC. This group had the opportunity to work with DTSC to contribute to the Alternatives Analysis guidelines as public policy.

By collecting and using available data and evaluating life cycle impacts of alternative formulations or designs for paint strippers, the Bren Group Project team aimed to use the case study of alternatives to methylene chloride-based paint strippers to inform the development of life cycle guidelines for conducting Alternatives Analysis. This project provided an opportunity to strengthen a unique, progressive environmental policy aimed at reducing the use of toxic substances and systematically integrating life cycle thinking into manufacturing decisions. This work is important for reducing unintended consequences of alternatives and improving the ability of responsible entities to conduct a practical study in a reasonable time frame.

Background & Literature Review

General Background

1. DTSC

The California Department of Toxic Substances Control (DTSC) is a government agency that is part of the Cal/EPA. Its mission is to:

> Protect California's people and environment from harmful effects of toxic substances by restoring contaminated resources, enforcing hazardous waste laws, reducing hazardous waste generation, and encouraging the manufacture of chemically safer products…[DTSC] regulates hazardous waste, cleans up existing contamination, and looks for ways to reduce the hazardous waste produced in California.[2]

2. AB 1879

In 2008, Governor Arnold Schwarzenegger signed AB 1879 as part of California's Green Chemistry Initiative. AB 1879 increases regulatory authority over Chemicals of Concern (CoCs) in consumer products. It requires DTSC to assess and prioritize the most toxic chemicals in consumer products for potential restrictions or bans.[3] Furthermore, DTSC is tasked with evaluating alternatives. It also established an advisory panel of scientists called the Green Ribbon Science Panel to guide research, set up an Internet database of toxins, and create regulations.[3]

3. Safer Consumer Products Regulations

Federal and state laws often ban the use of certain chemicals in consumer products as their danger becomes evident. However, these laws frequently result in a switch to chemicals that still share many of the toxic effects of the banned substance. In an attempt to avoid these regrettable substitutions, the State of California passed the Safer Consumer Products (SCP) Regulations to encourage manufacturers to eliminate CoCs and to create products that are safer for consumers and the environment throughout their entire life cycles, including impacts that occur through the production, use, and disposal of the product.[4] Traditional assessments of human health and environmental impacts focus on the hazardous impacts generated only during the use phase of a product. Considering the entire life cycle of a product widens the scope of consideration for the environmental and human health impacts of a product to include all relevant impacts generated, from raw material extraction to end of life disposal.

Under the SCP Regulations, manufacturers are required to conduct an Alternatives Analysis to determine if there are feasible, safer substitutes for the CoC. When DTSC lists a CoC as part of a Priority Product, an Alternatives Analysis must be conducted to assess public health, environmental, and waste impacts. The Alternatives Analysis is broken into two stages: the First Stage focuses on the identification of potential

alternatives, the screening of those alternatives, and the identification of factors relevant for consideration; the Second Stage focuses on thoroughly investigating relevant factors, conducting a final comparison of alternatives, and making a decision. Upon completion of an Alternatives Analysis, manufacturers are not required to remove the CoC if the comparison does not support a switch.

Existing Methodologies Background

1. Life Cycle Assessment

Companies are encouraged to partake in life cycle thinking because information about the environmental impacts of one stage of a life cycle does not provide a sufficient basis for understanding the environmental performance of a product. Life Cycle Assessment (LCA) is "a compilation and evaluation of inputs, outputs, and potential impacts of a product system throughout its life cycle."[5] The life cycle of a product incorporates the processes that occur upstream (pre-use) and downstream (post-use) of a product's use. It is intended to provide a scope of assessment that includes all of the impacts generated by a product as opposed to only the impacts generated by a product's use. See Figure 1 for an example of a life cycle flow chart.

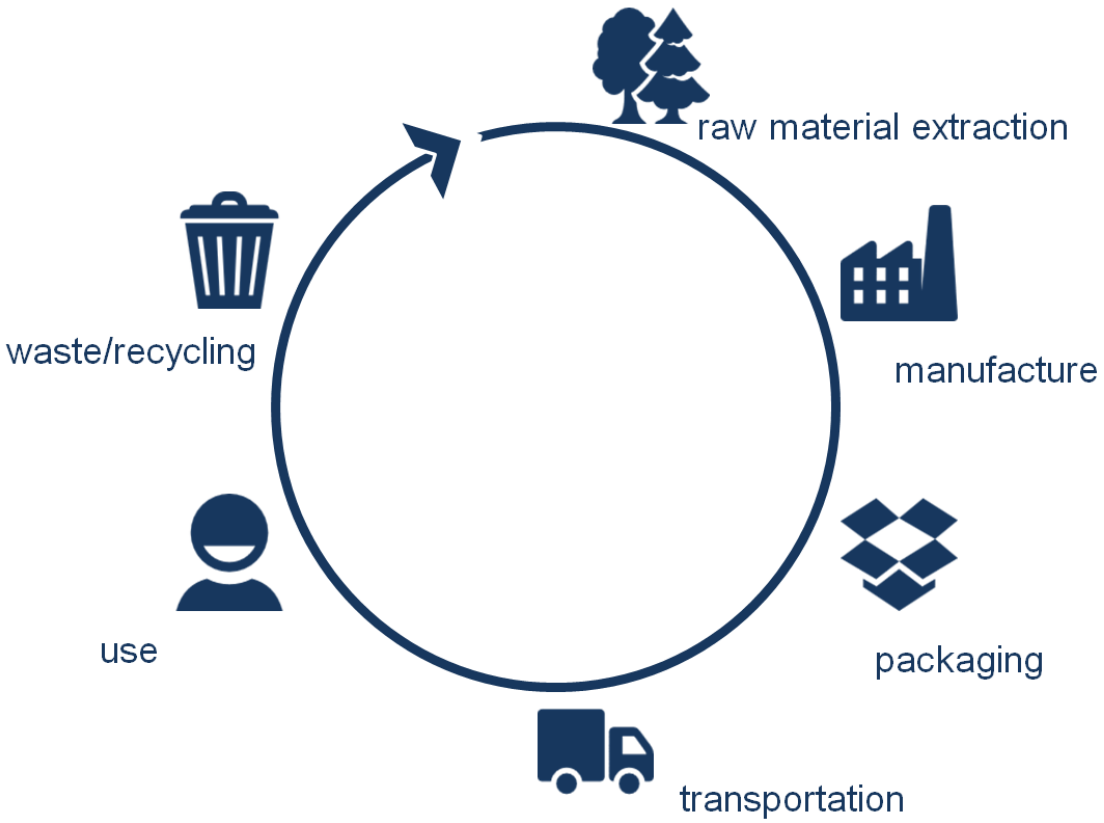

Figure 1. Generic life cycle flow diagram indicating phases of a product's life cycle, from raw material extraction through manufacturing and use, into disposal.
Icons by Icons8

Life cycle phases that must be considered for the Safer Consumer Products Regulations include:

- Raw material extraction
- Resource inputs and consumption
- Intermediate material processes
- Manufacturing
- Packaging
- Transportation
- Distribution
- Use
- Operation and maintenance
- Waste generation and management
- Reuse and recycling
- Waste disposal and end-of-life

LCA avoids problem shifting from one issue to another by addressing a broad spectrum of environmental impacts. However, despite being science-based, it is not free from subjective judgment. Moreover, it has barriers to progress such as low level of experience, undue expectations, and over-assumption.[6] These barriers inhibit LCA from being a perfect solution to considering life cycle impacts. Further challenges include cost, data, need for methodological expertise, and lack of communication to a broader audience.[7] LCA standards are presented as the ISO 14040 and 14044 standards. The four parts of an LCA are (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation.

An LCA begins by defining a functional unit. A functional unit is "a quantified performance of a product system for use as a reference unit;" it should be directly defined in the goal and scope, and should be measurable.[5] An impact category is "a class representing environmental issues of concern to which life cycle inventory analysis results may be assigned".[5] The impact categories to be considered under the SCP Regulations are: public health; environmental: air quality, soil quality, water quality, ecological; and waste and end-of-life.

Attributional LCAs are the most common life cycle approach. An attributional LCA uses historical data to describe energy and material flows into and out of a product or process.[8,9] However, this approach is simplified and is not predictive of real world impacts.

A consequential LCA model incorporates how a new product or product system would alter future material supplies and impacts. The consequential LCA aims to incorporate changes in the real world and is thus scenario-dependent and uncertain.[8,9] It shows how flows to and from the environment would be affected by different potential decisions, and estimates the effects of a specific action.[8,9] For example, a consequential LCA for a switch from a scarce to a non-scarce metal would consider the possibility of the non-scarce metal becoming scarce due to increased demand and the potential increase in mining impact.

Both attributional and consequential LCAs are subjective; results will be affected by the data and assessment strategy used, and are at risk for truncation errors that occur when the scope of an assessment is too narrow to include all major impacts.

a. Life Cycle Considerations

In many instances, a full LCA is not a viable option. With new or less-distributed products and components, there may be a lack of information in existing LCA databases to perform an assessment. Additionally, completing a comprehensive LCA can be time consuming. There may not be the available time to complete an LCA during the span provided for an Alternatives Analysis, particularly if datasets must be created for some of the alternatives.

When a full LCA cannot be completed, there are varying depths to which life cycle considerations can be taken into account. A common tool used to quickly gauge the environmental impacts of a given product is the Economic Input-Output (EIO) LCA tool.[10] The tool can output data in terms of air pollution, greenhouse gases, energy, hazardous waste, toxic releases, water withdrawals, transportation, land use, or impact categories from the US EPA's TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts). Values generated from EIO-LCA are on the industry-level and based on monetary value or mass of a product used. While this tool can be helpful in gauging general impacts, it is not an ideal option for comparing alternatives because it will not adequately differentiate between similar alternatives (e.g. multiple alternatives may be categorized by the same industry).

A 2014 article in the International Journal of Life Cycle Assessment explored the potential to simplify the LCA process using the case study of a mobile phone.[11] The paper explored five methods for simplifying an LCA: (1) exclude certain environmental impact categories or life cycle stages/processes; (2) use secondary process data from a commercial LCA database; (3) use economic input-output data from national environmental accounts; (4) use a linear model; and (5) exclude life cycle stages/processes from consideration. The study found that for mobile phones and similar technical devices, the methods for simplification that most accurately maintained the impact results were those using LCA database information and EIO data when primary or secondary data was not available. Using the best available data

and supplementing with less specific or precise data when necessary is a way to address information gaps.

2. *Alternatives Assessment*

Alternatives Assessment refers to the systematic comparison of safer alternatives to an existing process, product, or product component. Alternatives Assessments traditionally focus on hazard and exposure effects. Determination of potential alternatives for a given process or product is based on the functional use of the process or product needing amendment as opposed to the specific component being assessed. This widens the scope of potential alternatives and opens the assessment up to systems-based thinking.[12] Qualitative and quantitative information are used in an iterative process to ensure a thorough assessment with continuous improvement.[12] The overall goal of performing an Alternatives Assessment is similar to that of an LCA: to avoid shifting from one negative human health or environmental impact to another when switching to an alternative process, product, or product component. Alternatives Assessments, while based on scientific data, are subjective in the selection and application of data, methods, and scope.

Many frameworks currently exist for performing Alternatives Assessments on hazardous chemicals. Several prominent methods include: the Interstate Chemicals Clearinghouse (IC2); EPA's Design for the Environment (DfE); and Registration, Evaluation, Authorization and Restriction of Chemicals (REACH). Additional frameworks include: (1) BizNGO; (2) German Guide on Sustainable Chemicals; (3) Lowell Center AA Framework; (4) UNEP Persistent Organic Pollutants Review Committee General Guidance on Alternatives; (5) TURI Alternatives Assessment Process; and (6) UCLA Multi-Criteria Decision Analysis.[13] None of these frameworks have established methods for incorporating life cycle considerations into an Alternatives Assessment. As frameworks are tested, they continue to grow and improve. Some of the common frameworks are explored below:

Interstate chemicals Clearinghouse (IC2)

The stated goal of IC2 is to protect and enhance human health and the environment by ensuring that CoCs within a product or process are replaced by an inherently safer alternative. The primary steps for performing an IC2 assessment are: (1) identification of the CoC; (2) initial evaluation; (3) scoping; (4) identification of alternatives; and (5) evaluation of alternatives. These steps work to identify a CoC that is in need of replacement based on existing regulations, consumer concern, business concern or other reasons. During the initial evaluation phase, it is determined if the product needs an Alternatives Assessment to eliminate the CoC based on the existence of feasible alternatives. Only if it is determined that an assessment could yield a viable alternative is the process taken through the final evaluation step.[14]

Design for Environment (DfE)

The Environmental Protection Agency (EPA) developed DfE for the assessment of hazardous Chemicals of Concern within the United States. Primary steps of a DfE assessment include: (1) determining feasibility of the Alternatives Assessment; (2) collecting information on chemical alternatives; (3) convening stakeholders; (4) identifying viable alternatives; (5) conducting the hazard assessment; (6) applying economic and life cycle context; and (7) applying results to decision-making for safer chemical substitutes.[15] DfE brings life cycle thinking into the guidelines; however, it only calls for such considerations after viable alternatives have been identified. Waiting to bring life cycle considerations in at the end of the assessment prevents the functional unit approach to finding alternatives; it limits consideration of alternatives beyond drop-in substitutes.[12] DfE has assessed alternatives for flame-retardants in furniture and printed circuit boards as well as Nonylphenol ethoxylate (NPE) in surfactants.[15]

Registration, Evaluation, Authorization and Restriction of Chemicals (REACH)

The REACH guidelines focus on exposure scenarios for a CoC and how to find an alternative that reduces impacts at the points of exposure. The steps of a Chemical Safety Assessment (CSA) through REACH are: (1) compiling and assessing available information; (2) conducting a hazard assessment; and (3) decision-making on refining the assessment, at which point iteration may begin. The European Chemical Agency (ECHA), responsible for developing REACH, is working to incorporate economic considerations into its assessment model. This would make REACH one of the more comprehensive Alternatives Assessment methodologies available[16].

Alternatives Analysis

The DTSC Alternatives Analysis framework incorporates aspects of these existing Alternatives Assessment methodologies. Based on the requirements of the Safer Consumer Products (SCP) Regulations, which states that human health and environmental impacts must be considered at every stage of a product's life cycle, the Alternatives Analysis process will be more comprehensive and wide-reaching than a traditional Alternatives Assessment. However, these existing assessment methodologies are useful for informing the hazard assessment and the economic considerations aspects of an Alternatives Analysis. Combining these materials with the life cycle considerations processes currently in development will help in making well-informed Alternatives Analysis reports.

3. *Hotspot Analysis*

Hotspot analysis, an Alternatives Assessment approach, is defined as a methodological framework that allows rapid assimilation and analysis of large volumes of information to identify and prioritize hotspots—the most significant economic, environmental, ethical, and social impacts of a product. The results deduced from hotspot analysis can be used to identify opportunities for impact improvement and to prioritize impact reduction actions. It boasts a user-friendly format and can be accessed by both technical and non-technical audiences. It also serves as a precursor for further investigation or action by industry, governments and other stakeholders. Unlike the life cycle approaches that base their evaluation on tools with limited outputs, hotspot analysis adopts a materiality-focused approach, often absorbing a range of research inputs and stakeholder views.

Four common methodological steps in conducting a hotspot analysis have been identified: (1) goal and scope definition; (2) data gathering, expert insight and analysis; (3) hotspot identification and validation; and (4) prioritizing action. However, there is a lack of a generic approach to hotspotting; no effort has been made to consolidate or share best practices amongst those organizations or initiatives currently developing and deploying these methods. No accepted guidance on how to convert the findings of hotspot analysis into meaningful sustainability information and render them applicable in practice within industry, governments and other stakeholders has been developed.

The benefits of hotspot analysis are: (1) rapid assimilation and processing of voluminous evidence threads and the creation of accessible outputs to facilitate the decision-making required to eliminate, reduce or mitigate identified hotspots; (2) provision of a highly cost-effective approach with life cycle thinking as a management tool to be applied across multiple impact categories and issues, sectors or product categories; (3) bearing a "beyond LCA" view of hotspots that helps users to surpass the boundary inherent in traditional LCA (e.g., the assessment of various, cumulative impacts from different activities within fixated geographical location; better understanding of wasted resources in an industrial sector or production cycle; and the considerations of ethical and governance issues); and (4) offering both technical and non-technical information in an easy-to-interpret format to decision-makers in government, business and civil society.[17]

Paint Stripper Chemical of Concern & Alternatives Background

Due to the availability of chemical substitutes and full product replacements, paint strippers containing methylene chloride were chosen as the ideal Priority Product to inform the development of life cycle framework for Alternatives Analysis.

Paint strippers are chemical or physical products used to remove paint from a particular substrate such as wood or metal. They may be used to restore the substrate to its original condition or to prepare it for new paint or varnish. Chemical products cause the paint to "bubble" and separate from the substrate, allowing for easier removal using a paint scraper. Physical products such as manual or mechanical sanding scrape the paint off the substrate. In reality, stripping a painted substrate may combine chemical and physical methods in order to achieve a 100% paint-free surface. Alternative products should, however, achieve the same function as the Priority Product alone, and in the same time period. For paint strippers, in the case of a chemical substitute, the alternative chemical is likely to be another solvent.

