A consensus-based single-score for life cycle assessment of space missions

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CSID 2023 – 17/10/2023

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SPACE SUSTAINABILITY RATING

About me

- MSc student at TU Delft
- Space Exploration

- Thesis from May until October
- Supervised by the TU Delft & daily at eSpace, EPFL space center

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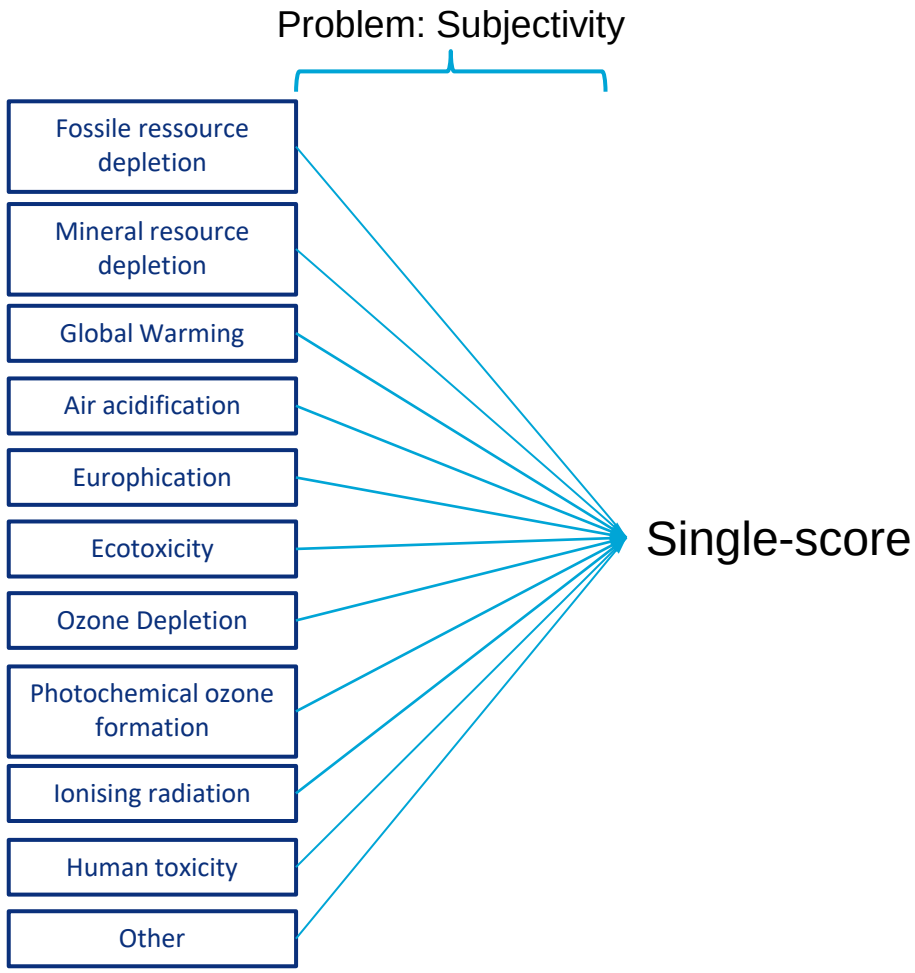
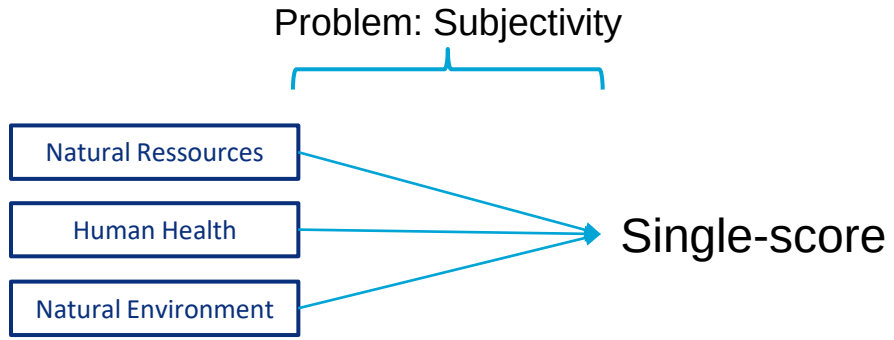
Simplifying LCA for ecodesign





