Directional Life Cycle Assessment (LCA) of Aerospace Paint Removal

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Motive

How do the environmental and ergonomic impacts of aircraft depainting by chemical stripping and laser ablation compare when analyzed through an LCA framework?

- Aircraft depainting is essential for service life and inspection/maintenance.
- Chemical stripping is conventional but has many negative impacts.
  - ➢ Toxic waste is generated, it requires rigorous labor demands, and workers are exposed to hazardous conditions.
- Reducing hazardous waste and manual labor improves both sustainability and workplace safety.
  - ➢ Emerging laser technology could support future automated maintenance.
- This project uses a directional LCA to evaluate if laser ablation offers a sustainable and efficient alternative.

Fig. 1: Depainting by chemical stripping. Shown is the manual debris removal step via sanding[1].

Fig. 2: Depainting by laser ablation. Shown is a Titan Robotics laser system actively ablating[2].

Chemical stripping (Fig.1)
- Common and established method.
- Various strippers contain hazardous ingredients[3].
- Removed paint comes off in a liquid slurry.
- Low capital expenditure (CAPEX), moderate operational expenditure (OPEX)

Laser ablation (Fig. 2)
- Currently used for small-scale parts, and not for full aircraft bodies.
- Ablates paint into a solid and gas state, captured as a solid[4].
- High CAPEX, low OPEX.

Approach

Jan. Feb.

Literature Review & Data Gathering
- Conduct literature review on aircraft depainting methods and LCA to gain background knowledge of project (Fig. 3).
- Develop process flow diagrams for methods (Fig. 4).

March

Initial Prototype & Data Generation
- Collect and analyze process data for LCA (Fig. 5).
- Build initial OpenLCA models, incorporating simplifications and assumptions for early-stage modeling.
- Define major process units, material/energy flows, and tracked inputs/outputs.

April

Refine/Revise Design
- Generate preliminary impact assessment results for LCAs.
- Refine input/output data to improve accuracy.
- Identify model limitations, uncertainties, and areas requiring further refinement.

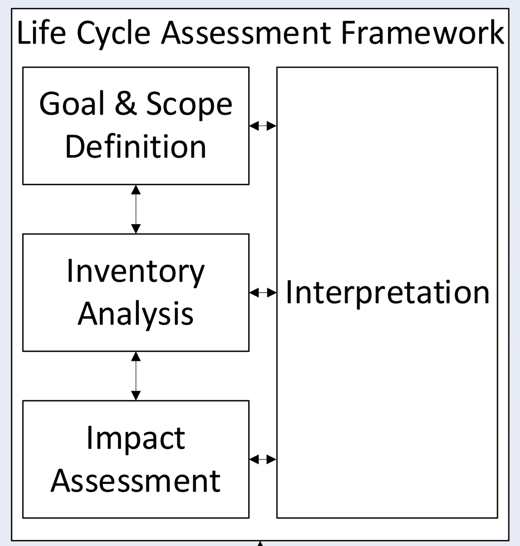
May

Final Data Collection & Analysis
- Generate final models and quantitative results (Fig. 6-7).
- Compare environmental impacts and operational tradeoffs, evaluating project objectives (Fig. 8-12).

June

Document Project
- Write report on project in accordance with ISO 14040[5], the international standard outlining framework for conducting a LCA.

Model Development



Direct Applications:
- Product development and improvement
- Strategic planning
- Public policy making
- Marketing
- Other

Fig. 3: Background on LCA from ISO 14040 and phases in the LCA development process[5].