1. Methylene Chloride (Current Chemical)

Methylene chloride is highly volatile liquid that is a probable human carcinogen.[18] Acute exposure to methylene chloride can lead to dermal, ocular, liver, cardiovascular, or respiratory toxicity, and can even result in death.[18] As a volatile organic compound (VOC), methylene chloride is considered a toxic air pollutant under the 1990 Amendments to the Clean Air Act. Despite its health concerns, it is the most widely used solvent in chemical paint and varnish removers because it is the fastest-working and most effective solvent and has low flammability hazard.[19] A study by W.M. Barr and Company, Inc., a manufacturer of paint stripper containing methylene chloride, has concluded there is no alternative product as effective that is also non-flammable.[19] Based on consumer surveys, it is estimated that a typical household consumer's annual exposure time to methylene chloride in paint strippers is approximately 2 hours and 25 minutes per year.[20] Air purifiers, masks and gloves may not provide adequate personal protection. An estimated 9.68 tons of methylene chloride are emitted to the air every day from consumer paint strippers.[21]

2. Chemical Substitutes

a. Benzyl Alcohol

Benzyl alcohol is a chemical alternative to methylene chloride. Benzyl alcohol is produced commercially by the catalytic hydrolysis of benzyl chloride.[22] It is a colorless liquid with a mild aromatic odor and sharp burning taste.[23] It is a mild acute toxin (LD50 of 1.2 g/kg in rats, LD50 of 100 mg/kg bw for 2 species of birds and LD50 of 150-160 l/hectare for mosquitos),[24] contact allergen, and is severely toxic and irritating to the eyes.[22] It is harmful by inhalation and has sensitizing properties if swallowed.[23] Benzyl alcohol is not classifiable as to its carcinogenicity.[22]

Benzyl alcohol has low volatility and is not expected to be an air pollutant. The half-life for the gas-phase reaction of benzyl alcohol with photochemically produced hydroxyl radicals can be estimated at 2 days.[22] The half-life for oxidation (reaction of benzyl alcohol with alkylperoxy radicals) is 9 days.[22] It is not persistent and is readily biodegradable.[23] It is not expected to bioaccumulate.[23] Its bioconcentration factor

(BCF) is 4.04.[22] It is highly mobile and readily leaches in soil, and adsorption is not expected to be an important fate process.[22] Benzyl alcohol underwent 60.8% degradation in a 5-day test under aerobic conditions, and anaerobic degradation was complete within 2 weeks.[22] It is moderately soluble in water and soluble in most organic solvents. It is more toxic to the aquatic environment than methylene chloride.[23] While benzyl alcohol itself is a VOC, some products may be labeled as a VOC-free.[23] The MSDS for Dumond's Peel Away Smart Strip, a paint stripper containing 30-50% benzyl alcohol, labels it as highly biodegradable, water-based and containing no VOCs.[25]

Between 2000 and 2007, the use of benzyl alcohol increased significantly.[23] Benzyl alcohol is commonly used in the aircraft stripping industry.[23] It adheres well to vertical surfaces and remains active for approximately four hours.[23] However, it takes longer—by approximately 25%—to strip paint and is also more labor intensive than methylene chloride.[23]

b. Dimethyl Adipate

Dimethyl adipate (DMA), also known as hexanedioic acid, is marketed as a "green" chemical alternative to methylene chloride. Some concerns for human health and the environment do exist for this alternative, particularly when the product contains a high loading level of DMA. These concerns include reports of blurred vision and lung irritation when workers are exposed to high concentrations of DMA. These reports are likely also linked to poor ventilation in work areas. Animal studies performed on rats indicate mild irritation to skin and eyes upon contact exposure and minimal toxicity from oral exposure. The low vapor pressure and high water solubility of DMA create a concern about the chemical's toxicity to aquatic organisms. It has been shown to have a 96-hour lethal dose (LD50) of 18-24 mg/l for fathead minnows.[26]

c. Acetone

Acetone is a common alternative to methylene chloride. It is a highly flammable and volatile solvent. Acetone is readily absorbed into the bloodstream from the lungs and is also absorbed directly from the skin, making inhalation and dermal exposure a concern.[27] Because acetone occurs naturally in the human body, the liver is capable of breaking it down to non-harmful substances that leave the body.[27] The effects of high exposure to acetone are not fully understood and its human carcinogenicity is not currently classifiable.[27] Presently, the greatest concern regarding acetone in chemical paint strippers is its flammability risk.[27] Acetone was considered for the group's economic assessment because information was available in relevant databases, but was not considered for the development of the framework or visualization approach due to its flammability.

3. Process Substitute

Manual & Mechanical Sanding
Sanding, which includes hand sanding and mechanical sanding, is a physical method to remove paint from the substrate, and is usually considered as an alternative to chemical paint strippers such as methylene chloride.

Sandpaper comes in a number of different shapes and sizes such as sandpaper sheets, sand belts, or sand disks. Typical sandpaper consists of an abrasive mineral, backing, and adhesives. Backings for sandpaper are generally made of paper, cotton, polyester, or rayon. Aluminum oxide and resin bonds are the most commonly used components in a wide variety of sandpaper grits and adhesives, respectively. The grit sizes determine the finish of the work, with larger grit sizes resulting in rougher finishes.[28]

Hand sanding is both time-consuming and physically demanding but can be very effective for smaller, more delicate surfaces. Mechanical sanding involves the collective use of a variety of power tools in order to brush off the old layers of paint. Circular sanders, belt sanders, and orbital sanders are often used due to their capabilities to remove paint layers quickly and easily. A great deal of sanding dust is generated during the process. Thus, the EPA has suggested performing sanding tasks in a ventilated area, using vacuum sanders, and operating sanders with the use of personal protective equipment including a mask, gloves and goggles to reduce the potential exposure to harmful matter and dust.[29] It has been reported that hand-sanding results in a 90% reduction in concentrations of airborne dust generated compared with mechanical sanding and 99% of the exposure to dust can be reduced in a ventilated area.[30] Sanding dust may contain airborne particles such as wood dust, which may cause respiratory symptoms and health problems. It also may be hazardous if it contains heavy metals such as copper or nickel, which can result from the sanding process on a metal substrate.[31]

Methods & Data

Framework Development

Methods

Alternatives Assessment, Life Cycle Assessment and hotspot analysis methodologies were reviewed to inform the framework development. Key aspects and factors were identified to develop a life cycle screening framework, which allowed for modification of existing methodologies to suit the needs of the SCP Regulations. A case study was used to develop, test, and refine the framework. Current literature related to industry, state, and international case studies was reviewed to form a basis for the group's case study of paint stripper containing methylene chloride.

Data

Visualization of data was modeled after heat map approaches developed by the Clean Production Action's GreenScreen® method and the Department of Defense Sustainability Analysis Guidance Draft. The incorporation of uncertainty (high, medium, low) evaluation was modeled after the GreenScreen® method.

Impact level evaluation criteria were borrowed and modified from the Toxics Use Reduction Institute (TURI) guidance. The EPA's Design for Environment Alternatives Assessment Criteria for Hazard Evaluation is also consistent with these criteria, demonstrating the validity of the utilized evaluation criteria.

Case Study

Methods

To develop a case study of life cycle screening and to test potential methods for completing this aspect of the First Stage Alternatives Analysis, a Chemical of Concern (methylene chloride) and alternatives (benzyl alcohol, dimethyl adipate and sanding) were identified and assessed for life cycle impacts. To identify alternatives, existing alternatives in the marketplace were researched. Additional potential alternatives were provided by W.M. Barr & Company (W.M. Barr). However, W.M. Barr did not contribute to the group's framework document; the company only provided a list of potential alternatives.

Because an Alternatives Analysis incorporates life cycle thinking into a traditional Alternatives Assessment, three alternatives were ultimately considered: (1) benzyl alcohol; (2) dimethyl adipate; and (3) sanding. These three in particular were selected to represent one chemical alternative (benzyl alcohol), one "green" chemical alternative (dimethyl adipate), and one process alternative (sanding). Rather than limiting the alternatives to only chemical alternatives that would achieve the same function as methylene chloride, the scope was expanded to include any alternative that achieved the same function as the process (e.g. sanding) to test the applicability of the developed framework to both formulated and composite products.

Manufacturers' answers to a REACH questionnaire asking them to state their methylene chloride-free formulations listed many of the chemical alternatives identified here (e.g. Dibasic Ester (DBE)-based products, benzyl alcohol-based products). However, other alternatives were not considered in this project due to the need to create a manageable scope of alternatives for an effective example. REACH also listed mechanical sanding in its report.

The SCP Regulations provided life cycle phases and impact categories to consider and research. Before beginning any research on methylene chloride and its alternatives, the actions included in each life cycle phase and the boundaries of each life cycle phase were identified. The DTSC SCP Regulations presents examples of factors to consider (e.g. duration, route, and concentration of exposure for human health impact). During this process, questions that would help to focus and guide research were formed and compiled into a Generalized Worksheet (Appendix B in results). Additionally, at this point in the research process, the functional unit—one m^2 of painted hard wood that has been 95% stripped of its acrylic paint in less than three hours—was defined to serve as a reference point for comparison.

Data

Research and reports from governmental (e.g. EPA, NIOSH, OSHA, ATSDR) and some non-governmental sources (e.g. Material Safety Data Sheets, UseTox) provide reliable information for initial analysis of each alternative. These sources provided qualitative information about the severity of impacts as well as some quantitative data on animal testing studies (e.g. LC50, ED50) and environmental impacts (e.g. Comparative Toxic Units (CTUe) in air, water, and soil). Each source of information was cited to easily keep track of research and uncertainty.

Data was recorded in a table with life cycle phases in columns and impact categories in rows. The information found was filled into the intersections of columns and rows, called segments (Table 1).

Table 1. Example table for displaying results of a life cycle screening analysis.

Chemical Name	Raw material extraction	Resource inputs and consumption	Intermediate material processes	Manufacture	Packaging	Transportation	Distribution	Use	Operation and maintenance	Waste generation and management	Reuse and recycling	EOL disposal
Public health impact												
Air quality												
Soil quality												
Water quality												
Ecological Impacts												
Waste and EOL												

Based on the quantitative and qualitative information found, the severity of impact ("minimal to no," "low," "medium," "high") was designated according to the most severe data point within each life cycle segment to take the most conservative approach. Colors were assigned to each level of severity:

- "minimal to no" = green;
- "low" = yellow;
- "medium" = orange; and
- "high" = red.

When there was a lack of data on which to evaluate impacts, or when the life cycle phase either did not apply or could be reallocated to other phases, more colors were added to the heat map (black and grey, respectively). Furthermore, life cycle phases that were not expected to change between alternatives (Packaging, Transportation, Distribution, Resource Inputs and Consumption) were designated with a blue color.

A level of uncertainty ("high," "medium," "low") was also given based on the reliability and robustness of the data, and the likelihood of the impact.

The resulting heat maps allowed for an easy visual comparison of life cycle impacts across products and across impact categories. Throughout the life cycle screening process, the steps involved have been documented and assessed in the Framework (see "Results" section).

Economic Considerations

A benefit-cost comparison as well as comparison of net present value (NPV) for methylene chloride and two chemical alternatives (benzyl alcohol and acetone) was conducted. These alternatives were selected based on available information in the databases used for comparison (TRACI 2.1 and USETox). Material costs were calculated using available online resources. The dollar values for environmental costs are based on emissions factors from Tool for the Reduction and Assessment of Chemical Impacts (TRACI) 2.1 and the Material Environmental Benefits Calculator (MEBCalc). TRACI 2.1 was developed by the US EPA and contains emissions data for the assessed alternatives. Emissions data were grouped across nine impact categories such as non-cancer human health impacts, eutrophication, and acidification. The MEBCalc tool was developed by Sound Resource Management Group to estimate the costs to society for various environmental emission impact categories.

Methods

The benefit and cost values obtained for each chemical were forecasted for a ten-year time horizon. A time horizon of ten years was selected to reflect the relatively short time considerations a company will give to a particular product. No sensitivity analysis was performed for the time horizon because our study includes no upfront costs. The lack of upfront costs reflects that a supplier will not pay the fees associated with switching manufacturing. An end distributor (e.g. Home Depot) may be responsible for conducting an Alternatives Analysis if no supplier conducts the analysis and the end distributor continues to offer the identified product. Scaling the time horizon does not affect the results of a cost benefit analysis and only changes the magnitude of a net present value assessment. A private firm discount rate of 7% was used because the company pays the direct costs and is required to consider the indirect costs. This discount rate represents a reasonable value for private entities.

Net Present Value was calculated by subtracting the forecasted costs from forecasted benefits and discounting future values to get an estimated present value.

$$NPV = \sum_{t=10}^{T} \frac{forecasted\ benefits_t - forecasted\ costs_t}{(1 - discount\ rate)^t}$$

Similarly, the cost and benefit values for the cost benefit analysis (CBA) were discounted to obtain NPV. For the CBA, the NPV of costs was divided by the NPV of benefits to obtain a ratio of costs over benefits, which demonstrates the extent to which costs outweigh benefits without consideration of total NPV.

$$Cost\ Benefit\ Ratio = \frac{NPV_{benefits}}{NPV_{costs}}$$

Material Data

The shelf price of the paint stripper products was used in conjunction with the gross profit margin of a typical hardware store to account for the amount that a hardware store would gain in revenue from each paint stripper. This benefit estimation method was chosen because data regarding the amount of money that Home Depot pays and earns for a given product was not readily available due to its confidentiality. Gross profit margin, while less applicable than specific product margins, was selected because the information available for gross profit margins is more current and consistent than the publicly available, product-specific data.

In-store shelf prices were available through Home Depot for all alternatives: methylene chloride; benzyl alcohol; and acetone. While the prices were taken from online sources, they reflect in-store values and any sale or discount pricing was ignored. The gross profit margin values are the most recent quarterly values available at the time of the economic assessment (Fall 2014) and were obtained through Y-Charts, which are Yahoo's financial charts. The methylene chloride product selected as a baseline was Klean-Strip KS-3 Premium Stripper, which retails for $22.98 per gallon at Home Depot.[32] Pure acetone was also available under the Klean-Strip brand at a cost of $4.97 per liter ($18.81 per gallon).[33] Ready Strip, which uses benzyl alcohol as the primary solvent, was sold for $39.97 per gallon.[34] The gross profit margin for Home Depot was 35.02% as of October 31, 2014.[35]

To obtain annual profit for each alternative, it was assumed that the volume of sales would be consistent for all scenarios. The underlying assumption for consistent sales is that demand for paint stripper is relatively inelastic (i.e. customers are not price-sensitive). Home Depot had 27.2% of the home improvement product sales for the United States in 2013.[36] This market share was assumed to be representative of paint stripper sales throughout the United States. Revenue was calculated assuming Home Depot as the responsible entity. Volume of sales was extrapolated from the annual demand for methylene chloride as a solvent in paint stripper in the US that came from the US EPA's Chemical Data Access Tool. The density of the paint strippers was calculated using the volume and weight provided on supplier websites. Average loading level of methylene chloride (i.e. percent of the chemical in the overall product) came from Material Safety Data Sheets (MDSDs) from suppliers. These values, combined with the portion of the paint stripper market held by Home Depot, were used to estimate volume of paint stripper sales. Additionally, it was assumed that Home Depot would run the assessment based on total US sales, despite only being required to consider sales within California, because it would be simpler to consider a nationwide replacement scheme. Furthermore, it is not completely unlikely that other states may establish similar regulations (e.g. the "California Effect" on automobile emissions standards).

Environmental & Human Health Data
TRACI 2.1 provides environmental and human health impacts across nine impact categories identified in Table 2.

Table 2. Human health and environmental impact categories for which TRACI 2.1 provides emissions data.

TRACI 2.1 Impact Categories
Global Warming Potential
Acidification
Particulate Matter (PM 2.5)
Eutrophication
Ozone Depletion
Smog Air
Ecotoxicity emitted*
Human Health Non-Cancer*
Human Health Cancer*

*Emissions are calculated to six environmental compartments

This database contains the solvent chemicals being assessed: methylene chloride (baseline), benzyl alcohol, and acetone. Due to the variety of formulations and loading levels that exist for each alternative, it was assumed that only the primary solvents generated enough impact to warrant measurement for comparison to simplify the study.

Emission factors were converted to dollars per kilogram using the Measuring Environmental Benefits Calculator (MEBCalc) tool developed by Sound Resource Management Group. Dollar values were available for all impact categories except smog and ozone and have incorporated information from as recently as 2013. Impact category values for the tool were estimated from existing literature.[37] It was assumed that the human toxicity and human cancer dollar values used in MEBCalc that were estimated based on toluene and benzene emissions, respectively, would be accurate for the scope of our study, given that they were based on chemicals used in the production of the chemicals under consideration. Values for the human toxicity and cancer impact categories may underestimate the true cost because they are based on

hospital treatment costs as opposed to using a revealed preference method to determine willingness to pay (WTP) for the avoidance of risk, which tends to yield higher values of statistical life (VSL). MEBCalc was also chosen because it takes into account environmental costs across the life cycle of a product (e.g. production, use, disposal), which reflects the requirements of the SCP Regulations.