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Content

Background

- Past work
- Thesis methodology

Relevant findings

- Preferred ways of showing LCA results
- Drivers & inhibitors of space LCA

Single-score and LCA

- Single-score weighting factors
- Single-score calculation of a CubeSat

Future work & Conclusion

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Background

Past work on single-score LCA

Using ESA LCA database

Approach used:

- PEF
- PEF with “space normalisation”
  - Based on reference GreenSat
- PEF with adapted weights
  - Based on internal weighting

Using Strathclyde Space Systems Database (SSSD)

Approach used:

- Normalisation identical to PEF
  - `EU-27 domestic inventory’ in 2010 per EU citizen
- Weights based on PEF
  - Selection of most critical midpoint impact categories

Images taken from: https://www.esa.int/ and https://www.strath.ac.uk/

Sources:
- E. Tormena, “*Internship ESA Clean Space - Final Report,*” ISAE-SUPAERO, 2022
- A. R. Wilson, M. Vasile, C. Maddock, and K. Baker, “*The Strathclyde space systems database : a new life cycle sustainability assessment tool for the design of next generation green space systems*,” in 8th International Systems & Concurrent Engineering for Space Applications Conference, 2018. [Online]. Available: https://strathprints.strath.ac.uk/65685/ (visited on October 14, 2023).

Methodology

Multi-round survey with systematic feedback on average answers

Definition of single-score weighting factors

LCA of CubeSat and **single-score calculation**

Ecodesign with single-score

- Goal: Understand **which aspects of sustainability are the most critical** according to the space sector as a whole
- Secondary objective: Obtain a **preliminary consensus** on the weights for a **single-score**

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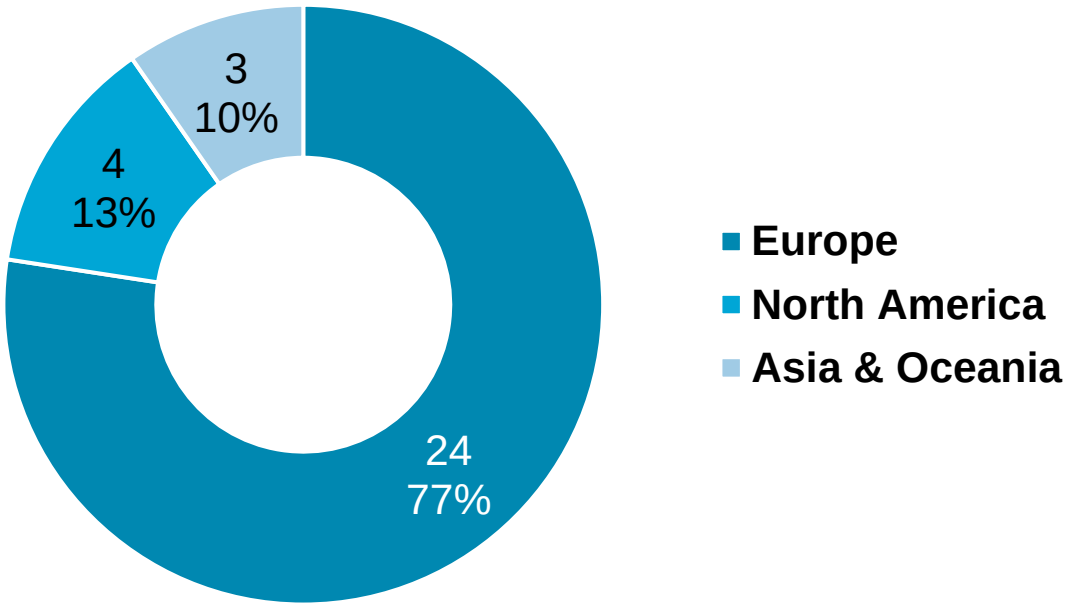
Relevant survey result

