A Methodology for Integrating Life Cycle Assessment into a Multidisciplinary Design Analysis and Optimization Framework for Sustainable Launcher Development

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Background

- **Life Cycle Assessment (LCA) practices for launch vehicles:**

➢ ESA promoted the use of the LCA methodology [1]

To transport a [payload of V kg] from destination A to destination B in T time

➢ A Life-Cycle Inventory (LCI) analysis must be conducted

*Interaction between **background** data (from LCI databases [2,3,4]) and **foreground** data*

➢ Life-Cycle Impact Assessment (LCIA) must be performed

*Use of **environmental impact categories indicators** computed from **available methods** [5]*

➢ Interpretation of the results

*Identification of the **areas for improvement***

Background

- **Life Cycle Assessment (LCA) practices for launch vehicles:**

➢ ESA promoted the use of the LCA methodology [1]

To transport a [payload of V kg] from destination A to destination B in T time

Current drawback:
LCA achieved after the system architecture is finalized

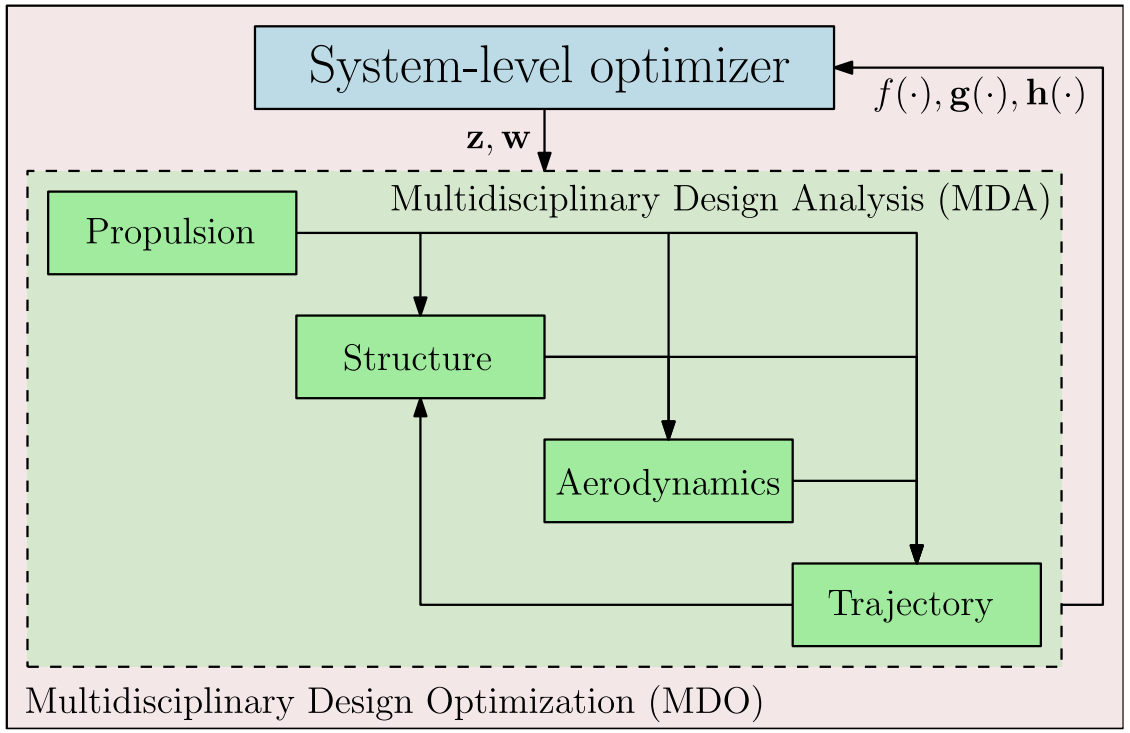
Solution:
Using Multidisciplinary Design Analysis and Optimization (MDAO) methods for early-stage design studies.

➢ Interpretation of the results

*Identification of the **areas for improvement***

Background

- **MDAO methods for early-stage design of launch vehicles:**



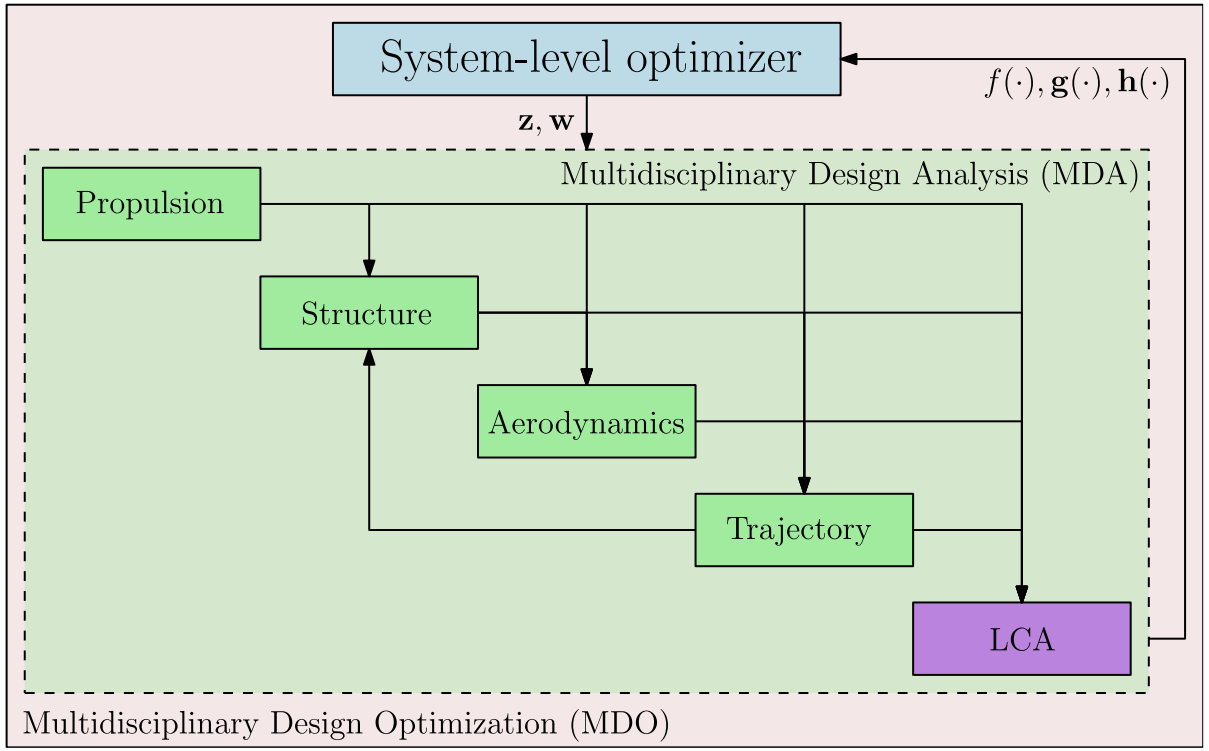
Example of MDAO problem:

minimize GLOW (Gross Lift-Off Weight)

w.r.t. design variables

s.t. equality or inequality constraints

Background



- Design and coupling variables selection and level of fidelity of the LCA discipline
- Optimization problem formulation
- Classification of the environmental impacts
- Building the LCI (resource- and time intensive)
- Level of available data and knowledge at early design