The dollar values based on emissions factors from TRACI 2.1 and MEBCalc were multiplied by the annual use of each chemical to obtain environmental and human health costs for one year. It was assumed that annual use of chemical paint strippers would remain consistent over the ten-year time horizon based on market data for methylene chloride sales. To address loading levels, low, medium, and high loading levels for each product were used to test the sensitivity of the results. The low and high loading levels were based on the extremes of the range provided in each chemical's Material Safety Data Sheet (MSDS) and the middle loading level was an average of the high and low values.

Results

Framework/Approach for Initial Life Cycle Screening in Alternatives Analysis

The following document outlines an approach for incorporating life cycle thinking into a First Stage Alternatives Analysis, as set forth in the California Safer Consumer Products (SCP) Regulations. Established Alternatives Assessments focus on use-phase hazards and incorporating life cycle thinking captures aspects of the production, use and disposal of the product to reduce the occurrence of regrettable substitutions.

A full life cycle assessment is time- and data-intensive and is not required by the SCP Regulations. This framework was developed to aid small businesses unfamiliar with life cycle concepts to take into consideration impacts that occur throughout a product's life cycle, and to do so within the time constraints of the SCP Regulations. This framework draws from established Alternatives Assessment and Life Cycle Assessment methodologies, but focuses on hotspotting as a technique to reduce the time and data necessary for decision-making.

This document serves as a screening framework that aims to help identify relevant factors and alternatives to be assessed in a Second Stage Alternatives Analysis. A Second Stage Alternatives Analysis involves a thorough investigation of relevant factors identified in the First Stage, a final comparison of alternatives, and making a decision.

The framework outlined in this document includes six primary steps that are explored below in Figure A.

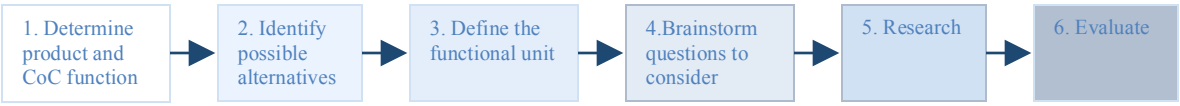

Figure A. Primary steps for incorporating life cycle screening into a First Stage Alternatives Analysis

A case study of methylene chloride-based paint strippers was used to test this framework for its applicability to both formulated and composite products. Methylene chloride is a solvent that causes paint to separate from the substrate, allowing for easier removal using a paint scraper. Examples from this case study are provided in this document to improve understanding of how to implement the framework.

Note: For a complete list of definitions and potential factors that must be considered for an Alternatives Analysis, please refer to the SCP Regulations.

1. **Step 1: Determine the function of product and Chemical of Concern**
   To begin the alternatives identification and comparison process, it is important to first understand what the function of the product is and to subsequently identify the purpose of the Chemical of Concern (CoC) within that product.

   Example:
   Product: Methylene chloride-based paint and varnish removers.

   Product Function: To remove paint or varnish from a particular substrate such as wood or metal, to restore the substrate to its original condition, or to prepare it for new paint or varnish.

   Chemical Function: Solvent that dissolves paint by bonding to the chemical, causing it to separate from the substrate.

   Alternative products, therefore, should achieve the same function as the Priority Product. In the case of a chemical substitute for paint strippers, the alternative chemical is likely to be another solvent.

2. **Step 2: Identification of potential alternatives**
   To identify potential alternatives, the function of both the product and the Chemical of Concern should be considered. In the paint stripper example, focusing on the function of the product as a whole (i.e. removing a certain type of paint) allows the responsible entity to consider entirely new alternatives (e.g. power sanders) as opposed to only chemical replacements.

   Many information sources for identifying alternatives exist. When DTSC lists a Priority Product it generally includes a list of potential alternatives in the Priority Product Profile. Looking at comparable products already on the market that do not contain a Chemical of Concern can be a good place to start. Additionally, contacting chemical suppliers about alternatives can provide useful information. Reading literature from peer-reviewed sources regarding alternatives can provide another avenue for identifying alternatives, provided public concern or existing regulations have pushed for an assessment of potential alternatives for a product or CoC. *For a list of alternatives identified in the methylene chloride paint stripper case study, see Appendix A.*

2.1. *Alternatives that already exist on the market*

In many cases, alternatives to a Priority Product already exist. Most responsible entities will already know about alternatives on the market. It can still be informative to look at the market to ensure that no existing alternatives are overlooked. For the methylene chloride case study, an Internet search yielded a list of potential alternatives already on the market.

2.2. *Alternatives recommended by suppliers*

Chemical suppliers can be a valuable resource for identifying alternatives. These companies know the characteristics of the chemical that they currently supply for a given function (e.g. solvent for paint removal) and can identify other chemicals with similar characteristics and functionality.

3. Step 3: Defining a functional unit for comparison

A functional unit is defined as "a quantified performance of a product system for use as a reference unit,"[38] which allows for an evaluation and comparison of the Priority Product and the alternatives in a measurable way. A well-defined functional unit translates the purpose of the product into a useful metric for alternative comparison. When defining a functional unit, it is important to: (1) be specific in clearly defining goal and scope of the life cycle considerations, and (2) capture all relevant features (i.e. market expectations) of the product.

Example:

Functional Unit: One m^2 of painted hard wood that has been 95% stripped of acrylic paint in less than three hours.

$$Functional\ Unit = \frac{1\ m^2\ painted\ wood, 95\%\ stripped}{3\ hours}$$

The functional unit chosen for paint strippers reflects that it is difficult to remove all paint from a substrate (hence the 95% stripped as opposed to 100%), and that most consumers are satisfied without 100% paint removal because they will be refinishing the wood. It additionally takes into account a time span acceptable to most consumers (3 hours) for removing paint. If it is desired that the product have additional features, such as the ability to remove paint from multiple substrates (e.g. wood and metal), then this aspect should be included in the functional unit. A properly defined functional unit ensures that any selected alternative possesses all of the desired qualities of the original product/chemical combination.

4. Step 4: Brainstorming questions to consider

4.1. Setting up a roadmap for life cycle research

It is important to understand life cycle phases and impact categories identified by DTSC and how they apply to the product and alternatives before beginning research. Key questions emerge that will help to focus research efforts with an understanding of the boundaries between different life cycle phases and what sort of information is needed to assess impacts within those phases. A life cycle phase for a product captures some aspect of the production, use or disposal of the product.

For a detailed list of questions to consider, please refer to the "Generalized Life Cycle Considerations Worksheet" in Appendix B. This resource is intended as a guide to begin the assessment process, and may not cover all potentially relevant factors. It is not meant to be comprehensive and complete, and therefore may not cover all potentially relevant factors.

Example:

Life cycle phase: Raw Material Extraction

Considerations: If one of the raw materials used in a product is mined, some potential considerations include:

- Does the mining process release contaminants to water or air?
- Is there significant waste generated from mining?
- Is the waste generated hazardous?

Establishing important questions or considerations for different impacts within each life cycle phase will help guide research.

4.1.1. Life cycle phases

The life cycle of a product is the "consecutive and interlinked stages of a product system", from raw material extractions from natural resources to the end of life.[38] Life cycle assessment (LCA) is a systematic way to evaluate the impacts of a product or service system throughout the phases of its life cycle (Figure B), with a particular focus on human health and environmental impacts.

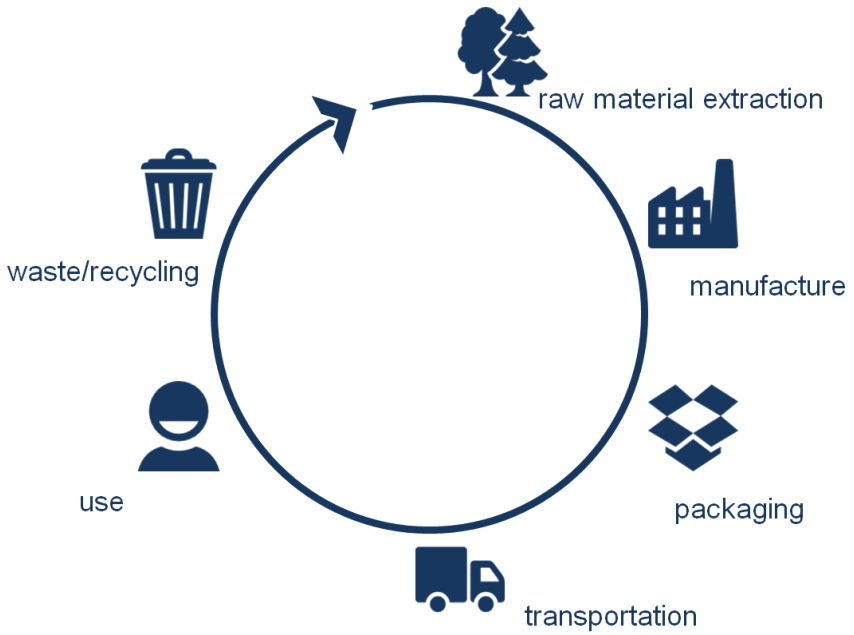

Figure B. Generic life cycle flow diagram indicating phases of a product's life cycle from raw material extraction through manufacturing and use, into disposal.
Icons by Icons8

The typical life cycle includes:

- Raw materials extraction;
- Resource inputs and consumption;
- Intermediate material processes;
- Manufacturing;
- Packaging;
- Transportation;
- Distribution;
- Use;
- Operation and maintenance;
- Waste generation and management;
- Reuse and recycling;
- Waste disposal and end-of-life.

A life cycle approach may reveal significant environmental issues (e.g. adverse ecological impacts and adverse human health impacts) related to the product of concern and its alternatives that may have been missed in a basic, traditional examination of use-phase impacts.

While there are many specific definitions for life cycle phases, the SCP Regulations do not define the boundary between one phase and another. In some cases, the phases may overlap. The phases as listed in the regulations can be considered separately (e.g. transportation, distribution) or may be grouped together (e.g. transportation/distribution). However it is decided to break up the life cycle phases, it is important to clearly define the distinct phases to avoid double counting of impacts.

4.1.2. Impact categories

Impacts resulting from the production, use, or disposal of a product are categorized by the type of impact (e.g. air quality impacts). The objective of this step is to identify the human health, environmental, waste stream, and end-of-life concerns for each life cycle phase. The results should be presented in a format that allows any interested party to have a clear understanding of the study's outcome. See Table A, below, for an example format. In this example, the impact categories are displayed in the rows and the life cycle phases are displayed in the columns. Impacts for a specific impact at a particular life cycle phase can be filled into the intersection of those two factors in the table.

Table A. Example table for displaying results of a life cycle screening analysis.

Chemical Name	Raw material extraction	Resource inputs and consumption	Intermediate material processes	Manufacture	Packaging	Transportation	Distribution	Use	Operation and maintenance	Waste generation and management	Reuse and recycling	EOL disposal
Public health impact												
Air quality												
Soil quality												
Water quality												
Ecological Impacts												
Waste and EOL												

Three elements are included in identifying and assessing relevant impact categories:

1) Conducting a qualitative check on the information of each life cycle phase to ascertain the likely impacts;
2) Applying a systematic approach to quantify identified impacts; and
3) Assessing the results with careful consideration given to conclusions drawn when there is a lack of information or data uncertainty.

These steps are further explained in Sections 5 and 6.

Within each phase of the product's life cycle, adverse effects to public health, the environment, and waste and end-of-life are investigated. Some examples of information to consider are provided below.

4.1.2.1. Adverse Human Health Impacts

The SCP Regulations define adverse public health impacts as:

> Any of the toxicological effects on public health specified in article 2 or article 3 of chapter 54 under Division 4.5, Title 22, California Code of Regulations, or exceedance of an enforceable California or federal regulatory standard relating to the protection of public health.

The health impact assessment should identify all potential population exposures to chemicals or conditions that may cause adverse impacts. Human health data is generally the easiest impact data to find, because government agencies produce reports summarizing such impacts for chemicals used in the United States.

A number of aspects warrant in-depth consideration in the course of the analysis, including:

1) Estimated quantity or concentration of substance and route of exposure (e.g. 14 mg dust/m^3 air inhaled by a worker);
2) The duration of exposure. Analysis is often based on realistic exposure conditions, but occasionally it may be necessary to make conservative assumptions of parameters, such as average time period of exposure, in order to get a quantitative estimate of overall exposure;
3) All potential routes of exposure and the exact exposure pathways involved, both of which must be identified by the end of the Second Stage analysis. The potential routes of exposure include ingestion, inhalation, dermal contact and ocular contact for any product;
4) Estimates of potential health effects caused from risk factors on subgroups of the population. These subpopulations may include: (1) workers involved in the activities in each of the life cycle phases; (2) uninvolved workers (i.e. workers present at the site of the activity, but not involved in the activity); and (3) the general public; and
5) Other factors that may influence the amount of exposure, such as the use of personal protective equipment.

Example:
Scenario: Inhalation of sanding dust as a result of sanding paint from wood surface.

Human Health Impact: Respiratory irritation or damage. Determining the level of expected impact, from no impact to severe impact, will be described in detail in Step 6: Evaluation. Respiratory irritation impacts can be rated on the severity of the impact from:

1) No impact – no respiratory irritation or damage
2) Minimal impact – minor respiratory irritation that fades quickly after exposure
3) Low impact –minor respiratory irritation that is reversible
4) Medium impact – moderate respiratory irritation that may take time to subside
5) High impact – respiratory irritation and some degree of permanent damage

Respiratory irritation is often covered in government reports. When respiratory irritation is a potential concern and data cannot be found, it represents a data gap that should be addressed in the Second Stage Alternatives Analysis.

Factors that may affect exposure: Variations in inhalation rate due to physical activity, the use of Personal Protective Equipment (PPE), and the existence of ventilation or other waste management or air quality equipment.

4.1.2.2. Adverse Environmental Impacts

When conducting an environmental impact assessment, both the physical-chemical environment (i.e. air, water, and soil) and the biological environment (i.e. plants and animal species) need to be considered. This holistic approach is important to evaluate the significance of the primary, secondary, and cumulative impacts of each life cycle phase by studying the fate and transport of the chemicals in each media and the biological effects on living creatures.

4.1.2.2.1. Air Quality

According to the SCP Regulations:

> Adverse air quality impacts" means indoor or outdoor air emissions of any of the air contaminants listed below that have the potential to result in adverse public health, ecological, soil quality, or water quality impacts:
>
> > (A) California Toxic Air Contaminants as specified in title 17, California Code of Regulations, sections 93000 through 93001;

(B) Greenhouse gases:

1. Carbon dioxide;
2. Hydrofluorocarbons;
3. Methane;
4. Nitrogen trifluoride;
5. Nitrous oxide;
6. Perfluorocarbons;
7. Sulfur hexafluoride; or
8. Gases that exhibit the global warming potential hazard trait, as specified in section 69405.4;

(C) Nitrogen oxides;
(D) Particulate matter that exhibits the particle size or fiber dimension hazard trait, as specified in section 69405.7;
(E) Chemical substances that exhibit the stratospheric ozone depletion potential hazard trait, as specified in section 69405.8;
(F) Sulfur oxides; or
(G) Tropospheric ozone-forming compounds, including compounds that exhibit the ambient ozone formation hazard trait, as specified in section 69405.1.

A wide variety of industrial or consumer operations could potentially affect air quality. These operations may include any activity that emits pollution into the atmosphere. This impact includes greenhouse gas emissions that occur throughout the product life cycle from factors such as fuel use and electricity production. For a screening level analysis, local air quality impacts are often provided in human health impact reports that indicate the emission levels and effects on human health for a given chemical. For more widespread air quality impacts, a chemical's listing as a volatile organic compound (VOC), greenhouse gas, or other air quality-affecting agent, is a good indicator of air quality impacts.

Be aware of the potential for double counting air quality impacts and human health impacts. When harmful emissions into the air are broad and cannot be tied to individual exposure, they fall under the "air quality" jurisdiction. When emissions are in an indoor or concentrated environment and associated with potential health impacts only for the individuals within the vicinity, they should be counted under "human health". It is possible for an air pollutant to have both immediate human health impacts and air quality impacts.

Air quality impacts for the case study were based primarily on government reports and listings. A few helpful lists that identify major air pollutants include:

- Listings under a California- or United States-wide hazard list:
  - USE EPA Air Pollutant Lists
    - US EPA List of hazardous air pollutants.

- Toxic Air Contaminants identified by the California Air Resources Board

Example:

Scenario: Toluene used in the production of benzyl alcohol.

Air Quality Impact(s): Toluene is highly volatile (i.e. it rapidly evaporates when exposed to air). Toluene can contribute to the formation of photochemical smog when it reacts with other volatile organic compounds (VOCs) in the air. It is on the US EPA List of hazardous air pollutants.

Factors that may affect severity of impact: Filtration systems on the production facility; quantity of toluene used.