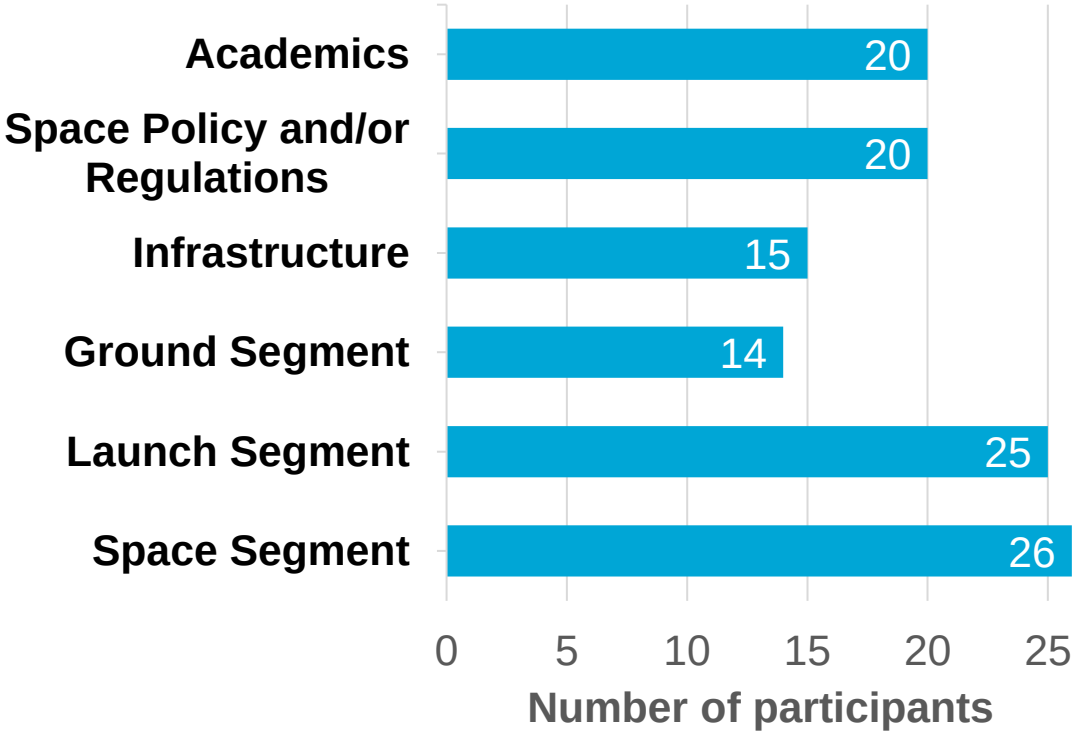
Survey Participants

Origin of participants



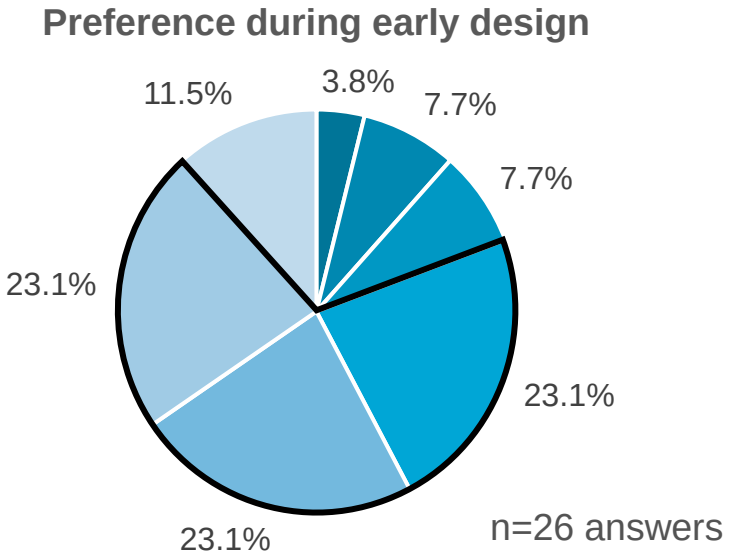
n=31 answers

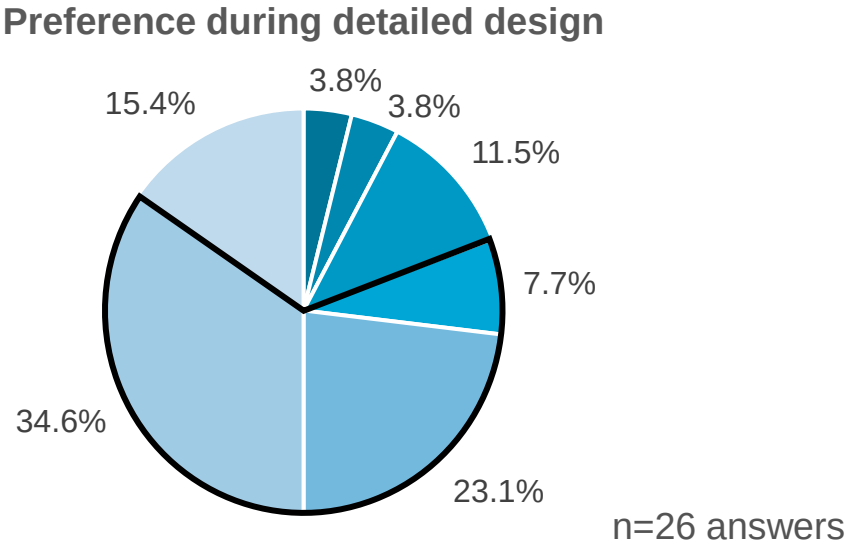
Fields of experience of participants



n=31 answers

Preferred way of showing of space LCA results





- Single score
- Values for each endpoint impact category
- Values for each midpoint impact category