Contents

I. Methodology for including a predictive LCA model within an early-stage MDAO framework for launch vehicles

II. Case study: application to a two-stage-to-orbit vehicle

III. Conclusions and future works

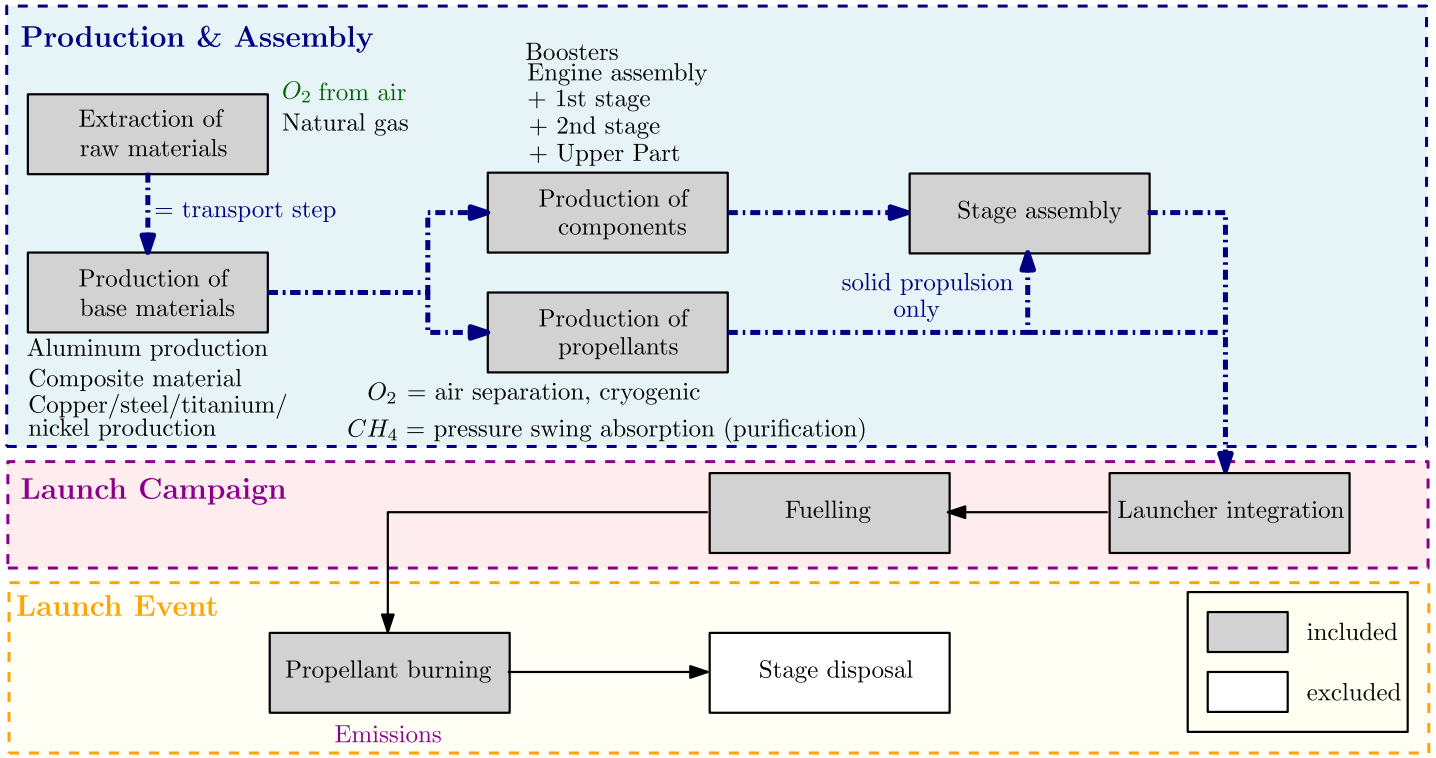
I. Methodology for including a predictive LCA model within an early-stage MDAO framework

- **Description of the predictive LCA discipline model:**

In compliance with the ESA guidelines [1], the following functional unit has been selected:

To transport 1 metric ton of payload from the launch site to destination B over 1 year's operations (multiple launches).

Results expressed in $\mathrm{t.orbit^{-1}.year^{-1}}$.



I. Methodology for including a predictive LCA model within an early-stage MDAO framework

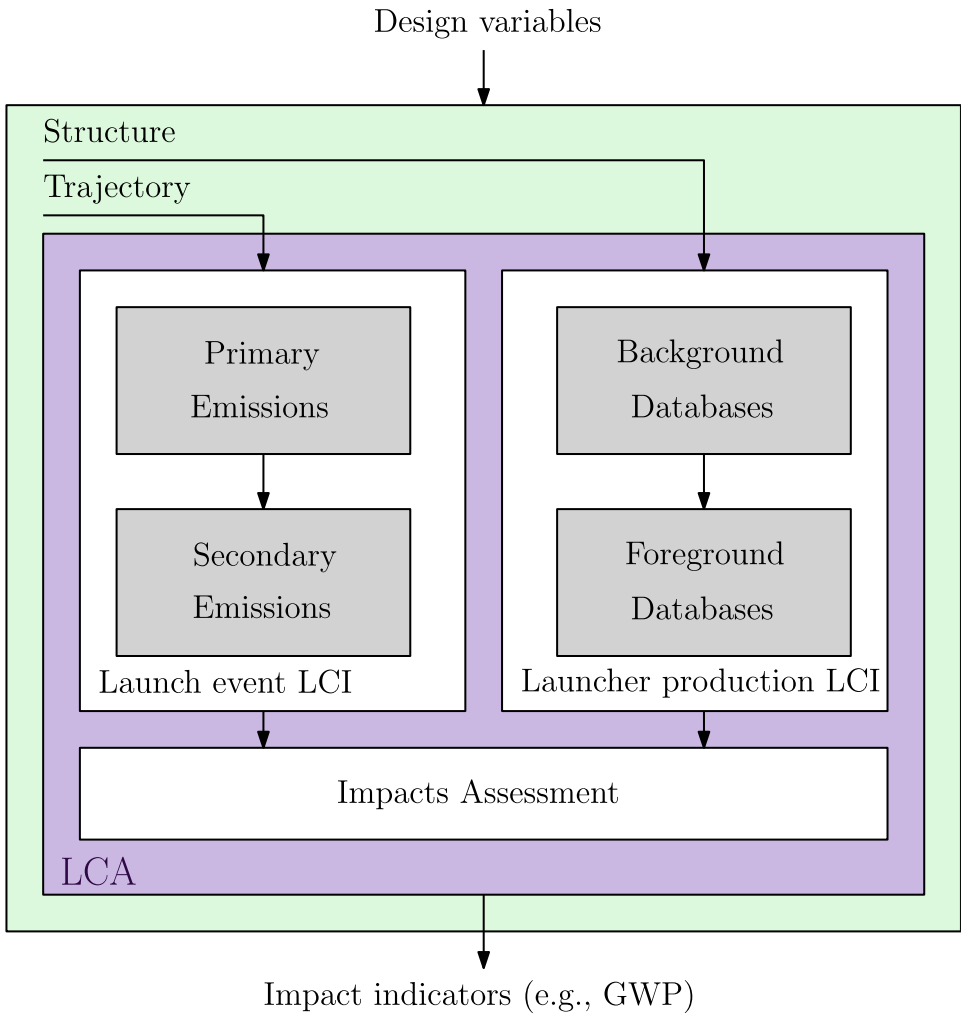
- **Description of the predictive LCA discipline model:**

Building the LCI (resource- and time intensive)

I. Parametric LCI for launch vehicle production

II. Model to estimate the launch vehicle emissions during flight

III. Characterization method for impact assessment



I. Methodology for including a predictive LCA model within an early-stage MDAO framework

- **Construction of the parametric inventories:**

Parametric inventories are based on dynamic parameters and supports fast processing speeds of the impacts assessment

Definition of *foreground* and *background* processes:

- *Background* = processes that are not under the direct control of the optimizer (e.g., production of 1 kg of aluminum)

Directly obtained from LCI databases (e.g., ecoinvent, ESA LCA database) and evaluated prior to their integration into the MDAO framework

- *Foreground* = processes that depends on the launcher design phase (e.g., the components' masses)