4.1.2.2.2. Water Quality

According to the SCP Regulations:

> Adverse water quality impacts means any of the following adverse effects on the beneficial uses of the waters of the State, which include groundwater, fresh water, brackish water, marsh lands, wetlands, or coastal bodies or systems, as specified in Water Code section 13050(f) or adopted in a Water Quality Control Plan under article 3 of chapter 3 and/or article 3 of chapter 4 of division 7 of the Water Code:
>
> (A) Increase in biochemical oxygen demand;
> (B) Increase in chemical oxygen demand;
> (C) Increase in temperature;
> (D) Increase in total dissolved solids; or
> (E) Introduction of, or increase in, any of the following:
>
> 1. Priority pollutants identified for California under section 303(c) of the federal Clean Water Act;
> 2. Pollutants listed by California or the United States Environmental Protection Agency for one or more water bodies in California under section 303(d) of the federal Clean Water Act;
> 3. Chemicals for which primary Maximum Contaminant Levels have been established and adopted under section 64431 or section 64444 of chapter 15 of title 22 of the California Code of Regulations;
> 4. Chemicals for which Notification Levels have been specified under Health and Safety Code section 116455; or
> 5. Chemicals for which public health goals for drinking water have been published under the California Safe Drinking Water

Act (commencing with Health and Safety Code section 116270).

The operation of manufacturing or processing facilities, waste sites and landfills, electricity generation, or other industrial processes potentially affects water quality. It can also be affected by the transportation of pollutants, sewage treatment, and raw material extraction processes such as mining. For a screening analysis, factors such as persistence of a chemical, effect on aquatic life (e.g. lethal dose), and effect on biochemical oxygen demand (BOD—the oxygen needed in water for microorganisms to decompose organic matter) can be used to evaluate water quality. These data points can be found within hazard reports and applied across life cycle phases based on estimated quantities and exposures of a chemical. To start the screening level process, there are many government lists that identify chemicals associated with water quality concerns; a few to focus on include:

- Chemicals identified as Priority Pollutants in the California Water Quality Control Plans
- Chemicals with Maximum Contaminant Levels (MCLs) from the California State Water Resources Control Board.
- Chemicals with a Total Maximum Daily Load (TMDL) identified by the US EPA

Example:

Scenario: Fertilizer used in the raw material extraction for cloth backing of sandpaper.

Water Quality Impact(s): Increase in biochemical oxygen demand, which can be rated by the half-life of the biochemical oxygen demand, because the half-life assesses the persistence of the impact. The following rating scale was adapted from the P2Oasys "Standardized Hazard Score Data Base:"

1) No Impact – no increase in BOD
2) Minimal Impact – 4 day BOD half-life
3) Low Impact – 10 day BOD half-life
4) Moderate impact – 100 day BOD half-life
5) High impact – 500 or more day BOD half-life

Alternatively, the impact rating can be based on water treatment and quantity of fertilizer used, as it was for the instance of fertilizer used in raw material extraction for sandpaper.

Factors that may affect severity of impact: Amount of fertilizer used; waste water pretreatment application.

Potential sources of water quality changes include:
1) Withdrawal of freshwater from surface water or groundwater due to raw material extraction, intermediate processes or manufacturing processes;
2) Discharge of untreated or treated wastewaters from the manufacturing process or waste treatment facilities;
3) Deposition of pollutants from smoke stacks, vehicle emissions, incinerators or landfills;
4) Storm water (e.g. contaminated storm water from incorrect management of sanding dust) and agricultural runoff (e.g. power sanders use a cotton rather than paper backing for the grit, and there may be pesticide or fertilizer use associated with this raw material); and
5) Unexpected accidents such as spills or explosions during chemical operations.

4.1.2.2.3. Soil Quality

According to the SCP Regulations:

> Adverse soil quality impacts means any of the following effects on soil function or properties:
>
> (A) Compaction or other structural changes;
> (B) Erosion;
> (C) Loss of organic matter; or
> (D) Soil sealing, meaning covering surface soil with a layer of impervious material or changing the nature of the soil so that it behaves as an impermeable medium.

Soil quality can be affected by activities related to mining, forestry, agriculture, release of pollutants, and a variety of other factors. These activities include raw material extraction, wet and dry deposition of pollutants and reactants during transportation through air and water media, and incinerators and landfills associated with waste disposal. In addition to the identification of the potential sources that may affect soil quality, the characteristics of the soil, such as the permeability and erodibility, should be considered. However, for the scope of a screening analysis, it is sufficient to take into account information regarding soil quality that is not location-specific (i.e. does not consider specific characteristics of the soil).

Example:

Scenario: Soil erosion and alteration due to natural gas extraction for chemical compounds used to make dimethyl adipate.

Soil Quality Impact(s): Nutrient depletion in the soil – erosion leads to the loss of nitrogen and phosphorus essential for plant life that subsequently supports soil stability. The amount of land affected by erosion and nutrient depletion can be calculated based on production volume of natural gas and the land affected per production volume.

For the case of dimethyl adipate, the volume of natural gas needed to produce the precursor chemicals was "minimal," so the impact was listed as "minimal" with high uncertainty, based on a lack of quantitative information regarding the volume and source of natural gas used to produce dimethyl adipate.

Reference for Measuring Impacts: McBroom, M., Thomas, T., Zhang, Yanli. Soil Erosion and Surface Water Quality Impacts of Natural Gas Development in East Texas, USA. *Water*. 2012. 4: 944-958.

Factors that may affect severity of impact: What the previous uses of the soil were (e.g. forestland versus agricultural land); quantity of gas extracted.

4.1.2.2.4. Ecological Health

Adverse ecological impacts denote all direct or indirect effects on living organisms and/or their environments.

According to the SCP Regulations:

> Adverse ecological impacts means any of the following direct or indirect effects on living organisms and/or their environments:
>
> (A) Adverse effects to aquatic, avian, or terrestrial animal or plant organisms or microbes, including:
>
> 1. Acute or chronic toxicity;
> 2. Changes in population size, reductions in biodiversity, or changes in ecological communities; and
> 3. The ability of an endangered or threatened species to survive or reproduce;
>
> (B) Adverse effects on aquatic and terrestrial ecosystems including:
>
> 1. Deterioration or loss of environmentally sensitive habitats;
> 2. Impacts that contribute to or cause vegetation contamination or damage; and
> 3. Adverse effects on environments that have been designated as impaired by a California State or federal regulatory agency;

(C) Biological or chemical contamination of soils; or
(D) Any other adverse effect, as defined in section 69401.2(a), for environmental hazard traits and endpoints specified in article 4 of chapter 54.

A complete understanding of the key ecological elements, including the identification of dominant, rare, unique and endangered plant and animal species within the areas of activity, is necessary in the assessment of ecological impacts. Additionally, a study of ecological interrelationships, such as habitat and food chains, may provide a basis to determine the potential impacts on the ecological community at large (e.g. land use change from a forest to agricultural land to produce raw materials, resulting in habitat conversion or loss). For a screening level assessment, it is sufficient to use existing reports about environmental damage or to extrapolate potential damage from animal health studies to assess ecological impacts.

Lists that reference persistence and bioaccumulation characteristics of chemicals can be useful in identifying chemicals with ecological impact concerns. These lists include:

- US EPA Persistent Bioaccumulative and Toxic (PBT) Priority Chemicals.
- State of Washington's list of PBTs
- Canada's chemicals that are identified as Persistent, Bioaccumulative and Inherently Toxic (PBiT)
- European Commission's list of chemicals that are PBT

For the screening level analysis, the components of the products under consideration (e.g. chemical ingredients, paper-backing, grit) should all be checked for impacts. Additionally, the products and chemicals used to produce the final products should be assessed.

Example:

Scenario: The primary release of methylene chloride to surface water and ground water occurs from effluents from industrial processing (i.e. the manufacturing phase).

Ecological Impact(s): Stated in Environmental Protection Agency report:
Methylene chloride has low acute toxicity to aquatic organisms;
Lethal concentrations are generally greater than 100 mg/L;
Ninety-six hour LC50 values for fish are 193 mg/L for *Pimephales promelas*.

Factors that may affect severity of impact: Proximity of aquatic habitat area to the manufacturing facility; water effluent processing at facility; method of disposal and diffusion of effluents from facility.

4.1.2.3. Waste and end-of-life

The characteristics and quantity of generated waste, and the waste management approaches collectively influence the odds of having significant environmental impacts.

According to the SCP Regulations:

> Adverse waste and end-of-life effects means the waste materials and byproducts generated during the life cycle of a product, and the associated adverse effects due to one or more of the following:
>
> (A) The volume or mass generated;
>
> (B) Any special handling needed to mitigate adverse impacts;
>
> (C) Effects on solid waste and wastewater disposal and treatment, including operation of solid waste and wastewater handling or treatment facilities, and the ability to reuse or recycle materials resulting from the treatment of solid waste and/or wastewater;
>
> (D) Discharge(s) or disposal(s) to storm drains or sewers that adversely affects operation of wastewater or storm water treatment facilities; or
>
> (E) Release(s) into the environment, as a result of solid waste handling, treatment, or disposal activities, or the discharge or disposal to storm drains or sewers, of chemicals contained in the product.

Waste sources include industrial processes and manufacture, consumer operations, and disposal of the product. The characteristics of waste materials generally refer to the explosiveness, corrosiveness, flammability, ignitability, or toxicity of the waste as well as its reactivity and biodegradability in the air, water, and soil media. Wastes left over after the use phase can be combined with data regarding the hazards of the chemical and product to estimate end-of-life impacts.

Example:

Scenario: Methylene chloride is considered a hazardous waste by the US EPA and paint stripping applications rarely use the entire volume of paint stripper purchased – the remaining packaged paint stripper must be managed as hazardous waste

Waste and End-of-Life Impact(s): The volume and hazard of methylene chloride waste produced from methylene chloride paint strippers warrants a high hazard rating for waste disposal during the use phase.

Factors that may affect severity of impact: volume of paint stripper leftover after use; consumer willingness to follow hazardous waste guidelines.

5. Step 5: Research

Research on the product and its alternatives can be organized into two major categories: qualitative and quantitative. Qualitative and quantitative data should be continuously gathered to refine information on which to perform an evaluation of life cycle segments. The amount of information necessary for a First Stage analysis is variable. The more information that is gathered in the screening analysis, the more effectively the scope of alternatives and factors under consideration can be narrowed for the more thorough Second Stage analysis. While there is no solid line of when to stop researching, it is recommended that a company apply as many man-hours as is reasonable in the 180 days allotted for the First Stage analysis to ensure that they Second Stage analysis is manageable. Compiling pieces of data into a **comparative analysis will be covered in section 6**, which discusses evaluation of gathered information.

Less significant life cycle phases (and specific impacts within a life cycle phase) that can be eliminated from further research should be identified. Removing an impact from consideration should be based on an agreed upon set of subjective criteria. The benefit of eliminating life cycle segments less likely to have a significant impact from the screening investigation is that it allows practitioners to focus their efforts on assessing areas of impact that are likely to generate more impact and require a more thorough assessment to compare products. Questions may arise during identification of impacts for each life cycle segment. It is wise to document these questions and compare them across products.

Devise a system for documenting data sources before starting research. References can be documented in a spreadsheet alongside a brief description of the information that they provided for future review. Documenting uncertainty about a given source or study will reduce work down the line when research is evaluated and compiled. There are multiple options available for the degree of research to be completed in the First Stage analysis. This will require devising an uncertainty rating system that is briefly explained in Section 8 of this report.

Note: It is important to differentiate between a lack of data and data that indicates no impact in a given area. When data is lacking, *do not* use it as a reason to eliminate an area from consideration.

Example:

Life cycle phases eliminated from the methylene chloride case study after assessing qualitative information included:

Packaging, transportation, and distribution because they did not vary significantly across products (this is based on similar packaging weights, relatively similar product weights and no change to transportation method or distribution route between alternatives); and
Operation and maintenance for chemical alternatives because they are a one-time use product and do not require maintenance or additional energy for operation. For sandpaper, the operation and maintenance phase was assessed to account for the potential impacts of powering and maintaining a sander. This information was gathered during the assessment of life cycle phases.

5.1. Qualitative Investigation

Initial research should follow a *qualitative* approach to the subject. This data should address adverse impacts or effects in each life cycle phase. Use the information gathered during Step 4, the brainstorming stage, to inform what processes and uses need to be assessed for impacts. For example, toluene is used in the production of benzyl alcohol and this warrants considering the human health and environmental impacts of toluene for the manufacturing phase of benzyl alcohol.

Material Safety Data Sheets (MSDSs) are a good place to gather basic information including:

- Exposure effects that can be useful for informing manufacturing, use phase and disposal human health impacts
- Hazard information, such as flammability and corrosivity
- Basic environmental and ecological information, such as whether the chemical is known to contribute to acid rain or greenhouse gas emissions.

MSDSs are available for individual chemicals as well as for complete products, so they are available whether or not the alternatives under consideration are already used as a substitute for the Priority Product.

When first assessing chemical alternatives, check whether they are on DTSC's "Candidate Chemical List" and to note the reason for listing. The authoritative list that warranted a chemical's listing may provide additional information, both quantitative and qualitative, about that chemical's human health or environmental impacts.

Government agency reports provided the bulk of the impact data for the methylene chloride case study. They often contain qualitative data that explains impacts in terms of "low", "moderate" or "severe". These assertions are often backed up with quantitative data, but in instances where the report simply makes a general statement and is the only source providing information for a given impact, it is acceptable to incorporate the information into the screening analysis, provided the qualitative nature of the information is noted. If quantitative information is found during the initial search, it should be thoroughly documented.

Sources that haven't been peer reviewed or come from a questionable origin should not be used in the screening level analysis. Additionally, if a report provides a value cited from a different source, it is best to check and cite the original source.

Example:

Acute inhalation exposure to methylene chloride that may occur during the use phase can affect the Central Nervous System (CNS). Potential affects include: decreased visual, auditory and psychomotor functions.

This information is enough to provide at least a "low impact" rating for human health during the use phase; however, the uncertainty will be high because the severity of the impact is unknown. Further information such as a general descriptor (e.g. moderate) of the impact generated for a given amount of exposure (e.g. one hour) or specific values about the concentration (e.g. 125 ppm for 15 minutes) must be gathered to decrease uncertainty and may increase the severity of the impact rating.

5.2. Quantitative Investigation

Once qualitative information has been gathered, research efforts should focus on quantitative information. Continue to record resources in the same fashion that qualitative data was documented. When quantitative data deepens the understanding of information from a qualitative data point, it can be used in place of that data to inform decisions. Table B, below, highlights sources used in the methylene chloride case study to obtain quantitative data. DTSC is compiling a more in-depth list of resources that can be found in the Guidance Document and through the DTSC's website.

Table B. Potential sources for finding quantitative data.

Resource	Applicability	Comparative Attributes	Data Quality/Sources
USEtox	Chemical fate and transport including some human health and environmental indicators	Ecotoxicity; sensitivity; human toxicity; fate; exposure	Endorsed by UNEP/SETAC Life Cycle Initiative
TRACI	Chemical specific human health and environmental data	Ozone depletion, global warming, acidification, human health cancer, human health non-cancer, eutrophication, smog formation, ecotoxicity, fossil fuel use, land use, water use	Listed in documentation of Excel or selected program for running analysis
EcoInvent	Agriculture; energy supply; transport; biofuels; biomaterials; bulk and specialty chemicals; construction materials; packaging materials; basic and precious metals; metals		"High quality generic LCI datasets based on industrial data and compiled by internationally renowned research institutes and LCA consultants"; compatible with all major LCA and eco-design software tools; data quality standards
National Toxicology Program	Chemical specific toxicology data	Toxicity measures (e.g. LD50)	United States government testing and modeling

Example:

CNS effects can occur following short-term (15 minutes) exposure to methylene chloride when an individual inhales methylene chloride at concentrations of 125 ppm or greater. For longer-term exposure, effects can occur with as low an exposure as 25 ppm over an 8-hour work shift.

For this information to be used in a comparative assessment, it must be determined if these concentrations are being reached during production, use, and/or disposal of methylene chloride paint stripper.

In the case of methylene chloride, it was determined that individuals would be exposed to concentrations of methylene chloride leading to long-term effects on health and warranting a 'high impact' rating from methylene chloride for human health during the use phase (factors such as carcinogenicity also played a role). Many consumers may not wear personal protective equipment (PPE) during the use phase to reduce exposure, so PPE does not reduce the severity of the impact.

6. Step 6: Evaluation

Following multiple iterations of qualitative and quantitative research, data can be standardized and evaluated. This step may culminate in a visualization of results to more easily identify hot spots within each product. A heat map can be useful for displaying results in an easy-to-understand manner. In a heat map for life cycle considerations, life cycle phases and impact categories make up the columns and rows; the intersection of the row and column would have a designated color to indicate the severity of an impact for a given life cycle phase. The heat maps shown below are for methylene chloride and its alternatives: benzyl alcohol, dimethyl adipate, and sanding.

Hot spots indicate where a given life cycle phase may generate significant adverse impacts/effects in a given impact category (e.g. human health effects during the use phase). The criteria for assigning low to high impact should be based on an agreed upon set of subjective/objective criteria and normalization of results.