- Single score + Values for each endpoint impact category
- Single score + Values for each midpoint impact category
- Single score + Values for each endpoint impact category + Values for each midpoint impact category
- Values for each endpoint impact category + Values for each midpoint impact category

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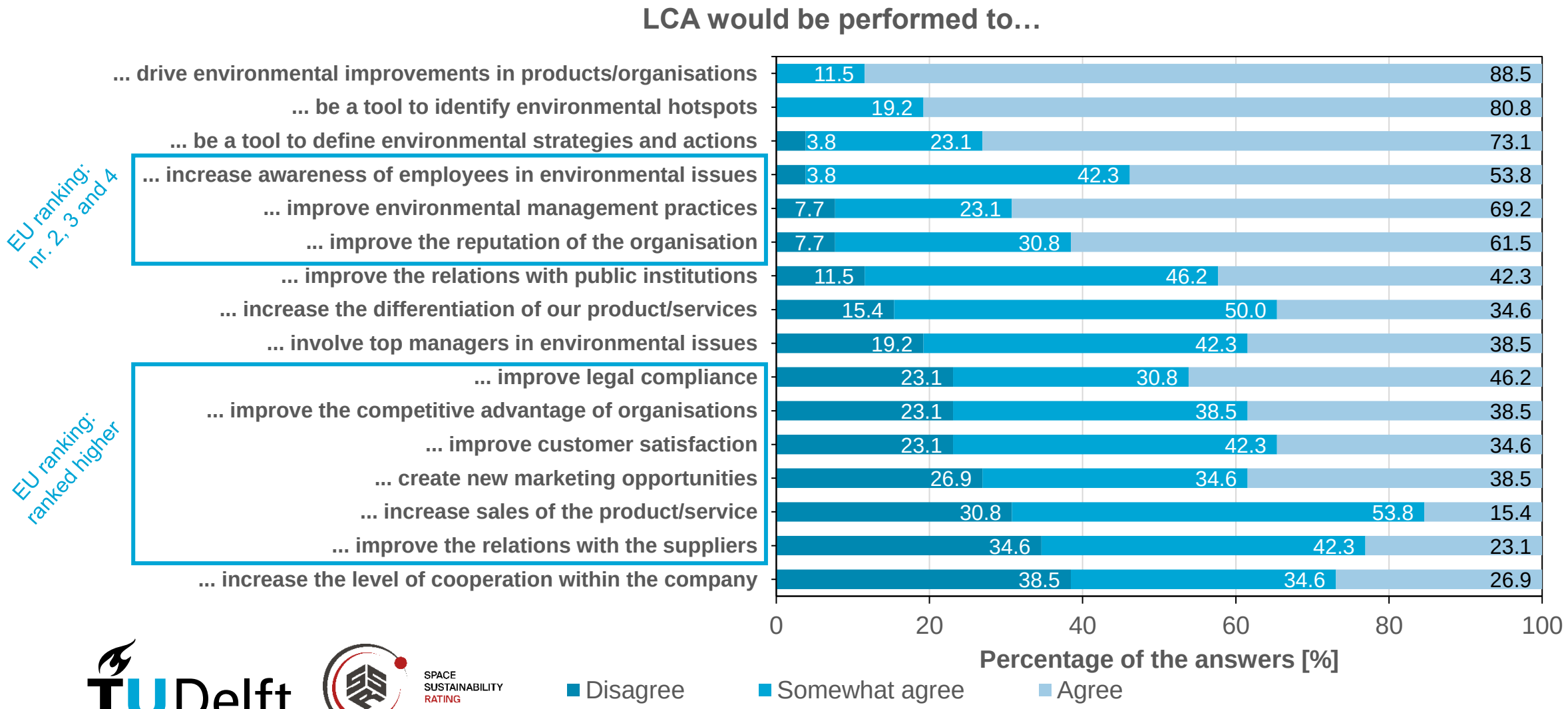
Drivers of a space LCA