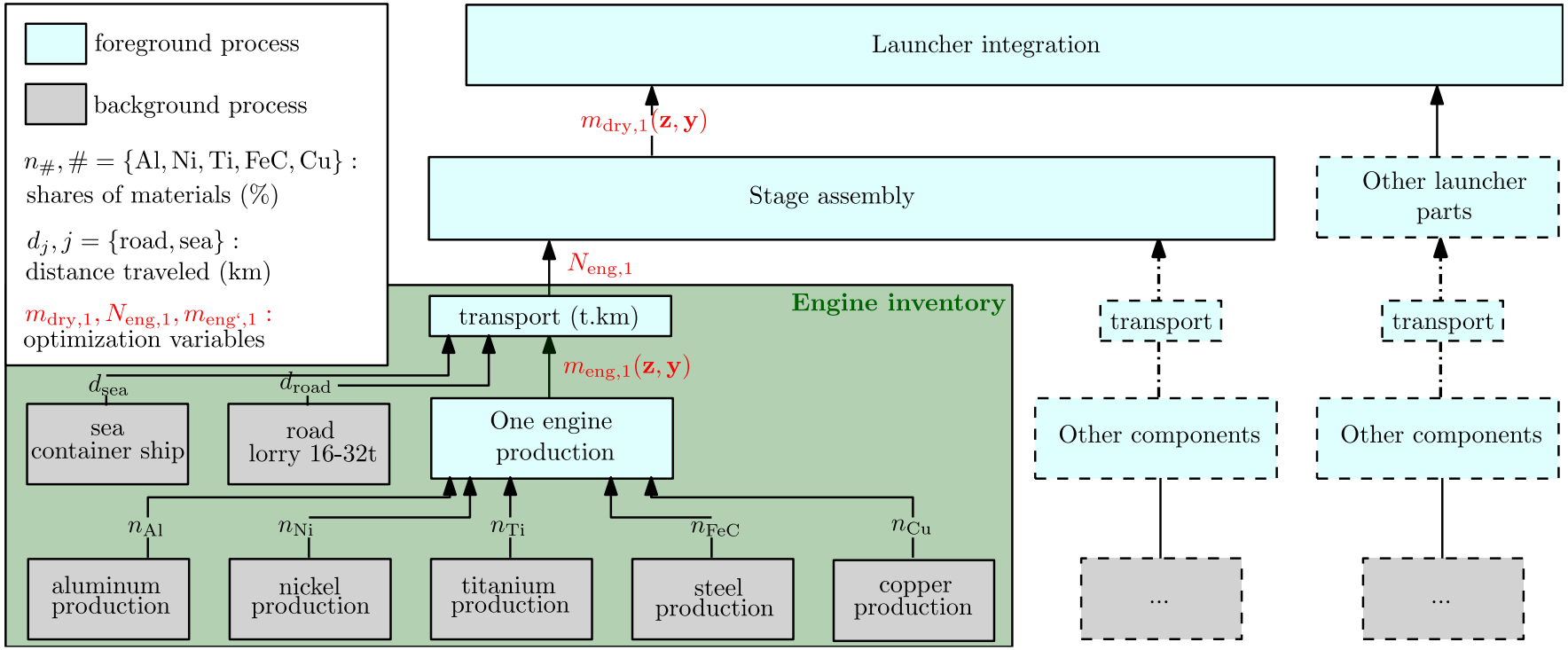
Defined as algebraic formulas depending on design and coupling variables of the MDAO framework as well as on the pre-generated *background* processes.

I. Methodology for including a predictive LCA model within an early-stage MDAO framework

- **Construction of the parametric inventories:**

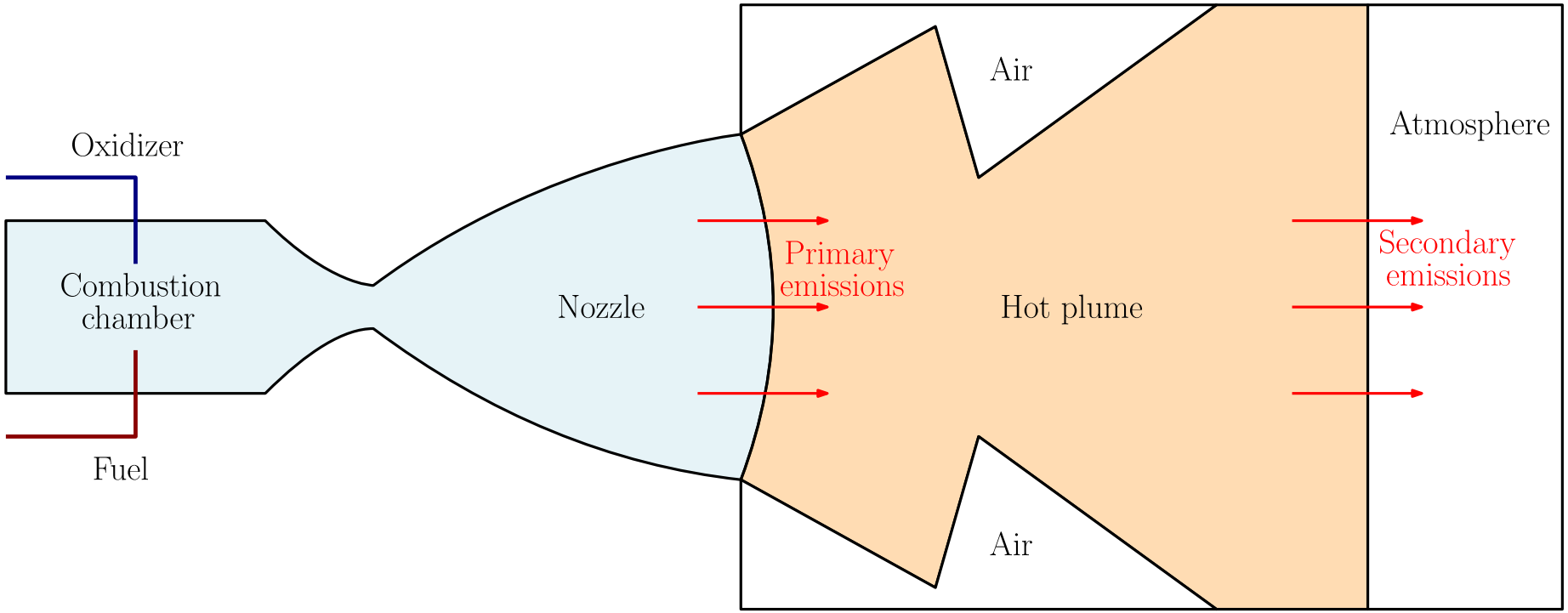
Example of the engine production inventory: corresponding algebraic formula

$$
\begin{aligned}
F_{\text{eng},1} &= F_{Components,\text{eng},1}(\mathbf{z},\mathbf{y}) + F_{Transport,\text{eng},1}(\mathbf{z},\mathbf{y}) \\
&= m_{\text{eng},1}(\mathbf{z},\mathbf{y}) \times \Big[(n_{\text{Al}} \times B_{\text{Al}} + n_{\text{Ni}} \times B_{\text{Ni}} \\
&\quad + n_{\text{Ti}} \times B_{\text{Ti}} + n_{\text{FeC}} \times B_{\text{FeC}} + n_{\text{Cu}} \times B_{\text{Cu}}) \\
&\quad + (d_{\text{road}} \times B_{\text{road}} + d_{\text{sea}} \times B_{\text{sea}}) \Big]
\end{aligned}
$$



I. Methodology for including a predictive LCA model within an early-stage MDAO framework

- **Estimation of the launch vehicle emissions for practical software implementation:**



$\times\ CF_{species}$

GWP (kgCO2-eq)