For the methylene chloride case study, the pre-established standards developed by the Toxics Use Reduction Institute (TURI) to inform its P2OAsys tool for comparison were used as a basis for ranking impacts. The TURI Guidance on L-M-H assessment provides a basis of evaluation criteria for multiple impact categories. With appropriate modifications to add evaluation criteria for impact categories not addressed in the TURI Guidance document, this tool is a useful guide for evaluation,

but must be complemented by a normalization or weighting method to determine hot spot impacts.

Normalization means putting usually incomparable factors (e.g. public health impacts compared to ecological impacts) on a percentage scale (100% being the worst impact) to allow for direct comparison. Many tools for normalization exist—among them are the US Environmental Protection Agency's (EPA's) Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) and EPA's Design for Environment (DfE) Alternatives Assessment Criteria for Hazard Evaluation. Table C, below, is a sample from the TURI Guidance document that highlights the ratings incorporation of both qualitative information (e.g. neurotoxicity) and qualitative information (e.g. persistence) into the decision process.

Table C. Sample impact evaluation criteria, borrowed from TURI.

Hazard	Characteristics	Minimal to No Impact	Low Impact	Medium Impact	High Impact
Chronic Human Health Effects	Neurotoxicity	Not classified or known to be neurotoxic	---	Chemical class known to produce neurotoxicity effects; or animal studies and analog data suggest neurotoxicity effects*	Evidence in humans shows potential neurotoxicity effects*
Persistence/ bioaccumulation	Persistence	Not classified as being persistent	Soil, sediment < 30 days; water < 7 days; or ready biodegradability	Soil, sediment 30 to 180 days; or water 7 to 60 days; or potential for long-range environmental transport	Soil, sediment > 180 days; or water > 60 days

The intersection of the life cycle segment and adverse impact/effect should be labeled on a color scale like the one demonstrated in the heat maps on pages 48, 52, and 54. Additional colors/criteria may be added depending on the project. The criteria for each color should differ between products and the scale of impacts should be considered when applying colors and uncertainty.

Heat Map Method:

Classification system for the heat map and examples from the methylene chloride case study:

- Grey indicates 'not enough information'
  - Not having enough information is not a reason to eliminate an alternative from consideration, nor does it assume that the impact or the alternative is benign.
- Black indicates 'non-relevant impact or life cycle phase'
  - The 'operation and maintenance' life cycle phase was not relevant for the chemical alternatives because no operation and maintenance of the product occurred. This life cycle phase was relevant for consideration for mechanical sanding due to the energy to run a power sander as well as the materials needed to clean and maintain a sander. However, it is important to note that only the sanding disc, but not the power sander itself was included in the study. To allow for comparison across all alternatives if one alternative has impacts for a life cycle phase or impact and the others have "black" the "black" can be assumed to be equivalent to "minimal to no impact" for the alternatives where the impact area was not deemed relevant. It is important to note that only the sanding disc but not the power sander itself was included in the study.
- Blue indicates 'impacts not expected to differ between products'
  - Transportation and distribution was assumed to be the same between all chemical alternatives, because the factory distances and weights of products would remain relatively constant. Sand paper or discs used for power sander are usually packed in the box and share the similar transportation and distribution process. Due to the limited access to the information, it was assumed that the factory distance and weights of packed sand paper or disc were similar to those of the chemical alternatives and that any differences in impact would be negligible.
- Green, yellow, orange, and red indicate increasing impacts from 'minimal to no impacts' to 'high impact'
  - An intersection of a life cycle phase and impact category was assigned a color based on the worst-case scenario
  - If respiratory irritation during the use phase was medium (yellow to orange) but dermal irritation was high (red) the intersection of 'Public Health' and 'Use' was designated as a high impact area (red).
- Uncertainty was indicated by an L for 'low uncertainty', M for 'medium uncertainty' and H for 'high uncertainty'
  - Uncertainty is the likelihood of an impact (e.g. whether personal protective equipment is utilized) and the robustness of the data (e.g. whether multiple studies demonstrate the same toxicity effects)

- If data regarding dermal irritation during the use phase was robust, but the likelihood of dermal irritation occurring during the use phase was moderate, the uncertainty would be ranked 'medium uncertainty' (M)

Further description of factors for determining low to high impacts in the methylene chloride case study:

1) Green (minimal to no adverse impact): no inherent impact, potential impact only from very large quantities;
2) Yellow (low adverse impact): some impact but not enough to be significant, some impact depending on improper human behavior;
3) Orange (medium adverse impact): moderate impact, potentially significant, but likely to be reversible
4) Red (high adverse impact): high impact, irreversible effects or significant damage is caused

A sample heat map for methylene chloride based on these subjective criteria and qualitative information gathering is shown in Figure C, on the next page (note: the information represented in this table must be standardized to allow for comparison between alternatives).

	Raw Material Extraction	Resource Inputs and Consumption	Intermediate Material Processes	Manufacture	Packaging	Transportation	Distribution	Use	Operation and Maintenance	Waste Generation & Management	Reuse and Recycle	EOL and Disposal
Public Health	H		M	L				L				L
Air Quality	H		M	M				L				L
Soil Quality	H			H				H				H
Water Quality	M		H	H				H				H
Ecological Impact	H		L	L				L				L
Waste/End-of-Life			L	M				M				M

Methylene Chloride

High Impact	Medium Impact	Low Impact	Minimal to No Impact	No Data	N/A	Not expected to change between products

H	High Uncertainty
M	Medium Uncertainty
L	Low Uncertainty

Figure C. Example heat map. Evaluation of impacts associated with methylene chloride based paint-stripping products. The heat map columns indicate life cycle phases; rows indicate impact category; colors indicate the severity of an impact; and L-M-H indicate the level of uncertainty associated with the evaluation. Life cycle segments colored grey indicate a lack of data upon which to evaluate, life cycle phases colored black do not apply to that product, and life cycle phases colored blue indicate a minimal expected difference among alternatives.

Three examples for how setting hazard criteria & uncertainty was performed in the case study:

1) Use phase ecological impacts for dimethyl adipate

Impact Rating: Orange (medium impact)

Justification: Relatively low lethal doses for aquatic organisms (18-24 mg/L for fathead minnows) and plants (4.35 mg/L for green algae). These doses are likely to be reached because packaging recommends dumping dimethyl adipate directly down drains (regardless of filtration processes) as a method of disposal.

Uncertainty: High

Justification:

- Data source has low uncertainty, because it is a US EPA report.
- Quality of studies has high uncertainty, because the values came from studies with few individuals or from predictive modeling of how a chemical will behave based upon its physical structure (e.g. quantitative structure-activity relationship modeling).
- Likelihood of occurrence has medium uncertainty, because it is unclear if individuals will follow the directions to rinse waste down drains and whether these drains have filtration that will reduce environmental concerns.

Overall rating was high to reflect the conservative nature of our selection process.

2) Manufacturing public health impacts for benzyl alcohol

Impact Rating: Red (high impact)

Justification: Benzyl chloride (used to produce benzyl alcohol) is intensely irritating to skin, eyes and mucous membranes in humans. The acute effects from inhalation consist of severe irritation of the upper respiratory tract, and lung damage and pulmonary edema in humans. **Permanent** eye damage may result from contact with the liquid or the vapor forms of benzyl chloride.

Uncertainty Rating: Moderate

Justification:
- Source uncertainty low: government report (US EPA).
- Study uncertainty low: observed in humans from actual exposure.
- Likelihood of occurrence medium: there are ways to protect workers from exposure, but conditions are not expected to provide consistent protection from exposure and long-term exposure increases severity of effects.

3) End of life disposal ecological impacts for sanding

Impact Rating: Green (minimal to no impact)

Justification: Government research finds that there is No Observed Effect Concentration (NOEC) of titanium dioxide from removed sandpaper grit on aquatic or terrestrial species. The amount of these compounds present in waste sanding paper is minimal and leaching from landfills is likely to also be minimal, so minimal to no impacts are expected to occur.

Uncertainty: Moderate

Justification:
- Source uncertainty low: government report (US EPA).
- Study uncertainty moderate: tested on aquatic and terrestrial organisms and results indicate no impacts, but number of individual organism types studied was low.
- Likelihood of occurrence moderate: waste goes to landfill where leeching can occur.

Interpretation of Heat maps
The two primary goals of the screening level analysis are to: (1) screen out clearly unacceptable alternatives; and (2) identify relevant factors for alternatives comparison. When looking to screen out unacceptable alternatives, the maps can be grouped by product. To identify potentially relevant factors, the maps can be grouped by impact category. These groupings are demonstrated below.

Screening alternatives: visualization by alternative
When comparing across products or impact categories, it is important to be aware of missing data points and the significance of underlying data for a given ranking. These factors complicate direct comparison. While comparison is not as simple as counting the number of segments for each impact level (e.g. high impact) and comparing them, instances where a product appears significantly worse than the status quo option could allow for elimination of the worst seeming alternatives. The worst 'seeming' is used because in some instances, an alternative may be eliminated from consideration that had the potential to be an acceptable alternative. Such an alternative still has the potential for reconsideration if the end of the analysis process is reached and no better alternative than the CoC is found. Eliminating the worst seeming alternatives allows for a deeper dive into the remaining alternatives in the Second Stage analysis. Figure D, on the next page, shows the heat maps for methylene chloride and the three alternatives (benzyl alcohol, dimethyl adipate, and sanding) displayed by product.

Methylene Chloride

	Raw Material Extraction	Intermediate Material Processes	Manufacture	Use	Reuse and Recycle	EOL and Disposal
Public Health	H	M	L	L		L
Air Quality	H	M	M	L		L
Soil Quality	H		H	H		H
Water Quality	M	H	H	H		H
Ecological Impact	H	L	L	L		L
Waste/End-of-Life		L	M	M		M

Benzyl Alcohol

	Raw Material Extraction	Intermediate Material Processes	Manufacture	Use	Reuse and Recycle	EOL and Disposal
Public Health	M	M	M	L		
Air Quality	L	H	L	L		M
Soil Quality	L		M			L
Water Quality		L	M	L	M	L
Ecological Impact	M			L		
Waste/End-of-Life		M		M	M	L

Dimethyl Adipate

	Raw Material Extraction	Intermediate Material Processes	Manufacture	Use	Reuse and Recycle	EOL and Disposal
Public Health	H	H	H	M		H
Air Quality		M	M	L		L
Soil Quality	M		M	H		H
Water Quality	M		M	H	H	H
Ecological Impact	M		H	H	H	
Waste/End-of-Life	M			H	H	H

Sanding

	Raw Material Extraction	Intermediate Material Processes	Manufacture	Use	Reuse and Recycle	EOL and Disposal
Public Health	M	M	H	H		H
Air Quality	M	M		M		M
Soil Quality	M	M		M		M
Water Quality	M	M		M		M
Ecological Impact	M	M		M		M
Waste/End-of-Life	M	M		L		M

High Impact	Medium Impact	Low Impact	Minimal to No Impact	No Data	N/A

H	High Uncertainty
M	Medium Uncertainty
L	Low Uncertainty

Figure D. Example heat maps by alternative. Evaluation of impacts associated with four paint-stripping products. The four heat maps are separated by product; columns indicate life cycle phases; rows indicate impact category; colors indicate the severity of an impact; L-M-H indicate the level of uncertainty associated with the evaluation. Life cycle segments colored grey indicate a lack of data upon which to evaluate, and life cycle phases colored black do not apply to that product.

This presentation of the evaluation allows for the identification of alternatives that have an overall similar or worse level of impact than the Priority Product.

For example, in our case study, no alternative is worse than methylene chloride-based paint strippers--all alternatives have lower aggregate impacts than methylene chloride, and therefore all may be carried through to a Second Stage analysis.

Methylene chloride was evaluated to have fifteen (15) life cycle segments with medium or high impacts; benzyl alcohol, dimethyl adipate, and sanding have ten (10) medium or high impacts.

Methylene chloride and benzyl alcohol were evaluated to have thirteen (13) life cycle segments with minimal or low impacts; dimethyl adipate has sixteen (16) minimal or low impacts; and sanding has fifteen (15) minimal or low impacts.

Identifying relevant factors: visualization by impact

Considering relevant factors and comparing the products across impact categories focuses the Second Stage analysis towards areas where impacts or changes between impacts are likely to be greatest. Impact categories that warrant primary focus include: impact categories where the results vary significantly across impacts and where the results indicate consistently moderate to high impacts across the life cycle phases. In an instance where all products have 'minimal to no impact' for a given intersection of a life cycle phase and impact category (e.g. soil quality during production), that particular intersection may not necessitate a deeper dive in the Second Stage analysis unless factors such as significant volume or high uncertainty are a concern.

Figure E, on the next page, shows heat maps from the case study displayed by impact category (public health, water quality, air quality, ecological impact, soil quality, and waste/end-of-life).

	Raw Material Extraction	Intermediate Material Processes	Manufacture	Use	Reuse and Recycle	EOL and Disposal
Methylene Chloride	H	M	L	L		L
Benzyl Alcohol	M	M	M	L		
Dimethyl Adipate	H	H	H	M		H
Sanding	M	M	H	H		H

Public Health

	Raw Material Extraction	Intermediate Material Processes	Manufacture	Use	Reuse and Recycle	EOL and Disposal
Methylene Chloride	H	M	M	L		L
Benzyl Alcohol	L	H	L	L		M
Dimethyl Adipate		M	M	L		L
Sanding	M	M		M		M

Air Quality

Methylene Chloride	H		H	H		H
Benzyl Alcohol	L		M			L
Dimethyl Adipate	M		M	H		H
Sanding	M	M		M		M

Soil Quality

Methylene Chloride	M	H	H	H		H
Benzyl Alcohol		L	M	L	M	L
Dimethyl Adipate	M		M	H	H	H
Sanding	M	M		M		M

Water Quality

Methylene Chloride	H	L	L	L		L
Benzyl Alcohol	M			L		
Dimethyl Adipate	M		H	H	H	
Sanding	M	M		M		M

Ecological Impact

Methylene Chloride		L	M	M		M
Benzyl Alcohol		M		M	M	L
Dimethyl Adipate	M			H	H	H
Sanding	M	M		L		M

Waste/End-of-Life

High Impact	Medium Impact	Low Impact	Minimal to No Impact	No Data	N/A

H	High Uncertainty
M	Medium Uncertainty
L	Low Uncertainty

Figure E. Example heat maps by impact. Evaluation of impacts associated with four paint-stripping products. The six heat maps are separated by impact category; columns indicate life cycle phases; rows indicate products/alternatives; colors indicate the severity of an impact; L-M-H indicate the level of uncertainty associated with the evaluation. Life cycle segments colored grey indicate a lack of data upon which to evaluate, and life cycle phases colored black do not apply to that product.

This format allows for an easier comparison of alternatives for specific impacts to determine whether a more in-depth investigation of a particular impact is warranted.

For example, methylene chloride has a high impact on air quality at the "use" phase, but all three alternatives have minimal or low impact on air quality at the "use" phase. Since all three alternatives have lower impacts than the Priority Product, a further investigation of air quality at this life cycle segment is not necessary. Similarly, since almost all impacts to soil quality are minimal to low, further investigation of soil quality impacts may not be necessary.

The public health impacts are predominantly evaluated as medium or high. To understand more specifically how these alternatives compare to methylene chloride at this life cycle segment, further analysis is warranted and this life cycle segment may be deemed relevant to consider in the Second Stage analysis.

Review of framework steps

Figure F, below, shows the six primary steps of the framework along with secondary details. This framework serves to guide practitioners in incorporating life cycle screening into an Alternatives Analysis as mandated by the SCP Regulations.

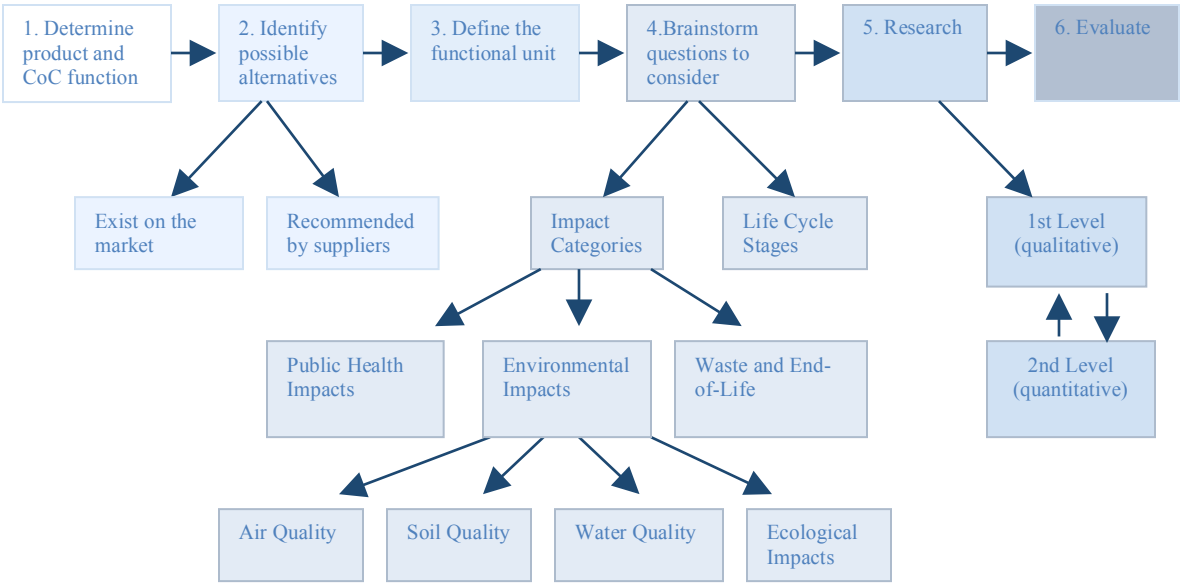

Figure F. Framework primary steps and secondary details.