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Source for the general EU industry ranking: F. Lupiáñez-Villanueva, P. Tornese, G. A. Veltri, and G. Gaskell, "Assessment of different communication vehicles for providing Environmental Footprint information, Final report," European Commission. Directorate General Environment., Directorate A-Green Economy, Env. A, 2018. [Online]. Available: https://www.oneplanetnetwork.org/sites/default/files/from-crm/2018_pilotphase_commreport.pdf (visited on Jul. 10, 2023).

Single-score and LCA

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Definition of the single-score weighting factors

Survey participants **rank midpoint impact categories** based on relative importance

The Launch Segment is excluded

Compute the **average of the ranking**

Apply **robustness factors** defined by the European Commission and **scale** to sum up to 100%

Result: the **final proposed single-score weighting factors**

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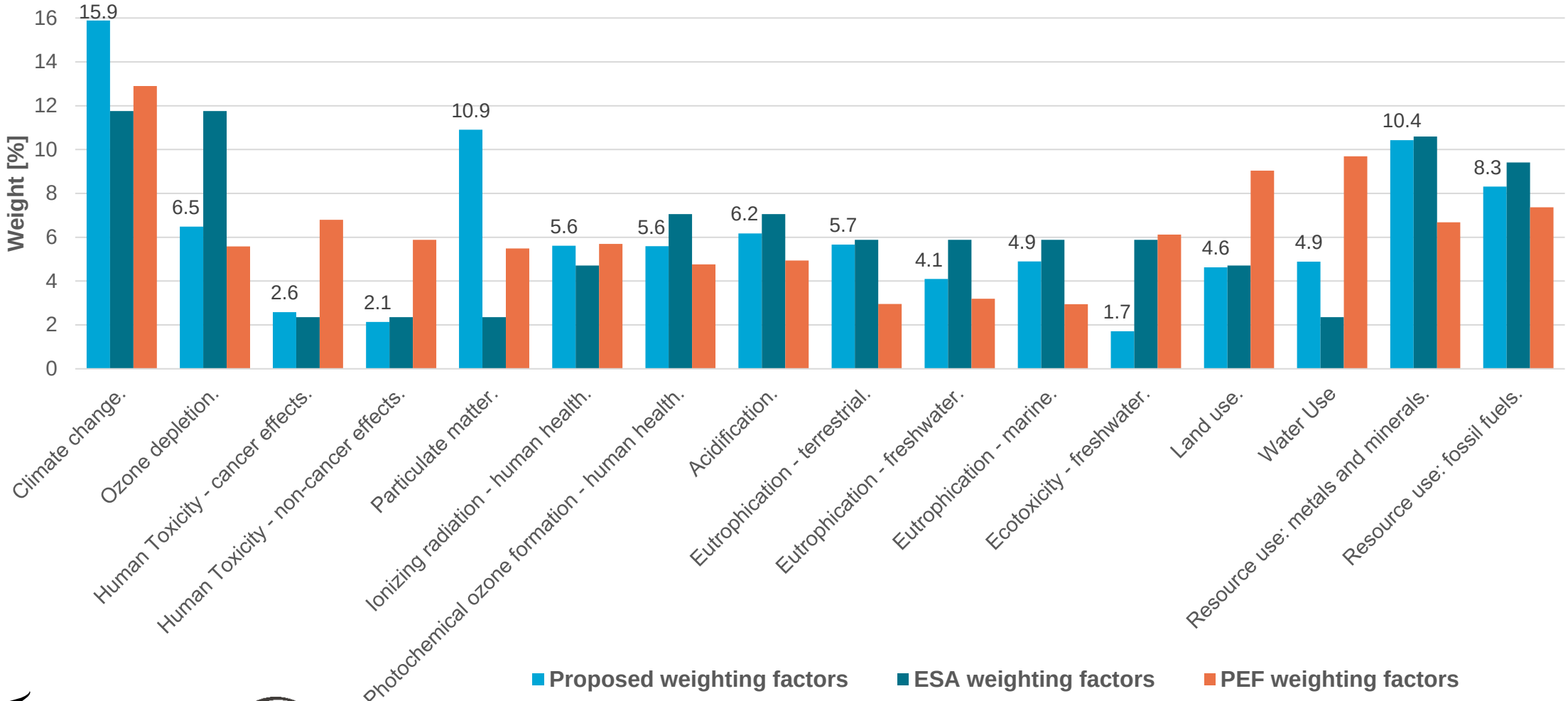
Source for robustness factors: S. Sala, et al., "*Development of a weighting approach for the Environmental Footprint*," Publications Office of the European Union: Luxembourg, 2018