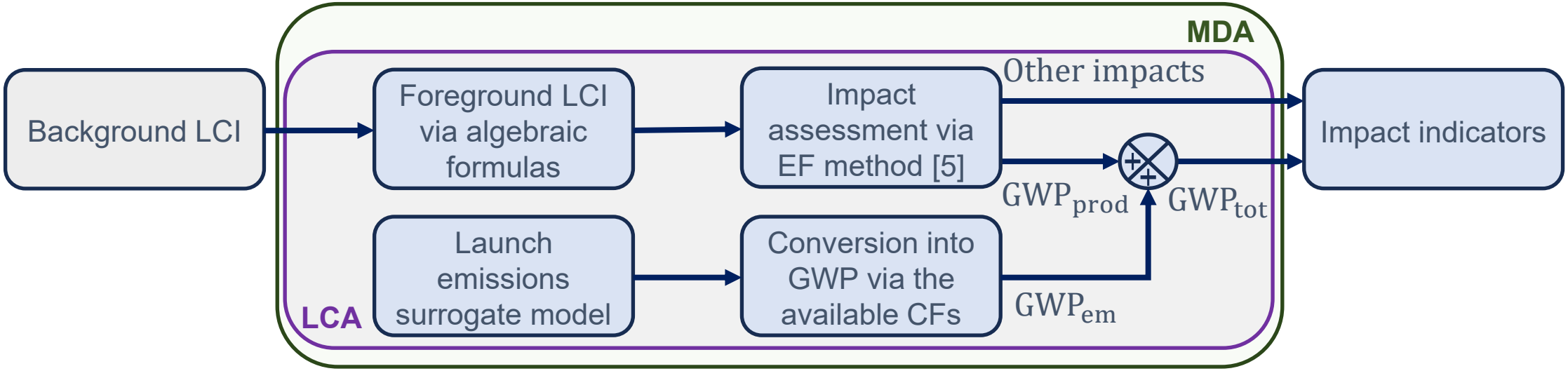
NASA CEA (rocketCEA) [6]

Fischer et al. [7]: NASA CEA hp

Development of a surrogate model

I. Methodology for including a predictive LCA model within an early-stage MDAO framework

- **Impacts assessment:**



Emission	Ground	Refs.	Aviation	Refs.
CO_2	1	[8]	1	[9]
CO	4.0 [1.6–7.6]	[8,10]	4.0	[10]
H_2O	0.0005	[11]	0.06	[9]
H_2	12.8	[12]	12.8	[10]
BC	900 [100–1700]	[8,10]	1166	[9]
NO_x	8.5 [7–10]	[10,13]	114	[9]

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II. Application to a two-stage-to-orbit vehicle

Case study: Two-stage-to-orbit launch vehicle

- Liquid Oxygen (LOx) / Liquid Methane (LCH4) for both stages
- 21 metric tons of payload
- LEO of 800 km altitude
- Launched from the Guiana Space Center.

Multi-objective optimization:

- $\mathrm{GLOW}(\cdot)$
- $f_{LCIA}(\cdot)$: environmental indicator among EF categories or single score

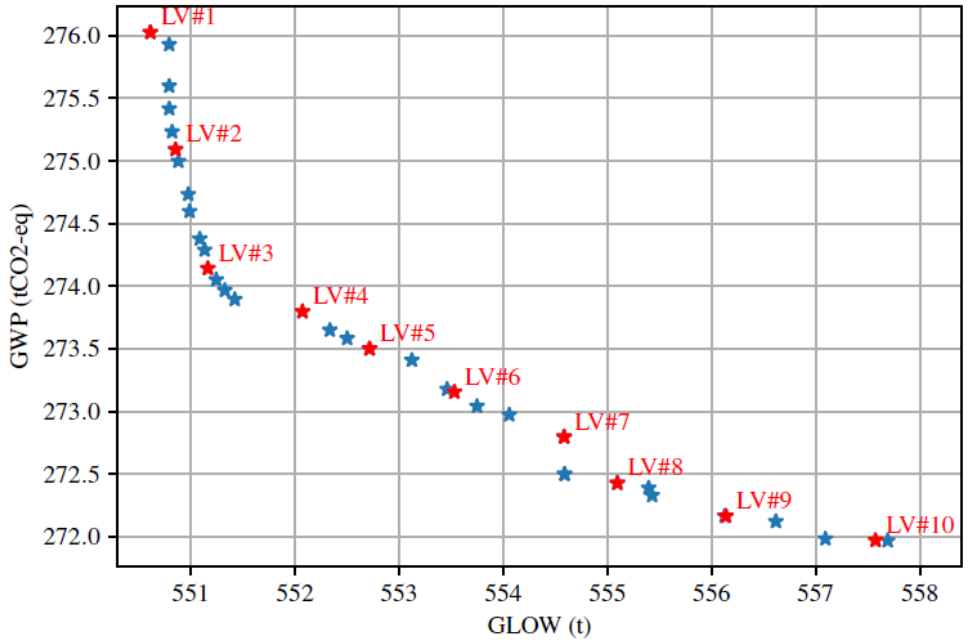
$$
\begin{aligned}
\min \quad & \left\{\mathrm{GLOW}(\mathbf{z},\mathbf{w}), f_{\mathrm{LCIA}}(\mathbf{z},\mathbf{w})\right\}, \\
\text{w.r.t.} \quad & \mathbf{z},\mathbf{w} \\
\text{s.t.} \quad & \mathbf{g}(\mathbf{z},\mathbf{w}) \leq 0 \\
& \mathbf{h}(\mathbf{z},\mathbf{w}) = 0 \\
& \mathbf{z}_{\min} \leq \mathbf{z} \leq \mathbf{z}_{\max}, \quad \mathbf{w}_{\min} \leq \mathbf{w} \leq \mathbf{w}_{\max}
\end{aligned}
$$

Variables	Notation	Bounds	Unit
1st stage mixture ratio	O/F_1	[1.9, 3.9]	–
2nd stage mixture ratio	O/F_2	[1.9, 3.9]	–
1st stage propellant mass	$m_{\mathrm{prop},1}$	[150, 600]	t
2nd stage propellant mass	$m_{\mathrm{prop},2}$	[5, 200]	t
1st stage mass flow rate	$\dot{m}_1$	[250, 600]	kg/s
2nd stage mass flow rate	$\dot{m}_2$	[5, 400]	kg/s
Diameter (equal for both stages)	D	[3.5, 4]	m
Trajectory commands	$\mathbf{w}$	–	–

II. Application to a two-stage-to-orbit vehicle

1st case: Minimizing GLOW and **GWP**

- GLOW is expressed in metric tons
- GWP is expressed in tCO2-eq, relative to 1 metric ton of payload per orbit per year ($\mathrm{t.orbit^{-1}.year^{-1}}$)



	Min GLOW LV#1	Median LV#5	Min GWP LV#10	Δ (%)
GWP (tCO_2-eq)				
Emissions	88.8	87.1	85.7	−3.5
Propellants	91.4	90.7	90.7	−0.8
Components	95.6	95.4	95.3	−0.3
Transport	0.2	0.2	0.2	0.0
% of total GWP				
Emissions	32.2	31.9	31.5	–
Propellants	33.1	33.2	33.3	–
Components	34.6	34.9	35.1	–
Transport	0.1	0.1	0.1	–

- Increase of the mixture ratio (2.9 ➔ 3.2)
- Reduction of the second stage ($m_{\mathrm{prop},2}$ and $\dot{m}_2$ reduced by 12.3 and 13.8%)

- Most of the GWP reduction comes from the launch emissions

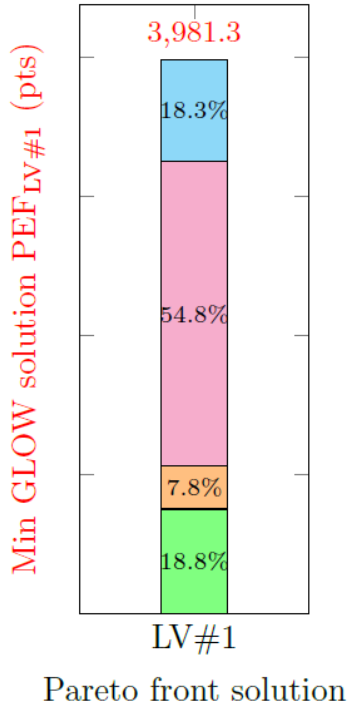
II. Application to a two-stage-to-orbit vehicle