7. Additional Considerations

7.1 Functional equivalence and normalizing data for direct comparison
It is important to normalize impacts to determine which factors are likely to have the greatest effects. Ideally, this normalization will have a quantitative basis. It is possible to use qualitative information to approximate impacts, though these results will have much greater uncertainty. This process is important to understand the scale of impacts relative to one another to allow for meaningful comparison.

Example:

Often power sanders use grit on cotton backing, which is more durable than a paper backing.

Impact Concerns: During the raw material extraction phase for cotton, pesticides or fertilizers are used to grow the cotton, which generate impacts such as increased biochemical oxygen demand (BOD) in water. This depletes oxygen and can kill flora and fauna.

Consider: The small fraction of cotton that makes up the entire power sander alternative providing the functional unit, indicating that this particular impact is likely relatively small.

Scope: For the case study, fertilizer and pesticide impacts were deemed outside of the scope for a First Stage analysis because the quantity is so small that it will not likely generate a significant impact.

Another important consideration is to account for the functional equivalence if it has not already been considered. For example, to achieve the same performance, one chemical alternative may require three 1-ounce applications, while a methylene chloride-based paint stripper may require a single 1-ounce application. The impacts of the alternative, therefore, should be assessed based upon the amount necessary to achieve the same performance as the methylene chloride product rather than a simple 1-oz.: 1-oz. comparison.

7.2 Further quantification of data
The screening process should inform decisions about which relevant factors and alternatives warrant consideration in the Second Stage analysis. Up to this point it is likely that only readily available data or information has been used. Following the screening process, though, additional data searches should be more focused and may require working with suppliers to obtain necessary data or purchasing relevant data

sets. To the extent possible, data should be more quantitative than it may have been in the screening process.

Example:

US EPA reports served as a major resource for the methylene chloride case study.

These reports use terms such as "low" or "moderate" to describe impacts.

For the initial screening it is acceptable to use data containing such terminology as long as sources are consistent for all alternatives. However, for the Second Stage analysis, ***quantitative*** *values would be more ideal for making a comparison across products.*

7.3 Reassessing decision boundaries

The purpose of the life cycle screening process is to identify potentially relevant factors to consider for further analysis and to eliminate unacceptable alternatives from further consideration.

It is possible that after the screening process, too many life cycle phases or alternatives have been eliminated to allow for an informative Second Stage analysis. This situation may require returning to the screening process to determine whether any life cycle phases or alternatives were eliminated from consideration too hastily. If it appears that no alternatives were deemed acceptable with reasonable standards based on relative impacts, it is important to consider alterations to considered alternatives that may lower impact. For example, recycling or reclaiming water for an alternative where water impacts were a significant factor for rejection may make it a more desirable alternative.

8. Data Interpretation and Challenges from the Methylene Chloride Paint Stripper Case Study

Government sources of data such as EPA chemical reports are generally reliable and robust; however, there may still be uncertainty in choosing a color for the heat map. For example, the original TURI guidance document did not cover all of the data points needed for an Alternatives Analysis. The EPA generally classified impacts with words (e.g. acute, moderate, severe) as opposed to the quantified values used in the TURI guidance. Colors were thus based on approximations of a scale. TURI guidance occasionally did not address an impact found in the research; colors were then approximated based on criteria used for similar impacts. The TURI guidance document was amended to suit the case study's needs. Uncertainty was noted in every segment of the heat map.

Uncertainty within the data was further complicated by uncertainty about potential for exposure. For some chemicals, there are multiple production methods, each of which has a unique energy intensity and combination of chemicals for manufacturing. In the case study, it was assumed that the specific production methods used could not be determined and the uncertainty notation was assigned a "high uncertainty" to reflect the lack of certainty regarding exposure. Additionally, for newer, untested products, the use phase handling patterns will not be well known and will likely result in high uncertainty for use phase and disposal impacts.

Data is often limited by constraints such as industry confidentiality. This is especially true of data related to upstream life cycle phases. Inadequate data can restrict the research power and weaken the conclusions of the impact assessment. This lack of information increases the workload for the Second Stage analysis by hindering the depth of information that can be easily gathered in the First Stage analysis. In the methylene chloride paint stripper case study, data was limited by such constraints, and the decision of whether to continue or halt the research for certain life cycle phases was largely determined by professional judgment.

Uncertainty within research in the downstream of life cycle phases mostly comes from two sources: 1) uncertainty of the individual data, such as the toxicity of chemicals, which results from the lack of scientifically substantiated evidence (e.g. animal toxicity experiments); and 2) uncertainty stemming from the circumstantial exposure scenarios.

For example, human exposure to sanding dust varies widely due to the uncertainty surrounding the material of the target substrate, the type of paint (e.g. lead-based paint), and the safety measures taken (e.g. PPE use) during the process of sanding. Thus, even when the toxicity data of chemicals is scientifically conclusive, high uncertainty still exists due to the indeterminacy of exposure scenarios.

Data standardization is critical to be able to compare alternatives. By using a set of standard criteria, such as modifying pre-established standards like the TURI (Toxics Use Reduction Institute) guidelines, it becomes easier to compare products. However, it is likely that the same types of data will not be available across products. For example, air quality during raw material extraction may be based on information about greenhouse gases and particulate matter for one alternative, but data on particulate matter alone may be used to assess air quality impact of a different alternative. For the purposes of screening, it is acceptable to have such uneven comparisons.

In this case study, the most severe individual impact was used to assess the overall public health, environmental, or waste impact at different life cycle phases. This approach seems reasonable given the variation in data. However, it is important to be

aware of the data used to make those categorizations to be sure results are not inappropriately skewed. For example, to get an overall high impact categorization, product A may have four data points indicating little to no impact and one data point indicating high impact, while product B may have three data points that indicate high impact. Understanding these limitations will be important, especially in the event of eliminating too few or too many alternatives in the screening process.

Results of Economic Considerations Assessment

Net Present Value

Net Present Value (NPV) for each alternative was calculated by subtracting the calculated NPV of environmental costs from the NPV profit for each ten-year scenario. The results from the assessment are in Table 3, below.

Table 3. Net Present Value of profit benefits and the potential reduction in benefits from environmental costs for three paint stripper chemicals, with green indicating the highest (and best) NPV.

NPV	Methylene chloride	Benzyl alcohol	Acetone
Profit Only (million US $)	192	334	157
Low Loading (million US $)	169	315	157
Medium Loading (million US $)	161	309	157
High Loading (million US $)	154	302	157

Regardless of loading level or consideration of environmental costs, benzyl alcohol is the best option when the alternatives are compared based on NPV. The most expensive product is the best alternative because it indicates the highest revenue, given the assumptions that markup rates are constant and demand for paint stripper is inelastic. This indicates that the environmental costs associated with the various scenarios were not significant enough to change the results of an NPV study of only profits (i.e. a traditional business NPV that does not include costs to society).

Cost Benefit Ratio

Benefits of profit were compared to environmental costs across the ten-year time span. Environmental costs were calculated by applying MEBCalc costs to the emission values from TRACI 2.1. The results of this analysis can be seen in Table 4.

Table 4. Benefit Cost Ratios of revenue received to environmental costs for methylene chloride, benzyl alcohol, and acetone, with green indicating the highest (and best) Benefit Cost ratio.

Scenario	Methylene chloride	Benzyl alcohol	Acetone
Low Loading (BC ratio)	8	18	266
Middle Loading (BC ratio)	6	13	266
High Loading (BC ratio)	5	10	266

The results indicate that every scenario had a desirable Benefit-Cost ratio (B/C ratio), as indicated by all values being greater than one. The benefits of revenue were compared only to the environmental costs. Even when the responsible entity considers the environmental costs to society, the revenue gained makes all options more desirable than not selling any chemical paint stripper. However, some scenarios have higher B/C ratios than others. Acetone consistently has the highest B/C ratio, followed by benzyl alcohol and then methylene chloride.

Discussion & Conclusion

Framework

The developed framework was intended to introduce life cycle concepts to a non-expert audience as a way to achieve the objectives of a First Stage Alternatives Analysis to: (1) identify alternatives; (2) screen alternatives; and (3) identify relevant factors to consider in a Second Stage Alternatives Analysis. This framework successfully addresses these three objectives. The second step of the framework presents a process for identifying alternatives, and the final step introduces a visualization tool to screen alternatives and aid in identifying relevant factors.

This framework is applicable to assessing both formulated and composite products. Consequently, this single framework is general enough to provide guidance to a wide variety of users. It serves as a starting point for the assessment, providing general questions that can generate more specific questions that are targeted to a particular product or process.

This approach was tailored to the SCP Regulations. The life cycle phases and the impacts assessed were those identified by the Regulations. Additionally, this framework addresses the time and data limitations expected under the SCP Regulations. While most LCA methods are time- and data-intensive, this framework allows for a relatively quick assessment of data to highlight and focus additional research on life cycle phases and impacts that are most likely to be relevant.

The framework draws from established methodologies, incorporating critical aspects of Alternatives Assessment and LCA methods into a hotspotting approach. The framework emphasizes the importance of a functional unit to compare product performance and the need for well-defined boundaries to avoid double counting of impacts.

The evaluation criteria suggested in this framework are well-established. The framework suggests the use of criteria developed by TURI, but it is important to note that these criteria are similar to other Alternatives Assessment evaluation criteria, such as those developed by the US EPA's DfE program. The mixture of qualitative and quantitative criteria lends itself to the combination of qualitative and quantitative data gathered under this approach.

While these evaluation criteria have validity, not all sub-impacts to be considered under the SCP Regulations have established criteria (e.g. Biochemical Oxygen Demand or Chemical Oxygen Demand water quality impacts). Further work is needed to develop sound criteria with which to evaluate these data points.

To assess uncertainty, several criteria were considered: (1) the degree of data available; (2) the robustness or the reliability of individual data; and (3) the likelihood of the impact occurring. There is subjectivity in determining a level of uncertainty for a given impact category, particularly with qualitative data. Factors to consider in determining uncertainty include the source of the data, peer reviewed status, and the size of the study. With more quantitative data, this uncertainty assessment can be more objective.

Though the SCP Regulations call for social and economic impacts in the Alternatives Analysis process, this framework did not address those issues. Rather, the framework focused on introducing the concepts of life cycle thinking and suggesting an approach to incorporate these considerations in a time- and data-limited environment. Currently, additional impacts would require a separate assessment. However, this framework is malleable, and the additional impacts could easily be incorporated into this model to avoid conducting a completely separate assessment.

Case Study

The primary function of the case study was to inform the framework development and to test its applicability. Since the framework was designed to be general enough to be applied to both formulated and composite products, both chemical (e.g. benzyl alcohol) and process (e.g. sanding) substitutions were considered in selecting the alternatives for the paint stripper containing methylene chloride.

Based on the results obtained, no alternative would be eliminated from consideration. This may be because only three alternatives were considered in the case study. However, the limited number of alternatives did not narrow or overlook the breath of factors or aspects that need to be considered in an Alternatives Analysis, since they represented sources of alternatives ranging from a “green” chemical substitution to a process substitution. The unique properties of the three alternatives enabled the group to incorporate diverse information for consideration.

The challenges encountered in the case study largely stem from inadequate data, which restricted the research ability and prevented the group from conducting a more in-depth investigation of each life cycle phase. Not all the information regarding the processes and resources involved, or the type and amount of waste generated during each phase was accessible due to constraints such as industry confidentiality. This was especially true of data related to upstream life cycle phases. However, manufacturers might not face as many limitations due to confidentiality when conducting an Alternatives Analysis on their own product. It is important to note that data limitations might be a challenge that future Alternatives Analysis practitioners could encounter, and thus it is critical for the practitioners to face and treat the issue with caution.

Most of the information and data adopted in the study were gathered from governmental or non-governmental agencies and authentic research institutes, such as Agency for Toxic Substances and Disease Registry (ATSDR), US Environmental Protection Agency (EPA), Occupational Safety and Health Administration (OSHA) and the National Institute of Occupational Safety and Health (NIOSH). These institutions provide relatively reliable information regarding toxic substances and harmful exposures that are substantiated by environmental sampling tests, animal laboratory experiments and human exposure assessments. However, the data reliability does not guarantee the robustness of data used in the study. When the human health data associated with less-studied alternatives was lacking, information from animal studies (e.g. lethal dose for rats) was used to extrapolate human health hazards. Thus, data robustness was weakened.

The likelihood of exposure, including almost all the factors integrated in the exposure assessment, was also considered. Factors relating to the concentration of chemicals to which individuals would be exposed (e.g. the application of personal protective equipment or the installation of ventilation), possible exposure pathways, exposure time, and the different exposure thresholds for the sensitive versus general populations, were all considered in the evaluation step. Although the data limitations were further aggravated by insufficient information about exposure scenarios, the consideration of likelihood of exposure enabled the group to identify and incorporate these critical factors or aspects into the framework, which provided a substantial stepping-stone for future practitioners.

Economic Considerations

The economic considerations assessment provided comparable results that incorporated human health and environmental impacts. However, measurement issues may arise due to potential inaccuracies in the data and models used. The human health costs from MEBCalc were calculated from estimated hospital visits and health care costs, meaning they did not incorporate other indirect health costs, such as missed workdays, and did not use data extrapolated from the value of a statistical life. Moreover, estimates of costs and benefits from health impacts are subject to criticism.

With many regulations, it is useful to also conduct a cost benefit analysis based on non-compliance. However, the SCP Regulations do not impose fees for not phasing out Chemicals of Concern; it only fines companies that do not conduct an Alternatives Analysis and file the appropriate paperwork. Therefore, for the scope of this project, the approach of measuring costs and benefits based on non-compliance fines was not applicable.

A number of assumptions were made to simplify the cost benefit model for the scope of this assessment. While sensitivity analysis was performed to test some of these assumptions (e.g. chemical loading level), further assessment of the results'

sensitivity to the various assumptions would prove beneficial. For example, no price elasticity was assumed based on a lack of publicly available information regarding price elasticity of demand for paint stripper products. In reality, there is probably some degree of price elasticity. Determining this value and assessing the impacts of price elasticity of demand would improve the robustness of results.

When working with data regarding business entities, much of the information needed to conduct an assessment is proprietary (i.e. owned by a company and unable to be publicly shared). For this reason, many assumptions were made to fill data gaps that resulted from a lack of access to valuable proprietary information (e.g. profit margins and sales rates specific to paint stripper for Home Depot). Future assessments should work to gain partnership with a business so that more accurate and precise data can be used to inform a cost benefit analysis. A future assessment may also benefit from looking at the costs as an intermediate supplier as opposed to an end-of-the-line supplier. This is because an end-of-the-line supplier, like Home Depot, pays minimal to no costs to switch from one product to another. Conducting the analysis as an intermediate supplier allows the costs of updating machinery and switching chemical suppliers to be accounted for. However, the intermediate supplier is not likely going to consider physical substitutions because the facility to make such a product would be entirely different.

Additionally, this study did not incorporate one of the chemical alternatives and the process substitution due to lack of information. For a complete economic assessment, all alternatives must be brought into consideration. To address these information gaps, one could look for existing literature on the alternatives (e.g. LCA of sanding) and use transferrable information. However, it is important to note that different practitioners may arrive at results using different methods. Thoroughly documenting sources and using only the highest quality information available will reduce the uncertainty and variation in results.

Based on the results of the example cost benefit analysis, acetone is the best alternative to replace methylene chloride as a paint stripper sold at Home Depot. Ultimately, a decision was made to use the benefit cost ratio and not the net present value as the metric to inform this recommendation. Of the three options, the results indicate that benzyl alcohol provides the highest net present value. If only the cost benefit analysis was guiding a business decision, then this would likely be the best option. However, the SCP Regulations require a responsible entity to complete an Alternatives Analysis and make a decision within the monetary constraints required to keep doing business. Since the benefits outweigh the costs for all three chemical products (i.e. it will still be cost-effective for Home Depot to continue selling any of the three products), the benefit cost ratio is a more appropriate metric for evaluation in this example. The paint stripper containing acetone has a higher benefit cost ratio than both the methylene chloride and benzyl alcohol products. The cost benefit analysis used to perform the Alternatives Analysis indicates that Home Depot should

replace the methylene chloride paint stripper with the acetone paint stripper in its retail line.

Conclusion

The objective of this group master's thesis project was to determine the best available methods for incorporating life cycle screening into the Alternatives Analysis process required by the SCP Regulations. A new framework was developed and tested using a case study of methylene chloride-based paint strippers and three alternatives. It incorporated critical aspects from LCA methods, Alternatives Assessment and hotspot analysis. The framework aims to introduce life cycle concepts to future Alternatives Analysis practitioners and to present a user-friendly visualization of results in a time- and data-limited environment. This framework is intended to aid future practitioners in achieving the objectives of a First Stage Alternatives Analysis.