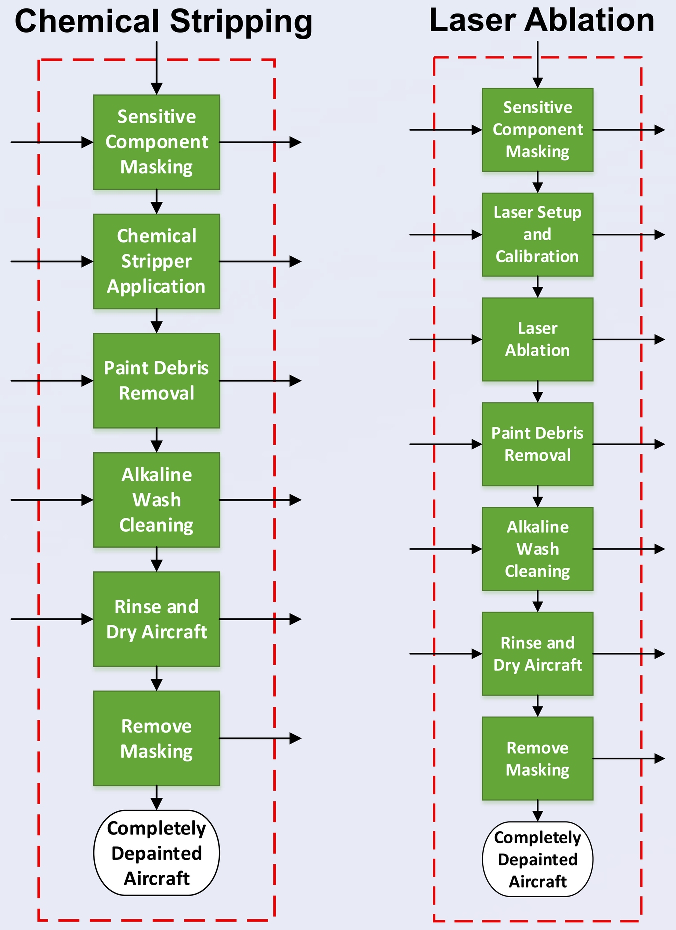


Fig. 4: Simplified flow chart of modeled processes and system boundaries for both depainting methods.

Chemical Stripping

Tier	Unit Process	Input/Output?	Flow Name
1	Chemical Stripper	Input	Chemical Stripper
		Output	Chemical Stripper 2-Mercaptobenzothiazole Formic Acid Benzyl Alcohol Water
	Surfactant	Input	Surfactant
		Output	Surfactant Benzophenone Diethanolamine Methanol Propylene Glycol Monobutyl Ether Water
	Masking	Input	Polyethylene Poly Tarp, 5 mil Wax-Coated Kraft Paper, 30#
		Output	Maskant
	Aircraft Paint	Input	Paint, on Aircraft
		Output	Paint, on Aircraft Chromium IV Epoxy Melamine Urea Formaldehyde Resin
2	Chemical Application (Liquid)	Input	Chemical Stripper Paint, on Aircraft Water
		Output	Sludge, Liquid, Chemical Application
	Chemical Application (Solid)	Input	Maskant Paint, on Aircraft
		Output	Sludge, Solid, Chemical Application
	Alkaline Wash	Input	Surfactant Water
		Output	Sludge, Liquid, Alkaline Wash
3	Liquid Waste Handling	Input	Sludge, Liquid, Chemical Application Sludge, Liquid, Alkaline Wash
		Output	Sludge, Liquid, Total
	Solid Waste Handling	Input	Sludge, Solid, Chemical Application
		Output	Sludge, Solid, Total
4	Total Waste	Input	Sludge, Liquid, Total Sludge, Solid, Total
		Output	Sludge, Total Depainted Area

Laser Ablation

Tier	Unit Process	Input/Output?	Flow Name
1	Electricity; at grid	Output	Electricity, AC, 2600 - 7650 V
	Chiller Unit	Input	Water
		Output	Chiller Unit
	Optics Unit	Input	Optical Lens Cover
		Output	Optics Unit Silica
	Filtration Unit	Input	Bag Filter HEPA Filter
		Output	Filtration Unit
2	Laser System Setup	Input	Electricity, AC, 2600 - 7650 V Chiller Unit Optics Unit Filtration Unit
		Output	Laser System
	Aircraft Paint	Input	Paint, on Aircraft
		Output	Paint, on Aircraft Chromium IV Epoxy Melamine Urea Formaldehyde Resin
	Surfactant	Input	Surfactant
		Output	Surfactant Benzophenone Diethanolamine Methanol Propylene Glycol Monobutyl Ether Water
3	Laser Ablation	Input	Laser System Paint, on Aircraft
		Output	Sludge, Solid, Laser Ablation
	Manual Scrubbing (Solid)	Input	Sandpaper
		Output	Sludge, Solid, Manual Scrubbing
	Manual Scrubbing (Liquid)	Input	Paint, on Aircraft
		Output	Sludge, Liqud, Manual Scrubbing
	Alkaline Wash	Input	Surfactant Water
		Output	Sludge, Liquid, Alkaline Wash
4	Liquid Waste Handling	Input	Sludge, Liquid, Manual Scrubbing Sludge, Liquid, Alkaline Wash
		Output	Sludge, Liquid, Total
	Solid Waste Handling	Input	Sludge, Solid, Laser Ablation Sludge, Solid, Manual Scrubbing
		Output	Sludge, Solid, Total
5	Total Waste	Input	Sludge, Liquid, Total Sludge, Solid, Total
		Output	Sludge, Total Depainted Area

Fig. 5: Inventory data gathered for both methods. Sorted into tiers corresponding to process sequences (Fig. 6). Processes in blue are unique to that method.