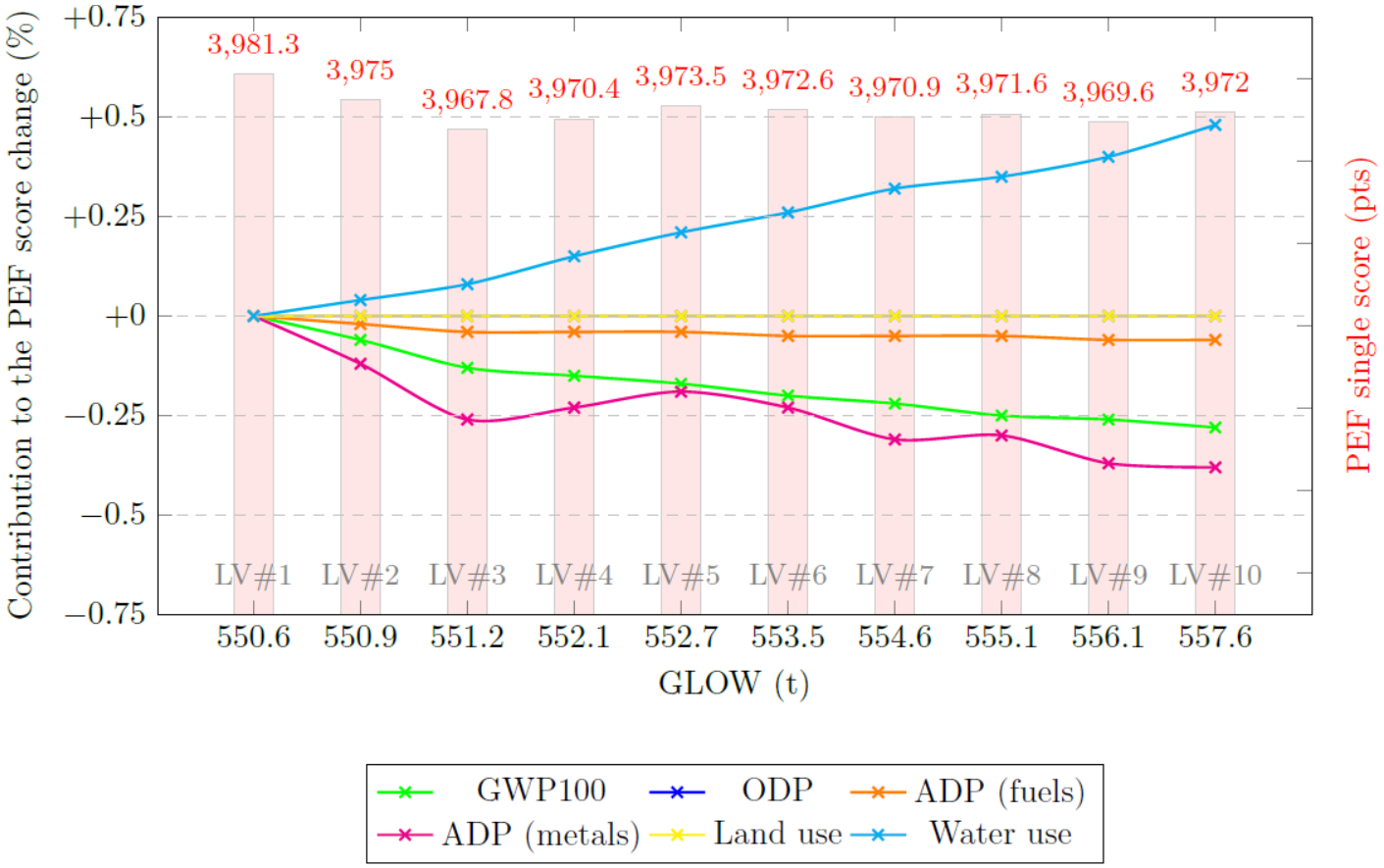
1st case: Minimizing GLOW and **GWP**

Analysis of the PEF single-score

$$\mathrm{PEF}(\mathbf{z},\mathbf{w}) = \sum_{k\in\mathcal{E}} \mathrm{PEF}_k(\mathbf{z},\mathbf{w}) = \sum_{k\in\mathcal{E}} \left(\frac{k(\mathbf{z},\mathbf{w})}{\mathrm{NF}_k} \times \mathrm{WF}_k \right),$$

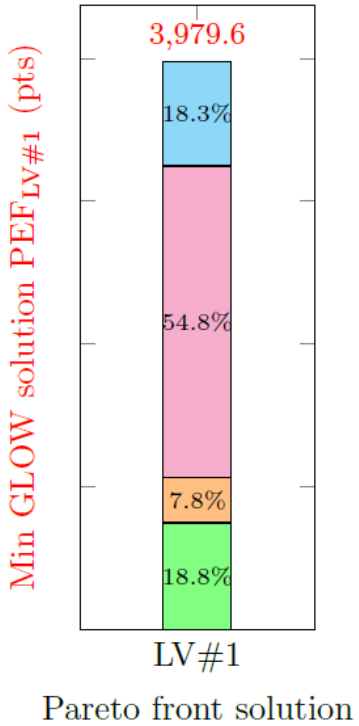
with $\mathcal{E} = \{\mathrm{GWP100}, \mathrm{ODP}, \mathrm{ADP\ (fossil)}, \mathrm{ADP\ (metals)}, \mathrm{Land\ use}, \mathrm{Water\ use}\}$