Proposed weighting factors (excl. Launch Segment)



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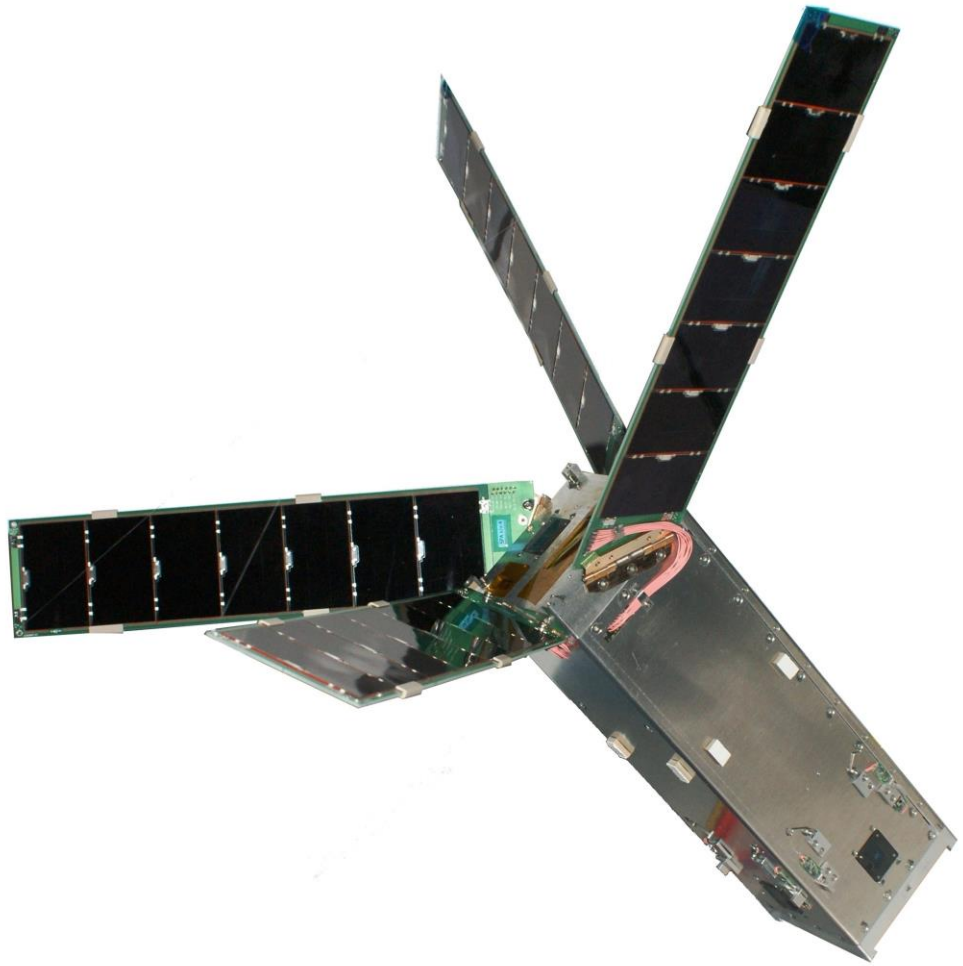
Source for ESA's weighting factors: E. Tormena, "*Internship ESA Clean Space - Final Report,*" ISAE-SUPAERO, 2022
Source for PEF's weighting factors: S. Sala, et al., "*Development of a weighting approach for the Environmental Footprint*," Publications Office of the European Union: Luxembourg, 2018