There is still a lack of objectivity in determining the level of uncertainty for a given impact category due to inadequate data, especially quantitative data, and this aspect of the framework will be refined and tested in future work.

Appendices

Appendix A. Paint stripper chemical alternatives

Paint Removal Options		Pros	Cons
Chemical or Chemical Class	Methylene Chloride	strong	hazardous
	Benzyl Alcohol	less toxic	expensive; slow
	Acetone	good on some surface	not all applications
	NMP (2-mmethyl-2-pyrrolidone)	can be effective	flammable; prop 65
	Dibasic Esters	low toxicity	minimally effective; not good for all applications
	1,3 Dioxalane	good on some surfaces	toxic; not all applications
	Caustic	effective for 1 purpose	only for white lead based paint
	Methyl Esters	effective on most paints	slow; difficult to package
	3-methoxy-3-methyl-1-butanol (MMB)	effective	Flammable liquid VOC
	3-methoxy-3-methyl-1-butyl acetate (MMB-AC)	effective on most paints	VOC; not effective in removing alkyd paints
	Anisole (methoxybenzene)	effective	Combustible; VOC
	Butyl Carbonate	effective on most paints	expensive
	dibutoxymethane (butylal)	effective	Combustible; VOC; not effective in removing alkyd paints
	diethoxymethane (ethylal)	effective	flammable; VOC
	dimethyl carbonate	effective	flammable
	eastmen omnia (butyl-3-	effective on most	VOC; not effective in removing alkyd paints

	hydroxybutryrate)	paints	
	glyercol formal	effective on most paints	VOC; not effective in removing alkyd paints
	PCBTF/Oxsol 100	effective on most paints	not effective in removing alkyd paints
	propylene carbonate	effective on most paints	not effective in removing alkyd paints
	n-butyl propionate	effective on most paints	flammable; VOC; not effective in removing all paints
	soya methyl ester	effective on most paints	not effective in removing alkyd paints
	Steposol MET-10U	effective on most paints	not effective in removing alkyd paints
	TOC (2,5,7,10 tetraoxaundecane)	effective on most paints	VOC; not effective in removing alkyd paints
	ethylene carbonate	effective	solid at room temperature
	trans-1,2 dichloroethylene	effective	VOC; flammable
	Dimethyl Adipate	effective on most paints	not as effective on alkyd paints
	Dimethyl Sulfoxide	relatively effective	toxic; rapid absorption
Physical	Heat	relatively efficient	volatilizes paint toxins; warps softer surfaces
	Sanding	efficient	particulate matter (inhalation concerns)
	Sand Blasting	strong, effective	particulate concerns; damages wood
	CO2 blasting	effective	difficult for consumer projects
	BiCarb blasting		
	Laser	relatively efficient	volatilizes paint toxins; warps softer surfaces

Appendix B. Generalized Worksheet

General questions for Initial Investigation

	Raw Material Extraction	Resource Inputs and Consumption	Intermediate Material Processes	Manufacture	Packaging	Transportation
Initial Investigation (Basic Information Involved in Each Phase)	What raw materials are needed in the final product	What are the major components or active ingredients in the final product	What is the process involved (material inputs, bi-products, etc.)	What is the process involved (material inputs, bi-products, etc.)	What is the size of package	How far is the product transported from the manufacturers to the retailers or consumers themselves
	What processes are used to extract raw materials (naturally or industrially derived)	Are there any additional components or ingredients needed in the products			What type of materials are used for packaging (e.g. paper, glass, plastic)	What type of fuel is used during transportation
						What is the loading size of shipment(s)
						What types of transportation methods are used (e.g. trailer, truck, plane, ship)
	Distribution	**Use**	**Operation and Maintenance**	**Waste Generation and Management**	**Reuse and Recycle**	**EOL and Disposal**
	Is the product sold in a retail store or online	Are there preferential uses of the product (e.g. preference for sandpaper use is on hard wood surface)	What frequency of product use or application	What kind of waste is generated during use	Is it possible to disassemble the product and reuse or recycle a component of the product	Is a permitted waste disposal facility required
	Can the product be rented and returned by multiple users	How large and what type of material is the target product (e.g. the area of the wood surface, is it flat or slope, etc.)	How often is product maintenance required	Are there any collection methods to handle the waste (e.g. dust collection bag in a vacuum sander) - If so, what is it	Are there any special processes involved in recycling and/or reuse of the product or its components	Are wastes landfilled or incinerated
	Can the product be delivered directly from the manufacturer	Is manual labor or electricity required	Are there any additional inputs (e.g. water, energy) required for maintenance			What kind of waste would be generated during incineration and landfilling
		What is the duration of use to achieve a functional unit				

		Is PPE (e.g. goggles, gloves, mask) recommended or required during use				
		Are there approaches to reduce the time or amount of product required to achieve the functional unit (e.g. primer used to make sanding easier)				
		Is the product used indoors or outdoors				

General Questions for Second Level Investigation

	Raw Material Extraction	Resource Inputs and Consumption	Intermediate Material Processes	Manufacture	Packaging	Transportation
Second Level Investigation (Detailed Information Involved in Each Phase)	Are there any hazardous wastes generated in the process of extraction	Are there any virgin or recycled inputs	Are other inputs (e.g. Energy, Water) required	Are additional materials required	How much material is used in packaging	What kind of machinery is required
	If hazardous wastes are generated, what kind of hazardous waste is it	How much of a particular input (e.g. energy) is required	What kind of waste byproducts would be generated (e.g. paint will result to lead exposure)	Are other inputs (e.g. energy, water.) required	What is the difference in the quantity of the materials used for packaging	What are the sources for different fuels required
	If hazardous wastes are generated, how much	How much would be considered as "Yield Loss"	Would engineered nano-materials be involved in the process (e.g. TiO_2 production is related to nano-materials)			What is the difference between emission factors of the fuels used for different transportation modes
	Are rare materials involved in extraction					
	Distribution	**Use**	**Operation and Maintenance**	**Waste Generation and Management**	**Reuse and Recycle**	**EOL and Disposal**

		How much manual labor, if any, is required to achieve a functional unit	What amount of additional inputs are used for maintenance (e.g. How much electricity is required to maintain the power sander)	How much waste is generated during the use	How often is the product or the components of the product recycled	What amount of waste is generated during the landfill or incineration process
		How much electricity, if any, is required to achieve a functional unit	What components can be replaced or repaired to extend the useful life of the product	Are hazardous waste exposure prevention methods required	How much of the product could be recycled or reused	What amount of the waste is released into the atmosphere
		How much of the product itself is required to achieve a functional unit		Is pretreatment required to reduce waste generation		What amount of the waste is released into water bodies
						What amount of the waste is released into the soil

Generalized Questions for Human Health Impacts

	Raw Material Extraction	Resource Inputs and Consumption	Intermediate Material Processes	Manufacture	Packaging	Transportation
Human Health Specific	Is there an inherent danger to the extraction process (e.g. explosives used in mining)	Are there inherent dangers	Are there inherent dangers (e.g. highly reactive intermediate chemicals used)	Are there inherent dangers (e.g. highly reactive intermediate chemicals used)	Are there inherent dangers (e.g. hazardous chemicals leaking; dangerous machinery)	Are there air quality concerns (e.g. exhaust fumes; greenhouse gas contributions)
	Are volatile organic compounds (VOCs) generated or released	Are VOCs generated or released	Are VOCs generated or released	Are VOCs generated or released		Are there risks of accidents depending on mode of transportation (e.g. chemical explosion)
	Is particulate matter (PM) generated or released	Is PM generated or released	Is PM generated or released	Is PM generated or released		
	Are workers exposed to toxic chemicals?		Are workers exposed to toxic chemicals	Are workers exposed to toxic chemicals		

	Do the physico-chemical properties create routes of exposure for workers		Do the physico-chemical properties create routes of exposure for workers	Do the physico-chemical properties create to routes of exposure for workers		
	Will the distribution of pollutants on a regional or global scale going to affect human environments		Will the distribution of pollutants on a regional or global scale going to affect human environments	Will the distribution of pollutants on a regional or global scale going to affect human environment		
	Distribution	**Use**	**Operation and Maintenance**	**Waste Generation and Management**	**Reuse and Recycle**	**EOL and Disposal**
	Are there concerns of physical harm from labor	What are the short-term and long-term effects on human health (i.e. human toxicity profile of a chemical)	What kind of chemicals and products are necessary for maintenance (e.g. washing clothes)	Is there any potential for human exposure to CoCs	Is there any potential for human exposure to CoC or other hazards	Is there any potential for human exposure to CoC or other hazards
		How is the product used	What kind of fuels are necessary for operation	Are there any special handling requirements (e.g. hazardous waste)	Human labor (e.g. physical strain of moving product)	Are there any special handling requirements (e.g. hazardous waste)
		What are the potential exposure sources for humans (e.g. air, soil, water)				Is manual labor (e.g. physical strain of moving product) involved
		What is the expected exposure concentration in each media?				
		What are the expected exposure routes (e.g. inhalation, ingestion, dermal contact)				

		Does the exposure, including exposure route and concentration vary with or without use of PPE (e.g. mask, gloves, goggles)				
		What is the likelihood of exposure to the CoC for a sensitive population				

Generalized Questions for Environmental Impacts

	Raw Material Extraction	Resource Inputs and Consumption	Intermediate Material Processes	Manufacture	Packaging	Transportation
Environmental considerations including ecological, soil, air, and water quality specific	Does raw materials extraction relate to land-use (e.g. clearing forests for mining)	How much energy is required	What is the fate and transport (downstream pathway) of the waste byproducts	How much energy is required	Are there environmental effects of resource inputs	Are there any GHG emission
	Are fertilizers used to produce a raw material (e.g. cotton, used for sandpaper backing, requires fertilizer)	How much of water would be used	How much of water would be used	How much water is used		Are VOCs released
	Are pesticides used to produce a raw material (e.g. cotton, used for sandpaper backing, is often applied with pesticides)	Are there GHG emissions. If so, will the amount generate adverse environmental impacts (e.g. climate change)	Are there GHG emissions. If so, will the amount generate adverse environmental impacts (e.g. climate change)	Are there GHG emissions. If so, will the amount generate adverse environmental impacts (e.g. climate change)		Is PM generated or released
	Are there GHG emissions. If so, will the amount generate adverse	Are there processes related to land use change	Are there processes related to land use change	Are there processes related to land use change		Are there any other emissions generated from burning fuels

	environmental impacts (e.g. climate change)					
	Will the processes involved in raw materials extraction threaten any species or habitats, especially endangered ones	Are pesticides used	Are pesticides used	Are pesticides used		
	Does the waste generated during raw material extraction adversely impact the water quality (e.g. increasing turbidity, BOD)	Are VOCs released	Are VOCs released	Are VOCs released		
	How is the landscape altered (e.g. compaction, contamination, erosion)	Is PM generated or released	Is PM generated or released	Is PM generated or released		
	What kind of physico-chemical properties are related to the probable phase distribution in the environment (i.e. what are the biodegradation pathways)	Does the waste generated during the process adversely impact the water quality (e.g. increasing turbidity, BOD)	Does the waste generated during the process adversely impact the water quality (e.g. increasing turbidity, BOD)	How are byproducts and wasted materials (e.g. yield loss) managed		
	What parameters would be involved for biodegradation and what kind of meteorologi			Is there any potential for leaks and emissions from facility to the environment		

cal parameters would be considered					
Distribution	**Use**	**Operation and Maintenance**	**Waste Generation and Management**	**Reuse and Recycle**	**EOL and Disposal**
What are the environmental effects of resource inputs	Does the target product generate hazardous waste during use (e.g. lead particles will be generated when using sandpaper to remove lead-based paints)		Is there potential for leaks and emissions into the environment during disposal	Are there hazardous wastes contaminating recyclable materials	Does the target product generate hazardous waste that must be disposed of
Are there any other emissions from fuel (e.g. for forklift)	Are there additional hazard wastes generated due to the use of the product (e.g. dust, noise from a power sander)	Are there GHG emissions. If so, will the amount generate adverse environmental impacts (e.g. climate change)	Are there GHG emissions. If so, will the amount generate adverse environmental impacts (e.g. climate change)	Are there GHG emissions. If so, will the amount generate adverse environmental impacts (e.g. climate change)	Are there GHG emissions. If so, will the amount generate adverse environmental impacts (e.g. climate change)
	Will terrestrial or aquatic plants be directly or indirectly exposed to the hazards generated (e.g. accumulation in terrestrial environments)				
	Will terrestrial, aquatic and/or aerial animals be directly or indirectly exposed to the hazards generated (e.g. accumulation in terrestrial environments)				

		Will any hazardous waste be accumulated in the terrestrial/ aquatic/aerial biosphere through the food chain (e.g. Hg will bioaccumulate in fat tissue)				
		Does the chemical react with other substances to form products that affect air quality (e.g. some VOCs could react with NO_x and form ozone)				

Generalized Questions for Waste and End-of-Life

	Raw Material Extraction	**Resource Inputs and Consumption**	**Intermediate Material Processes**	**Manufacture**	**Packaging**	**Transportation**
Waste and End-of-Life Specific	How much waste is generated	How much of the inputs (e.g. electricity) are lost during transmission & distribution	How much waste is generated	How much waste is generated	How much waste is generated	Transmission & Distribution Losses (i.e. how much of the inputs (e.g. electricity) would be lost during transmission & distribution)
	Is the waste flammable, corrosive or toxic		Is the waste flammable, corrosive or toxic	Is the waste flammable, corrosive or toxic	Is the waste flammable, corrosive or toxic	
	How is waste managed and disposed		What is the typical handling of waste	What is the typical handling of waste	What is the typical handling of waste	
					At what LC phase is waste generated (e.g. transportatio n, use)	
	Distribution	**Use**	**Operation and Maintenance**	**Waste Generation and Management**	**Reuse and Recycle**	**EOL and Disposal**

	Transmission & Distribution Losses (i.e. how much of the inputs (e.g. electricity) would be lost during transmission & distribution)	How much waste is generated	Are wasted generated during operation and maintenance	What kind of waste is generated during the use	What kind of waste is generated from reuse and/or recycling	Does the waste stay in the atmosphere or drop to the soil and surface water with precipitation
		Is the waste flammable, corrosive or toxic		How much of the waste would be managed or collected during the use	How much waste is generated	Does the waste react with other solid, liquid or gas substance to form products that will affect air quality during transportation
		What is the typical handling of waste			Would the waste put human and/or environmental health at risk	

References

[1] "Priority Products. CA Dept of Toxic Substances Control. 2014. Web. Nov 20. 2014. <http://www.dtsc.ca.gov/SCP/PriorityProducts.cfm>

[2] "DTSC: Who We Are and What We Do." *California Department of Toxic Substances Control*. State of California, 1 Jan. 2010. Web. 10 Dec. 2014. <http://www.dtsc.ca.gov/InformationResources/DTSC_Overview.cfm>.

[3] Assem. Bill 1879, 2008 Reg. Sess., ch. 559, 2011 Cal. Stat. <http://www.dtsc.ca.gov/PollutionPrevention/GreenChemistryInitiative/upload/ab_1879_GCI.pdf>

[4] "Safer Consumer Products Regulations." *California Department of Toxic Substances Control*. State of California, 28 Aug. 2013. Web. 2 Dec. 2014. <http://www.dtsc.ca.gov/SCPRegulations.cfm>.

[5] ISO 14044-1:2006: Environmental management — Life cycle assessment — Requirements and guidelines.

[6] Jensen, Allan A. *Life Cycle Assessment (LCA): A Guide to Approaches, Experiences and Information Sources*. Copenhagen, Denmark: European Environment Agency, 1998. Print.

[7] *Evaluation of Environmental Impacts in Life Cycle Assessment*. Paris: United Nations Environment Programme, Division of Technology, Industry and Economics (DTIE), Production and Consumption Unit, 2003. Print.

[8] Plevin, Richard J., Mark A. Delucchi, and Felix Creutzig. "Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation Benefits Misleads Policy Makers." *Journal of Industrial Ecology* 18.1 (2014): 73-83.

[9] Suh, Sangwon, and Yi Yang. "On the Uncanny Capabilities of Consequential LCA." *The International Journal of Life Cycle Assessment* (2014): n. pag.

[10] EIO-LCA. Carnegie Mellon. Web. Nov 30.2014 <http://www.eiolca.net/cgi-bin/dft/use.pl>

[11] Moberg, Asa; Borggren, Clara; Ambell, Christine; Finnveden, Goran; Guldrandsson, Fredrik; Bondesson, Anna; Malmodin, Jens; Bergmark, Pernilla. Simplifying a life cycle assessment of a mobile phone. *International Journal of Life Cycle Assessment*. 19:5 (p 979-993). (2014). Print.

[12] Kuczenski, B. and R. Geyer. Safer Product Alternatives Analysis: Methods, Models and Tools/Report to the Department of Toxic Substances Control. Santa Barbara, CA: N. p., 2011.