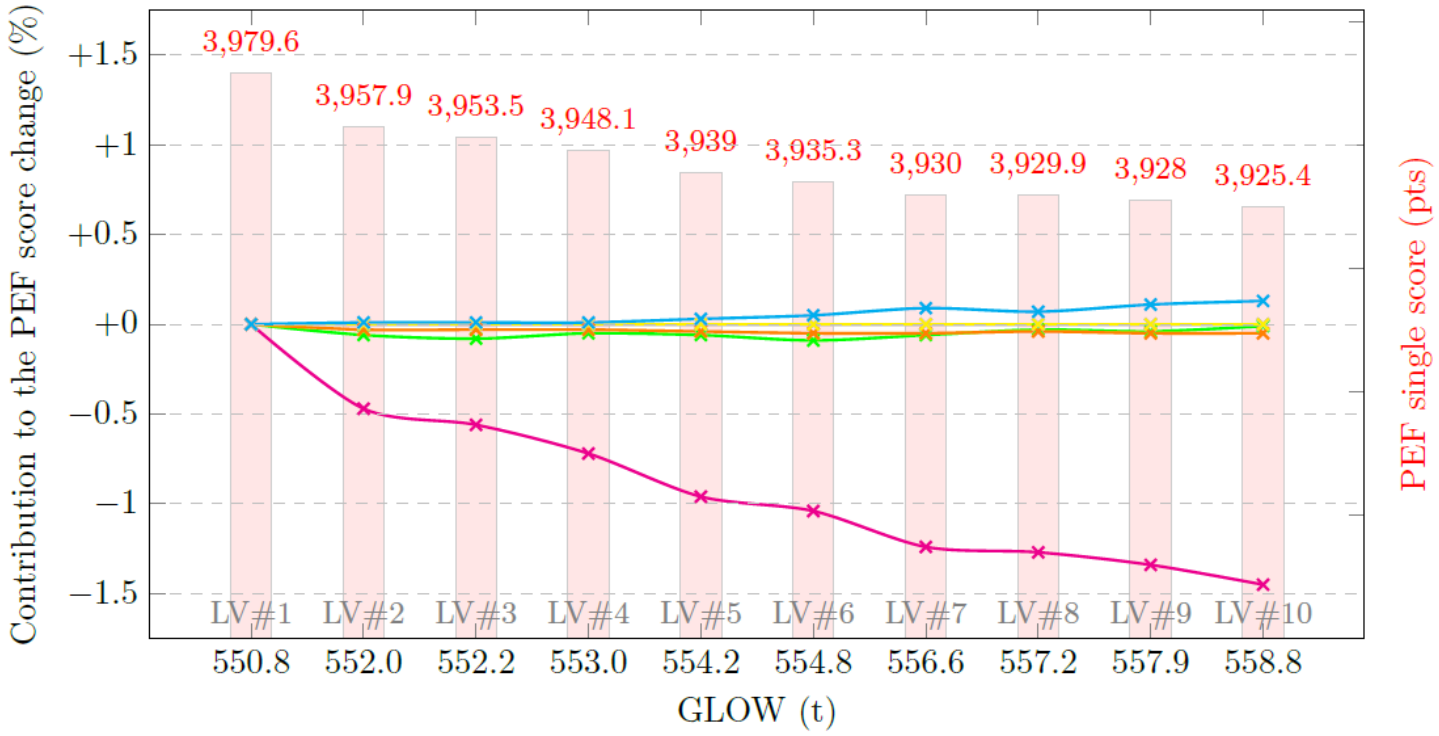




II. Application to a two-stage-to-orbit vehicle

2nd case: Minimizing GLOW and **PEF**





GWP100 | ODP | ADP (fuels) | ADP (metals) | Land use | Water use

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Key findings

- ✓ Demonstrated integration of **LCA within early-stage launcher design**
- ✓ Multi-objective optimization reveals **trade-offs between GLOW & environmental impacts**
- ✓ Environmental objectives are **antagonistic** and must be **carefully selected**
- ✓ Single-score indicators can hide **impact category conflicts**

Limitations

- Results depend on **disciplinary modeling assumptions**
- **Parametric LCI inventories**: component distribution, mass models, process scope/detail
- Lack of **space-specific data** and **high-altitude emission models**
- **Uncertainties** in LCI data and impact assessment

Future developments

- ➢ Flexible MDAO formulation **adaptable to different architectures**
- ➢ Modular LCA framework enabling progressive refinement: **improved databases, emission models & characterization factors**
- ➢ Extension to **additional life-cycle phases** and **other launch vehicle architectures**

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Thank you !

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More information in the journal paper (currently under review):

A. De Oliveira et al., A Methodology for Integrating Life Cycle Assessment into a Multidisciplinary Design Analysis and Optimization Framework for Sustainable Launcher Development, preprint submitted to Acta Astronautica.

Back-up

I. Methodology for including a predictive LCA model within an early-stage MDAO framework

- **Construction of the parametric inventories:**

Output from structure	Category	Parameter and associated background process
Boosters:		
Boosters' dry mass	Production	$n_{b,\mathrm{Al}}$ (AL2219 generic part, ESA) $n_{b,\mathrm{CFPR}}$ (CFPR honeycomb 5052, ESA)
$m_{b,dry} \times N_{booster}$	Transport	$d_{b,\mathrm{road}}$ (Lorry 16–32 t EURO4, ecoinvent) $d_{b,\mathrm{sea}}$ (Sea container ship, ecoinvent)
Solid propellant mass $m_{prop,sol}$	APCP propellant use, ESA	
1st stage: interstage included		
Interstage mass m_{IS}	Production	$n_{IS,\mathrm{Al}}$ (AL2219 generic part, ESA) $n_{IS,\mathrm{CFPR}}$ (CFPR honeycomb 5052, ESA)
	Transport	$d_{IS,\mathrm{road}}$ (Lorry 16–32 t EURO4, ecoinvent) $d_{IS,\mathrm{sea}}$ (Sea container ship, ecoinvent)
2nd stage: fairing, payload adapter, avionics and EPS included		
Fairing & payload adapter	Production	$n_{fairing,\mathrm{Al}}$ (AL2219 generic part, ESA) $n_{fairing,\mathrm{CFPR}}$ (CFPR honeycomb 5052, ESA)
$m_{fairing} + m_{PLA}$	Transport	$d_{fairing,\mathrm{road}}$ (Lorry 16–32 t EURO4, ecoinvent) $d_{fairing,\mathrm{sea}}$ (Sea container ship, ecoinvent)
Avionics mass m_{avio}	Production	$n_{Av,\mathrm{Unit}}$ (Electronic unit, ESA) $n_{Av,\mathrm{W20}}$ (Single wire AWG20, ESA) $n_{Av,\mathrm{W26}}$ (Single wire AWG26, ESA)
EPS mass m_{EPS}	Production	$n_{EPS,\mathrm{Unit}}$ (Power supply unit, ESA) $n_{EPS,\mathrm{Bat}}$ (Li-ion battery assembly, ESA) $n_{EPS,\mathrm{W14}}$ (Single wire AWG14, ESA)
Σ	Transport	$d_{avioEPS,\mathrm{road}}$ (Lorry 16–32 t EURO4, ecoinvent) $d_{avioEPS,\mathrm{sea}}$ (Sea container ship, ecoinvent)

Common to all stages i: tanks, TPS, thrust frame, engine, pressurization system, and propellants		
Fuel tank $m_{ftank,i}$ Oxidizer tank $m_{oxtank,i}$	AL2195 generic part, modified from ESA AL2195 generic part, modified from ESA	
Fuel TPS $m_{TPS\,f,i}$	Production	$n_{TPS\,f,i,\mathrm{CMC}}$ (CMC, ecoinvent) $n_{TPS\,f,i,\mathrm{foam}}$ (Polyurethane foam, ecoinvent) $n_{TPS\,f,i,\mathrm{inconel}}$ (Inconel alloy, ESA)
Oxidizer TPS $m_{TPS\,ox,i}$	Production	$n_{TPS\,ox,i,\mathrm{CMC}}$ (CMC, ecoinvent) $n_{TPS\,ox,i,\mathrm{inconel}}$ (Inconel alloy, ESA)
Intertank $m_{IT,i}$	Production	$n_{IT,i,\mathrm{Al}}$ (AL2219 generic part, ESA) $n_{IT,i,\mathrm{CFPR}}$ (CFPR honeycomb 5052, ESA)
Σ	Transport	$d_{t,i,\mathrm{road}}$ (Lorry 16–32 t EURO4, ecoinvent) $d_{t,i,\mathrm{sea}}$ (Sea container ship, ecoinvent)
Thrust frame $m_{TF,i}$	Production	$n_{TF,i,\mathrm{Al}}$ (AL2219 generic part, ESA) $n_{TF,i,\mathrm{CFPR}}$ (CFPR honeycomb 5052, ESA)
	Transport	$d_{TF,i,\mathrm{road}}$ (Lorry 16–32 t EURO4, ecoinvent) $d_{TF,i,\mathrm{sea}}$ (Sea container ship, ecoinvent)
Engines total mass $m_{eng,i} \times N_{eng,i}$	Production	$n_{eng,i,\mathrm{Al}}$ (AL2219 generic part, ESA) $n_{eng,i,\mathrm{Ni}}$ (Nickel Haynes 25, ESA) $n_{eng,i,\mathrm{Ti}}$ (Titanium generic part, ESA) $n_{eng,i,\mathrm{FeC}}$ (Stainless steel 304, ESA) $n_{eng,i,\mathrm{Cu}}$ (Copper coil, ESA)
	Transport	$d_{eng,i,\mathrm{road}}$ (Lorry 16–32 t EURO4, ecoinvent) $d_{eng,i,\mathrm{sea}}$ (Sea container ship, ecoinvent)
Pressurization system mass Tank $m_{PS,tank,i}$ Helium $m_{PS,He,i}$	AL2195 generic part, modified from ESA Market for Helium, GLO, ecoinvent	
Σ	Transport	$d_{PS,i,\mathrm{road}}$ (Lorry 16–32 t EURO4, ecoinvent) $d_{PS,i,\mathrm{sea}}$ (Sea container ship, ecoinvent)
Fuel mass $m_{fuel,i}$	LH_2/CH_4/RP-1 propellant loading, ESA	
Oxidizer mass $m_{ox,i}$	LOx propellant loading, ESA	