Delfi-n3Xt : TU Delft's second Cubesat

Key characteristics

- 3U-Cubesat (100x100x300mm)
- Mass: 3kg
- Launch date: 2013
- Operational for 2 months
- Loss of contact until a brief revival in 2021



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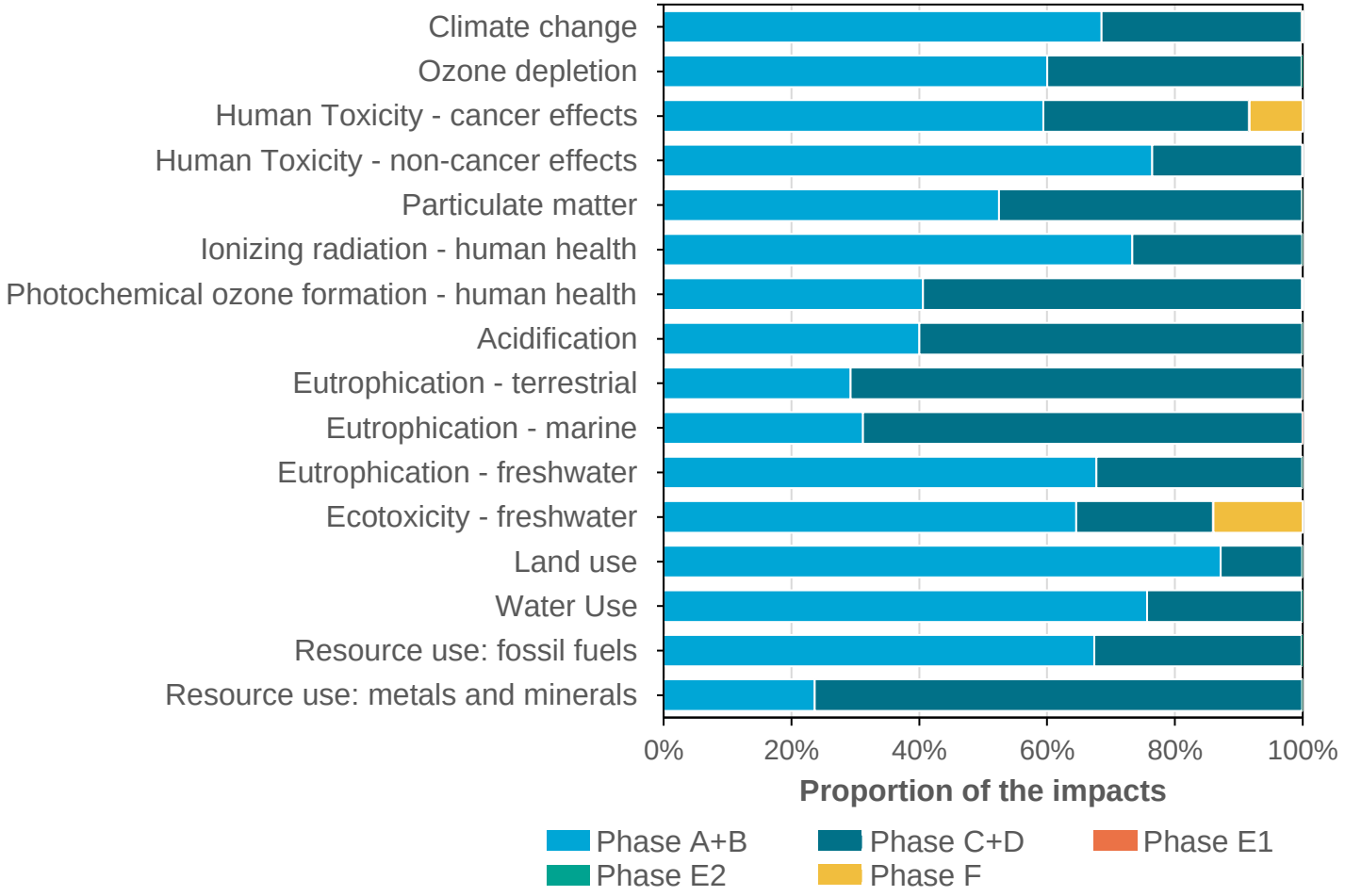
Source:

- Delft University of Technology. "Delfi Program," [Online]. Available: https://www.tudelft.nl/en/ae/delfi-space/delfi-program (visited on August 9, 2023).
- Delft University of Technology. "Delfi-n3Xt back to life after 7 years of silence," [Online]. Available: https://www.tudelft.nl/en/2021/lr/delfi-n3xt-back-to-life-after-7-years-of-silence (visited on August 11, 2023).
- J. Guo, J. Bouwmeester, and E. Gill, "In-orbit results of Delfi-n3Xt: Lessons learned and move forward," Acta Astronautica, vol. 121, pp. 39–50, 2016. doi: 10.1016/j.actaastro.2015.12.003.