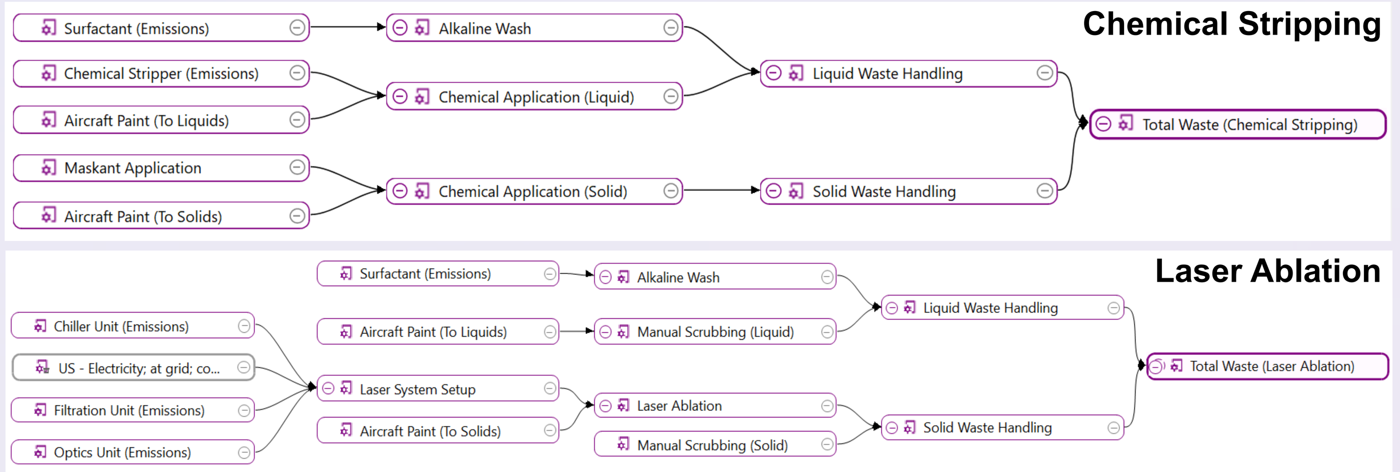


Fig. 6: Final OpenLCA models, synthesized from steps in Figs. 3, 4, and 5.

Contribution	Process	Total result [CTUeco]
100.00%	Total Waste (Chemical Stripping)	7.446E5
69.37%	Solid Waste Handling	5.165E5
69.37%	Chemical Application (Solid)	5.165E5
69.37%	Aircraft Paint (To Solids)	5.165E5
00.00%	Maskant Application	0.000
30.63%	Liquid Waste Handling	2.281E5
25.65%	Chemical Application (Liquid)	1.910E5
19.21%	Aircraft Paint (To Liquids)	1.430E5
06.44%	Chemical Stripper (Emissions)	4.794E4
04.99%	Alkaline Wash	3.713E4
04.99%	Surfactant (Emissions)	3.713E4

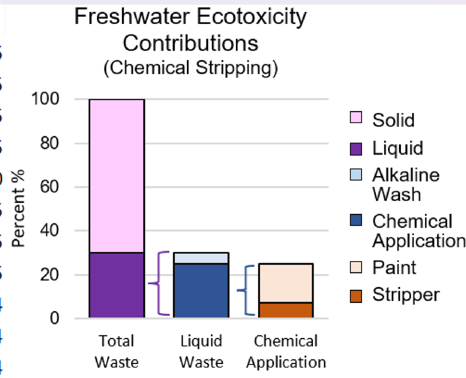


Fig. 7: Example of results from OpenLCA: contribution tree of freshwater ecotoxicity for chemical stripping (left) and visually (right).