[13] OECD "Current Landscape of Alternatives Assessment Practice: A Meta-Review." Environment, Health and Safety Publications: Series on Risk Management No. 26 (2013): 1-31.

[14] Interstate Chemicals Clearinghouse (IC2). "Alternatives Assessment Guide Version 1.0". (2013): 1-159. Print.

[15] Environmental Protection Agency (EPA). "Alternatives Assessment." Environmental Protection Agency. EPA, 3 Feb. 2014. Web. 6 May 2014 <http://www.epa.gov/dfe/alternative_assessments.html>.

[16] European Chemicals Agency (ECHA). "Guidance in a Nutshell: Chemical Safety Assessment." ECHA, 30 Sept. 2009. Web. 10 May 2014. <http://echa.europa.eu/documents/10162/13632/nutshell_guidance_csa_en.pdf>

[17] Barthel, Mark; James, Keith; Guinnes, Jacqueline; Barker, Claire; Fava, Jim; Harnanan, Curtiz; Smerek, Andrea; Adibi, Naeem; Valdivia, Sonia; Khan, Sofia. *Hotspots Analysis: mapping of existing methodologies, tools and guidance and initial recommendations for development of global guidance*. 2014. UNEP/SETAC. Print.

[18] ATSDR. "Toxic Substances Portal - Methylene Chloride." 21 10 2014. Agency for Toxic Substances & Disease Registry. 21 11 2014 <http://www.atsdr.cdc.gov/mmg/mmg.asp?id=230&tid=42#bookmark02>

[19] Confidential presentation to DTSC. W.M. Barr. June 2014.

[20] Abt Associates. "Methylene Chloride Consumer Products Use Survey Findings." Prepared for the U.S. Consumer Products Safety Commission, Bethesda, MD. 1992. Web. Oct 2 2014. <http://hero.epa.gov/index.cfm?action=reference.details&reference_id=1005947>

[21] Institute for Research and Technical Assistance (IRTA) (prepared for California Department of Toxic Substances). Methylene Chloride Consumer Product Paint Strippers: Low-VOC, Low Toxicity Alternatives. May 2006. <http://www.irta.us/PaintStrippers06.pdf>

[22] USA. U.S. Environmental Protection Agency. Environmental Criteria and Assessment Office. Health and Environmental Effects Document for Benzyl Alcohol. Cincinnati: Office of Research and Development, 1989. National Service Center for Environmental Publications. United States Environmental Protection Agency. Web. 30 Nov. 2014. <http://nepis.epa.gov/>.

[23] Zarogiannis, Panos, Nwaogu, Tobe, Tuffnell, Nigel, Lucas, Beatriz. "Impact Assessment of Potential Restrictions on the Marketing and Use of Dichloromethane in Paint Strippers." Risk & Policy Analysts Limited. April 2007. Web. <http://ec.europa.eu/enterprise/sectors/chemicals/files/markrestr/j549_dcm_final_report_en.pdf>

[24] *Committee for Veterinary Medicinal Products: Benzyl Alcohol Summary Report* [Online]; EMEA. 1997. Web. 2 Oct 2014. <http://www.ema.europa.eu/docs/en_GB/document_library/Maximum_Residue_Limits_-_Report/2009/11/WC500010973.pdf>

[25] *Smart Strip*; MSDS No. DCI-039 [Online]; Dupont: Malvern, PA, September 25, 2013. Web. 17 Feb. 2015. <http://www.dumondchemicals.com/pdf/MSDS/Smart_Strip.pdf>

[26] Thomas, R. and Franklin W.E. Life Cycle Assessment for PC Blend 2 Aircraft Radome Depainter. National Risk Management Research Laboratory Office

of Research and Development, US EPA. September 1996. Web. 25 Nov 2014. http://www.dtic.mil/dtic/tr/fulltext/u2/a349115.pdf

[27] ATSDR. "Toxic Substances Portal - Acetone." 3 3 2011. Agency for Toxic Substances & Disease Registry. 2 12 2014 <http://www.atsdr.cdc.gov/PHS/PHS.asp?id=3&tid=1>

[28] 3M industrial Products for Woodworking. "Woodworking solutions from start to finish." 12 12 2014 <http://multimedia.3m.com/mws/media/148465O/3mtm-industrial-products-for-woodworking-catalog.pdf>

[29] USA. U.S. Environmental Protection Agency. Design for the Environment -> Alternative Assessment- > "General Best Shop Practices." 12 12 2014 <http://www.epa.gov/dfe/pubs/auto/bestpractices/bestpr.htm>

[30] PAHO "Guidelines for Protecting Worker Health." Pan American Health Organization. 12 12 2014 <http://www.bvsde.paho.org/bvsacd/cd67/refractory/cap9.pdf>

[31] DTSC "Sanding Waste Management" May 2006. Department of Toxic Substance Control. 12 12 2014 <http://www.solanocounty.com/civicax/filebank/blobdload.aspx?BlobID=5922>

[32] "Klean-Strip 1-gal. KS-3 Premium Stripper." *The Home Depot*. Homer TLC, Inc. Web. 2 Dec. 2014. <http://www.homedepot.com/p/Klean-Strip-1-gal-KS-3-Premium-Stripper-GKS3/100144685#product_description>.

[33] "Klean-Strip 1-Pint Acetone." *The Home Depot*. Homer TLC, Inc. Web. 2 Dec. 2014. <http://www.homedepot.com/p/Klean-Strip-1-Pint-Acetone-PA12270/203713859>.

[34] "Ready Strip Pro" *The Home Depot*. Homer TLC, Inc. Web. 2 Dec. 2014. <http://www.homedepot.com/p/Ready-Strip-1-gal-Pro-Formulation-Environmentally-Friendly-Safer-Paint-Varnish-Remover-RP01/100665905>.

[35] "Home Depot Gross Profit Margin (Quarterly)." Home Depot. YCharts. Web. 31 Oct. 2014. <http://ycharts.com/companies/HD/gross_profit_margin>.

[36] "Robust Spring Sales Expected For Home Depot As U.S. Economy Recovers." *Forbes*. Forbes Magazine. Web. 2 Dec. 2014. <http://www.forbes.com/sites/greatspeculations/2014/08/15/robust-spring-sales-expected-for-home-depot-as-u-s-economy-recovers/>.

[37] "Discussion of Life Cycle Assessment Used in MEBCalc" *Ecocycle*. no date. Web. 2 Dec. 2014 <https://www.ecocycle.org/files/pdfs/Understanding_MEBCalc_and_Environmental_Impacts.pdf>

[38] ISO 14044-1:2006: Environmental management — Life cycle assessment — Requirements and guidelines.

Case Study References

Agency for Toxic Substance & Disease Registry. "Minimal Risk Levels (MRLs) for Hazardous Substances" Web. 19 Mar. 2015. <http://www.atsdr.cdc.gov/mrls/mrllist.asp#77tag>

Agency for Toxic Substances and Disease Registry (ATSDR). "Case Studies in Environmental Medicine - Arsenic Toxicity." ATSDR. September 2008. <http://www.atsdr.cdc.gov/csem/arsenic/docs/arsenic.pdf>

Agency for Toxic Substances and Disease Registry (ATSDR). "Toxicological Profile for Aluminum." ATSDR. September 2008. <http://www.atsdr.cdc.gov/ToxProfiles/tp22.pdf>

Agency for Toxic Substances and Disease Registry (ATSDR). "Toxicological Profile for Cobalt." ATSDR. April 2004. <http://www.atsdr.cdc.gov/toxprofiles/tp33.pdf>

Agency for Toxic Substances and Disease Registry (ATSDR). "Toxicological Profile for Lead." ATSDR. August 2007. <http://www.atsdr.cdc.gov/toxprofiles/tp13.pdf>

Agency for Toxic Substance & Disease Registry. "Uranium". Web. 19 Mar. 2015. <http://www.atsdr.cdc.gov/substances/toxsubstance.asp?toxid=77>

Agency for Toxic Substance & Disease Registry. "Thorium". Web. 19 Mar. 2015. <http://www.atsdr.cdc.gov/substances/toxsubstance.asp?toxid=121>

Agency for Toxic Substance & Disease Registry. "Radium". Web. 19 Mar. 2015. <http://www.atsdr.cdc.gov/substances/toxsubstance.asp?toxid=154>

"Background and Justification for Toxicity Testing of Dimethyl Adipate." U.S. Consumer Product Safety Commission. (1994). Web. Nov 25 2014. http://ntp.niehs.nih.gov/testing/status/background/execsumm/d/dimethyladipate/index.html

"Benzyl Chloride." United States Environmental Protection Agency. Technology Transfer Network - Air Toxics, Apr. 1992. Web. 01 Dec. 2014. <http://www.epa.gov/ttnatw01/hlthef/benzylch.html>.

Centers for Disease Control and Prevention (CDC). "Wood dust" CDC. 18 Sep. 2011. Web. 19 Mar. 2015. <http://www.cdc.gov/niosh/pel88/wooddust.html>

"Chemicals in the Environment: Chlorine (CAS NO. 7782-50-5)." United States Environmental Protection Agency. Office of Pollution Prevention and Toxics, Aug. 1994. Web. 01 Dec. 2014. <http://www.epa.gov/chemfact/f_chlori.txt>.

"Chemicals in the Environment: Toluene (CAS NO. 108-88-3)." United States Environmental Protection Agency. Office of Pollution Prevention and Toxics, Aug. 1994. Web. 01 Dec. 2014. <http://www.epa.gov/chemfact/f_toluen.txt>.

"Chlorine." United States Environmental Protection Agency. Technology Transfer Network - Air Toxics, Apr. 1992. Web. 01 Dec. 2014. <http://www.epa.gov/ttnatw01/hlthef/chlorine.html>.

Department of Toxic Substance Control (DTSC). "Pollution Prevention in Auto Body and Paint Shops. Sanding Waste Management" DTSC May 2006.

<http://www.solanocounty.com/civicax/filebank/blobdload.aspx?BlobID=5922>

DOW. "Product Safefy Assessment Methylene Chloride." 3 July 2007. DOW. 21 January 2015 <http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_0082/0901b8038008211c.pdf?filepath=productsafety/pdfs/noreg/233-00294.pdf&fromPage=GetDoc>.

International Agency for Research on Cancer (IARC). "Silica Dust, Crystalline, in the form of Quartz or Cristobatile." Web. 19 Mar. 2015. <http://monographs.iarc.fr/ENG/Publications/techrep42/TR42-4.pdf>

International Agency for Research on Cancer (IARC). "Titanium Dioxide (TiO2)." Web. 19 Mar. 2015. <http://monographs.iarc.fr/ENG/Monographs/vol100C/100C-08-Index-tables.php>

Kralj, Anita. "Selecting different raw materials for methanol production using an MINL model" Journal of Natural Gas science and Engineering. Volume 19, July 2014, Pages 221-227. Web <http://www.sciencedirect.com/science/article/pii/S1875510014001243>

Lenntech. "Environmental Effects of Thorium" Web. 19 Mar. 2015. <http://www.lenntech.com/periodic/elements/th.htm>

Made How. "How products are made – Sandpaper" Web. 19 Mar. 2015. <http://www.madehow.com/Volume-1/Sandpaper.html#ixzz3Fi8HbjFL>

National Department of Health and Human Service. "Criteria for a recommended Standard. Occupational Noise Exposure." June 1998. <http://www.cdc.gov/niosh/docs/98-126/pdfs/98-126.pdf>

Office of Air Quality Planning and Standards US Environmental Protection Agency (EPA). "Locating and Estimating Air Emissions from Sources of Methylene Chloride." February 1993. EPA. 21 January 2015 <http://www.epa.gov/ttnchie1/le/methlncl.pdf>.

Office of Chemical Safety and Pollution Prevention US Environmental Protection Agency (EPA). "TSCA Work Plan Chemical Risk Assessment Methylene Chloride: Paint Stripping Use CASRN: 75-09-2--EPA Document# 740-R1-4003." August 2014. EPA. 21 January 2015 <http://www.epa.gov/oppt/existingchemicals/pubs/DCM_OPPTWorkplanRA_final%208_27_14.pdf>.

Office of Pollution Prevention and Toxics, U.S. Environmental Protection Agency (EPA). "Chemical Summary for Methylene Chloride (Dichloromethane)--EPA 749-F-94-018a." August 1994. EPA. 21 January 2015 <http://www.epa.gov/chemfact/s_dcm.txt>.DOW. "Product Safefy Assessment Methylene Chloride." 3 July 2007. DOW. 21 January 2015 <http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_0082/0901b8038008211c.pdf?filepath=productsafety/pdfs/noreg/233-00294.pdf&fromPage=GetDoc>.

Office of Air Quality Planning and Standards US Environmental Protection Agency (EPA). "Locating and Estimating Air Emissions from Sources of Methylene Chloride." February 1993. EPA. 21 January 2015 <http://www.epa.gov/ttnchie1/le/methlncl.pdf>.

Office of Chemical Safety and Pollution Prevention US Environmental Protection Agency (EPA). "TSCA Work Plan Chemical Risk Assessment Methylene Chloride: Paint Stripping Use CASRN: 75-09-2--EPA Document# 740-R1-4003." August 2014. EPA. 21 January 2015 <http://www.epa.gov/oppt/existingchemicals/pubs/DCM_OPPTWorkplanRA_final%208_27_14.pdf>.

Office of Pollution Prevention and Toxics, U.S. Environmental Protection Agency (EPA). "Chemical Summary for Methylene Chloride (Dichloromethane)--EPA 749-F-94-018a." August 1994. EPA. 21 January 2015 <http://www.epa.gov/chemfact/s_dcm.txt>.

Organisation for Economic Co-operation and Development (OECD). "Risk Reduction Monograph No. 2: Methylene Chloride and Background National Experience With Reducing Risk--OCDE/GD(94)95." 1994. OECD. 21 January 2015 <http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=OCDE/GD(94)95&docLanguage=En>.

"Robust Summaries for Diabasic Ester Solvents: Dimethyl Adipate (DMA)." US EPA. 2002. Web. Nov 25 2014. http://www.epa.gov/hpv/pubs/summaries/dbe/c13453rs.pdf

Thomas, R. and Franklin W.E. "Life Cycle Assessment for PC Blend 2 Aircraft Radome Depainter." National Risk Management Research Laboratory Office of Research and Development, US EPA. September 1996. Web. Nov 25 2014. http://www.dtic.mil/dtic/tr/fulltext/u2/a349115.pdf

US Environmental Protection Agency (EPA). “Aluminum Production Waste.” EPA. Web. 19 Mar. 2015. <http://www.epa.gov/radiation/tenorm/aluminum.html>

US Environmental Protection Agency (EPA). “Drinking water contaminants” Web. 19 Mar. 2015. <http://water.epa.gov/drink/contaminants/index.cfm#List>

US Environmental Protection Agency (EPA). Methylene Chloride (Dichloromethane) 75-09-2. 2000. 21 January 2015 <http://www.epa.gov/ttn/atw/hlthef/methylen.html>.

US Environmental Protection Agency (EPA) “Particular Matter (PM) Health” Web. 19 Mar. 2015. <http://www.epa.gov/pm/health.html>

US Environmental Protection Agency (EPA)."Pesticides: Health and Safety - Human Health Issues” Web. 19 Mar. 2015. <http://www.epa.gov/pesticides/health/human.htm>

US Environmental Protection Agency (EPA). “Radiation Protection – Laws and Regulation” Web. 19 Mar. 2015. < http://www.epa.gov/radiation/tenorm/regs.html>

US Environmental Protection Agency (EPA). “Technology Transfer Network - Air Toxics Web Site - Arsenic Compounds” Web. 19 Mar. 2015. <http://www.epa.gov/ttnatw01/hlthef/arsenic.html>

US Environmental Protection Agency (EPA). “Technology Transfer Network - Air Toxics Web Site -Chromium Compounds.” Web. 19 Mar. 2015. <http://www.epa.gov/airtoxics/hlthef/chromium.html>

US Environmental Protection Agency (EPA). “UNIT CONVERSIONS, EMISSIONS FACTORS, AND OTHER REFERENCE DATA.” Nov. 2014. Web <http://www.epa.gov/cpd/pdf/brochure.pdf>

Wollbrinck, Thomas. "The Composition of Proprietary Paint Strippers." Journal of the American Institute for Conservation 32.1 (1993): 43-57.

World Health Organization Regional Office for Europe (WHO). "Chapter 5.7 Dichloromethane." 2000. WHO. 21 January 2015 <http://www.euro.who.int/__data/assets/pdf_file/0013/123061/AQG2ndEd_5_7Dichloromethane.pdf>.

3M Company. “3M™ Abrasive Products, Gold Film, 3M™ Stikit™ Gold Film, 3M™ Hookit™ Gold Film, 255L 02/24/14”. Web. 19 Mar. 2015. <http://multimedia.3m.com/mws/mediawebserver?mwsId=SSSSSuUn_zu8l00xlYteP8meMv70k17zHvu9lxtD7SSSSSS-->

3M Company. “3M™ Power Tools, Abrasives and Accessories”. Web. 19 Mar. 2015. <http://multimedia.3m.com/mws/media/524507O/3mtm-power-tools-abrasives-and-accessories-catalog.pdf>