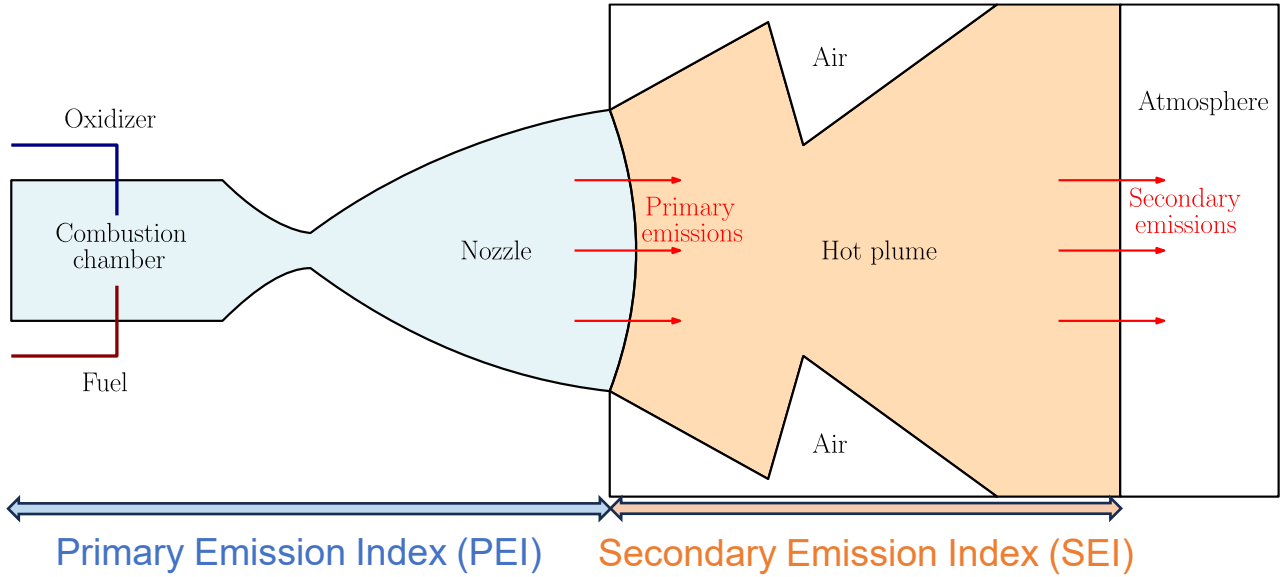
I. Methodology for including a predictive LCA model within an early-stage MDAO framework

- **Estimation of the launch vehicle emissions:**

Let us define the rocket emissions:

$$m_{\text{species},i} = \int_{t_i}^{t_f} EI_{\text{species},i}(h(t)) \times \dot{m}(t)\, dt$$

$m_{species,i}$: mass of a species i emitted
$\delta t = t_f - t_i$: duration of the trajectory segment
$EI_{species,i}(\cdot)$: emission index expressed in g/kg
$h(\cdot)$: altitude
$\dot{m}(\cdot)$: mass flow rate



Common framework in the literature:

1. Estimating PEI
2. Evaluating SEI
3. Determining the vehicle's trajectory profile
4. Converting the emissions into environmental impacts

➔ Subject to significant uncertainties

II. Application to a two-stage-to-orbit vehicle

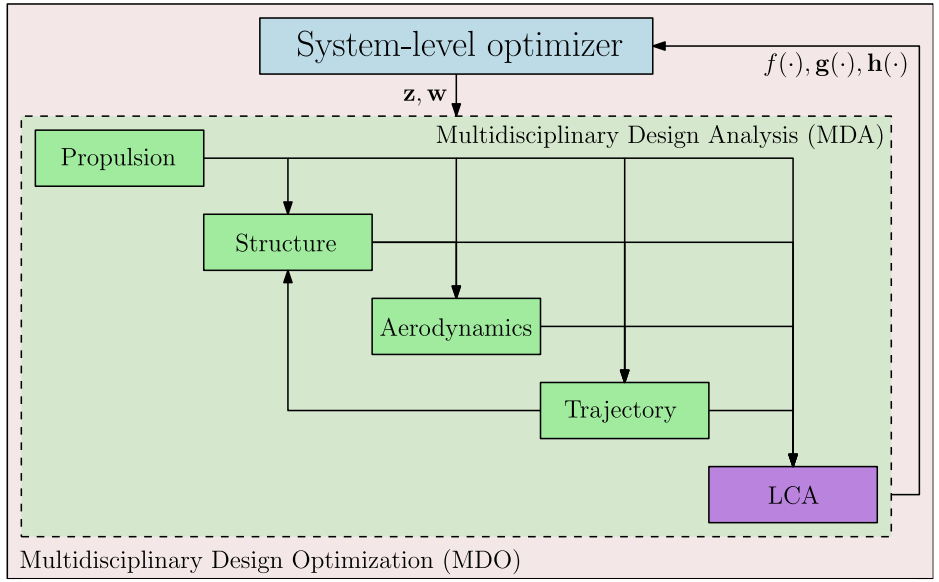
Case study: Two-stage-to-orbit launch vehicle able to inject 21 metric tons of payload into a circular and equatorial low Earth orbit of 800 km altitude from the Guiana Space Center.

- Liquid Oxygen (LOx) / Liquid Methane (LCH4) for both stage
- 7 engines for the 1st stage, 1 engine for the 2nd stage
- Chamber pressure and expansion ratio fixed for both stage [14]
- LCA discipline: 10 similar launches are performed over 1 year

Multi-objective optimization:

- $\mathrm{GLOW}(\cdot)$
- $f_{LCIA}(\cdot)$: environmental indicator among EF categories or single score
- Optimization solved using COMO-CMA-ES [15] (evolutionary strategy) combined with NGSA-II [16] (genetic algorithm).

$$
\begin{aligned}
\min \quad & \left\{\mathrm{GLOW}(\mathbf{z},\mathbf{w}), f_{\mathrm{LCIA}}(\mathbf{z},\mathbf{w})\right\}, \\
\text{w.r.t.} \quad & \mathbf{z},\mathbf{w} \\
\text{s.t.} \quad & \mathbf{g}(\mathbf{z},\mathbf{w}) \leq 0 \\
& \mathbf{h}(\mathbf{z},\mathbf{w}) = 0 \\
& \mathbf{z}_{\min} \leq \mathbf{z} \leq \mathbf{z}_{\max}, \quad \mathbf{w}_{\min} \leq \mathbf{w} \leq \mathbf{w}_{\max}
\end{aligned}
$$

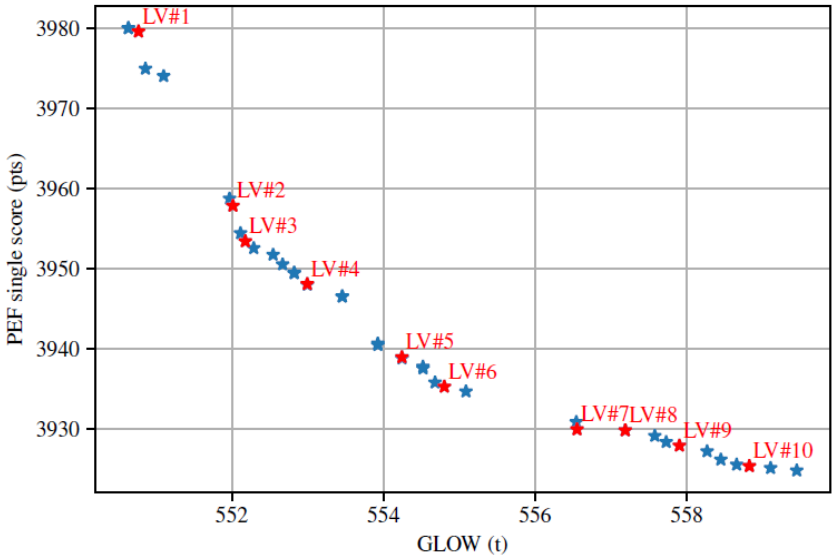


Variables	Notation	Bounds	Unit
1st stage mixture ratio	O/F_1	[1.9, 3.9]	–
2nd stage mixture ratio	O/F_2	[1.9, 3.9]	–
1st stage propellant mass	$m_{\mathrm{prop},1}$	[150, 600]	t
2nd stage propellant mass	$m_{\mathrm{prop},2}$	[5, 200]	t
1st stage mass flow rate	$\dot{m}_1$	[250, 600]	kg/s
2nd stage mass flow rate	$\dot{m}_2$	[5, 400]	kg/s
Diameter (equal for both stages)	D	[3.5, 4]	m
Trajectory commands	$\mathbf{w}$	–	–

Table X: Design variables of the MDAO framework studied with the bounds considered for optimization.