Results

Impact Categorization

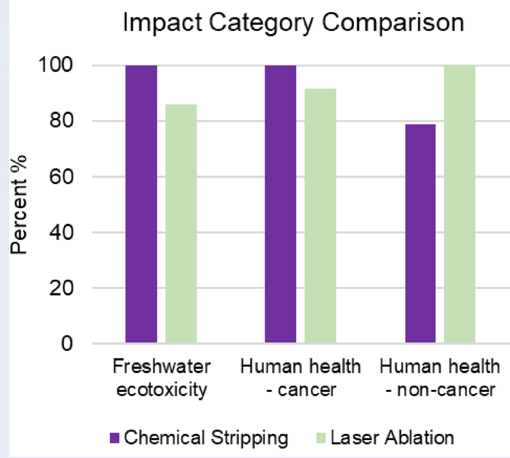


Fig. 8: Normalized impact category results generated for base models.

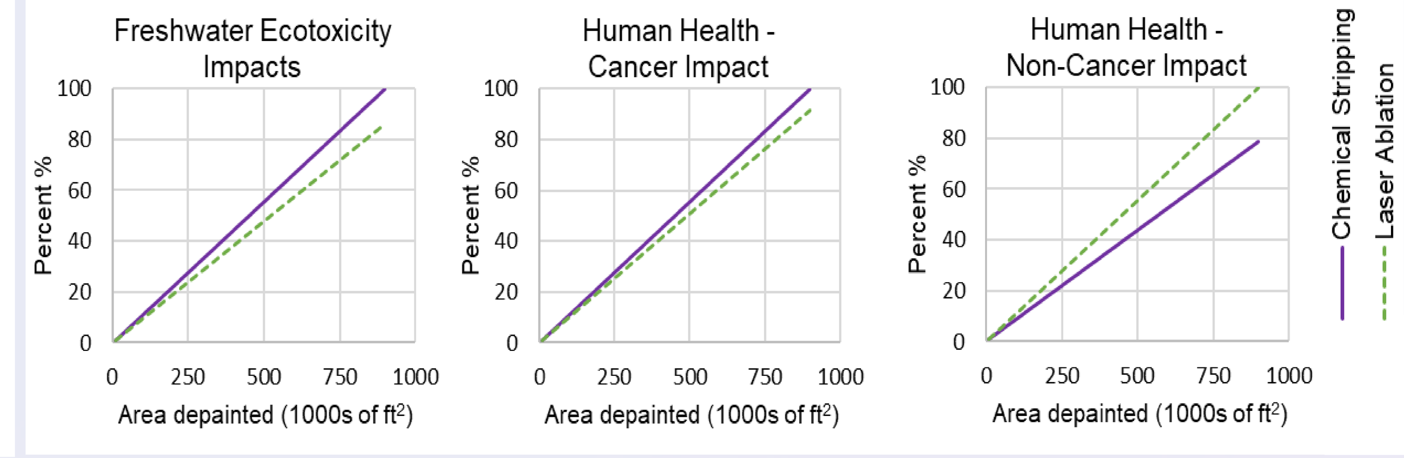


Fig. 9: Sensitivity analysis of impacts scaled with aircraft area depainted (9,000 ft^2 → 900,000 ft^2); values normalized based on maximum impact emission value.

Inventory and Mass Balance

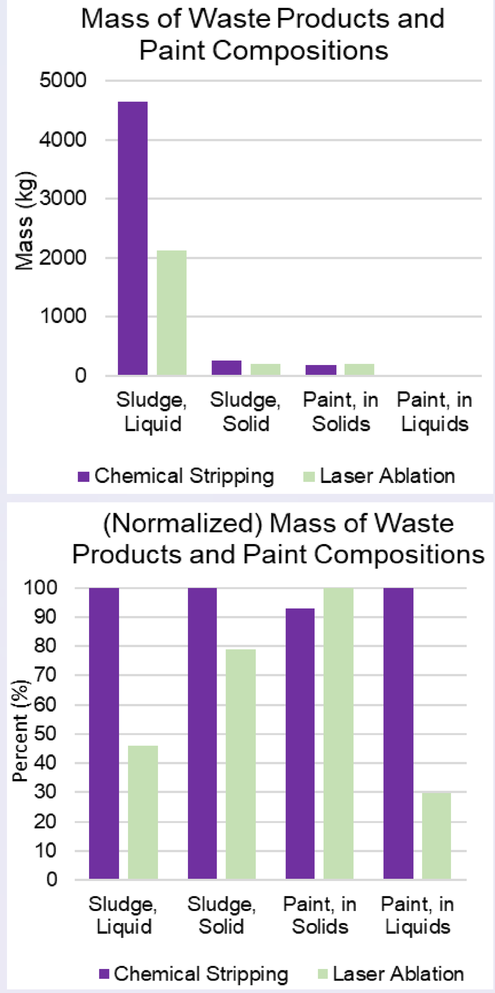


Fig. 10: Comparison of solid and liquid waste, and paint composition of base case. Normalized directly compares methods, while unnormalized retains relative magnitudes between categories.