II. Application to a two-stage-to-orbit vehicle

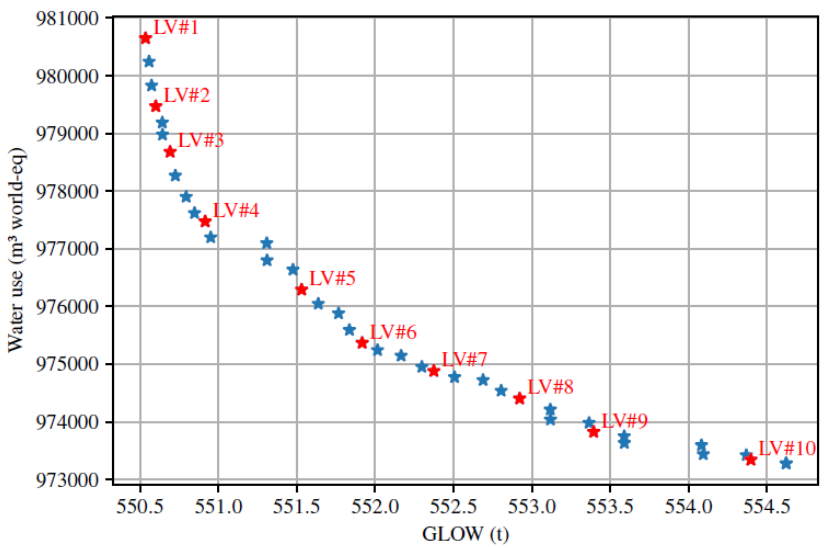
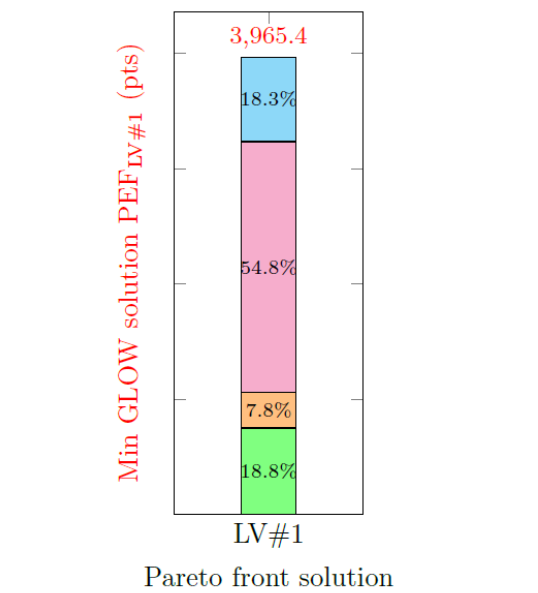
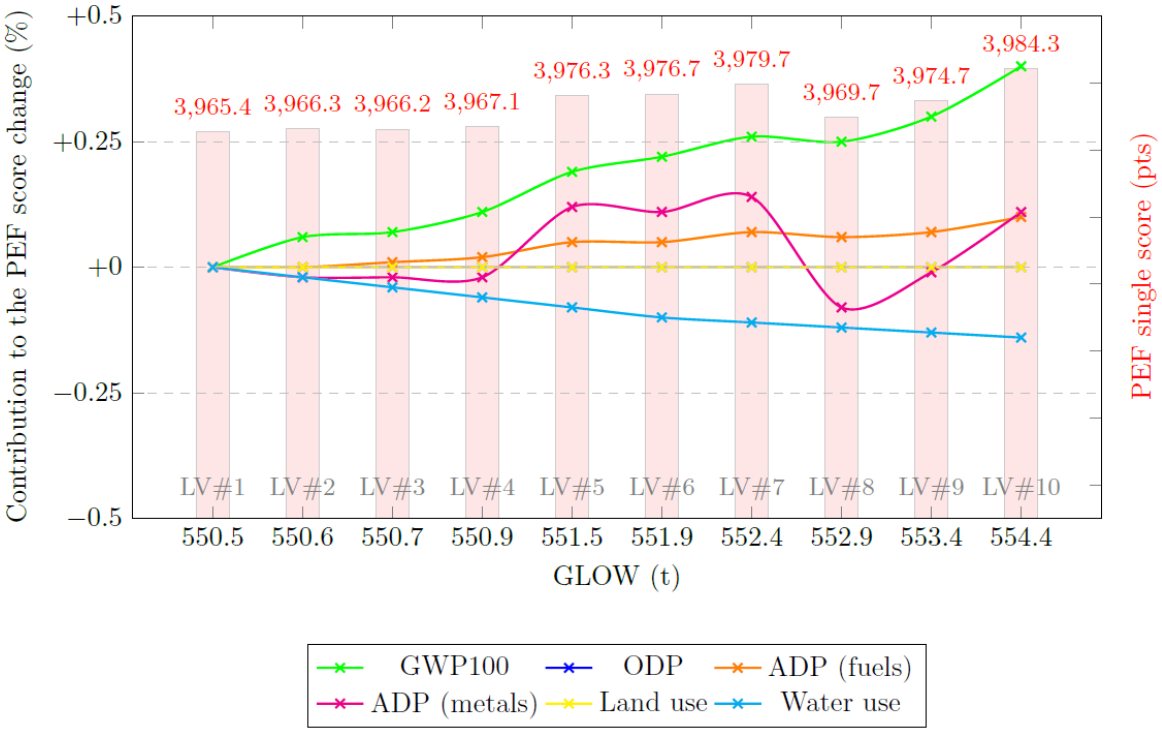
2nd case: Minimizing GLOW and PEF



	Min GLOW LV#1	Median LV#5	Min PEF LV#10	Δ (%)
PEF (pts)	3979.6	3939.0	3925.4	
Emissions	243.5	242.2	243.4	0.0
Propellants	973.7	981.3	991.2	1.8
Components	2761.4	2714.5	2689.7	−2.6
Transport	1.1	1.1	1.1	0.0
% of total PEF				
Emissions	6.1	6.2	6.2	–
Propellants	24.5	24.9	25.2	–
Components	69.3	68.9	68.5	–
Transport	0.0	0.0	0.0	–
GWP (tCO_2-eq)	276.0	275.2	275.9	
Emissions	88.9	88.3	88.8	−0.1
Propellants	91.4	92.2	92.9	1.7
Components	95.5	94.3	93.9	−1.7
Transport	0.2	0.2	0.2	0.0

- Values of PEF not obtained before
- Reduction of the second stage ($m_{\mathrm{prop},2}$ and $\dot{m}_2$ reduced by 21 and 25.5%)

- In the current formulation, minimizing the PEF = minimizing the ADP for metals and minerals.

II. Application to a two-stage-to-orbit vehicle

3rd case: Minimizing GLOW and water use