Time & Labor Analysis

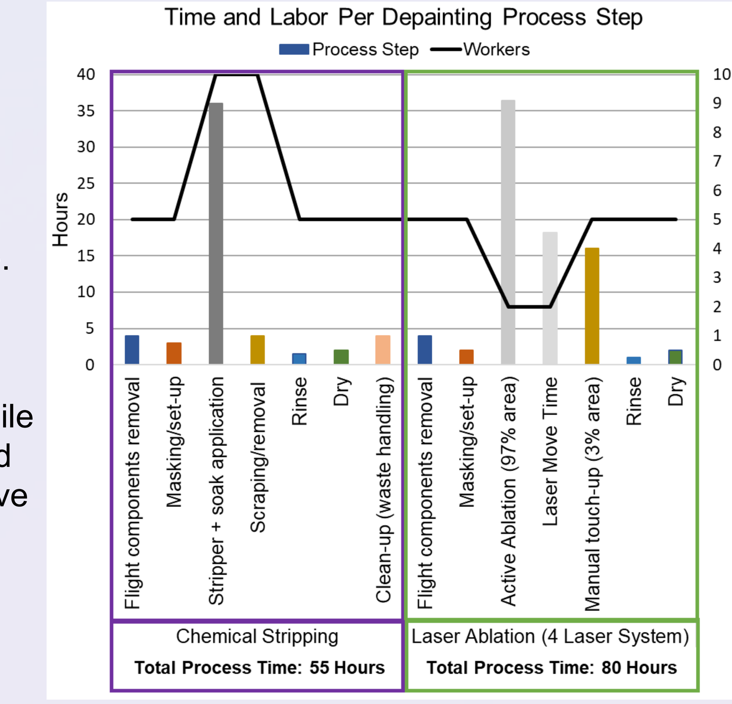
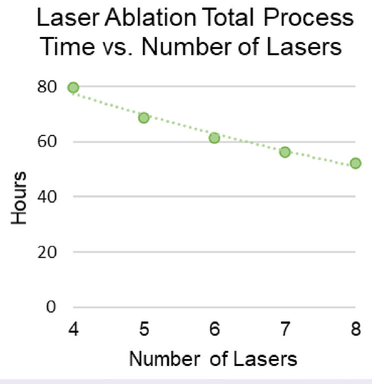


Fig. 11: (left) Breakdown of time and number of workers for each step for both depainting methods.

Fig. 12: (below) Sensitivity analysis on number of lasers in system vs. total process time.



Model Limitations
- Gate-to-gate: narrow model bounds due to complexity of waste disposal and exclusion of upstream equipment manufacturing.
- Simplified material inputs: chemical ingredients estimated from proprietary or unknown compositions, and large assumptions from stakeholder estimates.
- Limited database: only 3 comparable impact categories available (Fig. 8).

Conclusions

Chemical Stripping
- Higher freshwater ecotoxicity and cancer-related human health impacts (Figs. 8-9).
- Weak area-per-time scalability due to fixed chemical reaction time.
- Significant amounts of waste due to high chemical and maskant consumption (Fig. 10).

Laser Ablation
- Less hazardous liquid waste (54% decrease), contaminants turned into captured solid waste.
- Long-term operational sustainability potential for environmental impacts (Fig. 9).
- Reduces labor demands by 50% and worker chemical exposure hours by 44% (Fig. 11).
- Strong area-per-time upscaling potential by increasing number of operating lasers.

Due to model simplifications, results are preliminary and exclude comparisons for impact categories that contain missing information.

Future Work
- Expand LCA to include end-of-life waste treatment and disposal impacts.
- Perform more detailed sensitivity analysis to evaluate long-term operational and environmental impacts.
- Further optimize and evaluate scalability of laser ablation systems for industrial use.

Acknowledgments & References

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