LCA results of Delfi-n3Xt



1. **Normalisation** through the Environmental Footprint (EF) per person globally
2. Application of the **recommended weighting factors**

Weighting factors used	Single-score
Recommended ones	**14.30**
ESA's	20.17
PEF's	16.00

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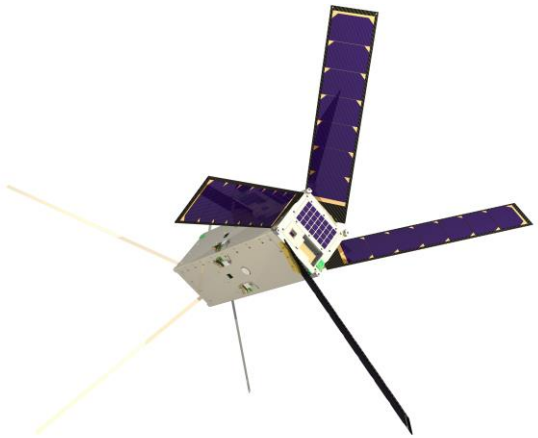
Source for the Environmental Foortprint (EF) normalisation factors: S. Sala, et al, "*Global normalisation factors for the Environmental Footprint and Life Cycle Assessment*," Publications Office of the European Union: Luxembourg, 2017. doi: 10.2760/88930
Source for ESA's weighting factors: E. Tormena, "*Internship ESA Clean Space - Final Report,*" ISAE-SUPAERO, 2022
Source for PEF's weighting factors: S. Sala, et al., "*Development of a weighting approach for the Environmental Footprint*," Publications Office of the European Union: Luxembourg, 2018

Use of single-score in Ecodesign



- Changing Li-ion battery into hypothetical NiMH battery
- Keeping the same masses (due to time constraints)

Old single score	New single-score
14.30	15.97

- The **new score is "worse"** (i.e. higher) than the old one.
- NiMH is therefore a "worse" design decision
- Coincidently, it was not chosen (but for different reasons)

The single-score could have been useful during the design.

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Future Work & Conclusion

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Future Work

Refining the survey:

- More participants to define drivers & inhibitors of LCA
- Assess the impact of normalisation methods
- Confirm preference of the way of showing LCA results

LCA datasets

- Space-specific datasets need more work (e.g. Re-Entry, Clean Room usage)
- More customisation needed in ESA External Database (e.g. electronic unit, etc)

Single-score:

- Need for more single-score LCA studies of missions
- Need for meta-study of single-score weighting factors

LCA in early-design:

- Work needed on the uncertainties of space LCA
- Embedding LCA in system engineering tools
- Including LCA experts in Concurrent Design studies.

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New steps into a more open discussion on the creation of a single-score space LCA.

More work needs to be done.

References for more detail

MSc Thesis

M. Verkammen, "*A Consensus-Based Single-Score for Life Cycle Assessment of Space Missions: Preliminary Results*," Delft University of Technology, Master's thesis, 2023. url: http://resolver.tudelft.nl/uuid:fe91662b-6885-41d4-85ee-3f303febded5.

Supporting Dataset

M. Verkammen, Data for MSc Thesis: "*Consensus-based single-score life cycle assessment for space missions*," English, Dataset, Delft University of Technology, 4TU.ResearchData, 2023. doi: 10.4121/3d497ca7-876c-4b77-b835-142cbbff1e14.

Preliminary results (Proceeding of the 10th EUCASS Conference):

M. Verkammen, "*A Consensus-Based Single-Score for Life Cycle Assessment of Space Missions: Preliminary Results*," in Aerospace Europe Conference 2023 - 10th EUCASS - 9th CEAS, 2023. doi: 10.13009/EUCASS2023-571.

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Thank you for your attention

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Appendix

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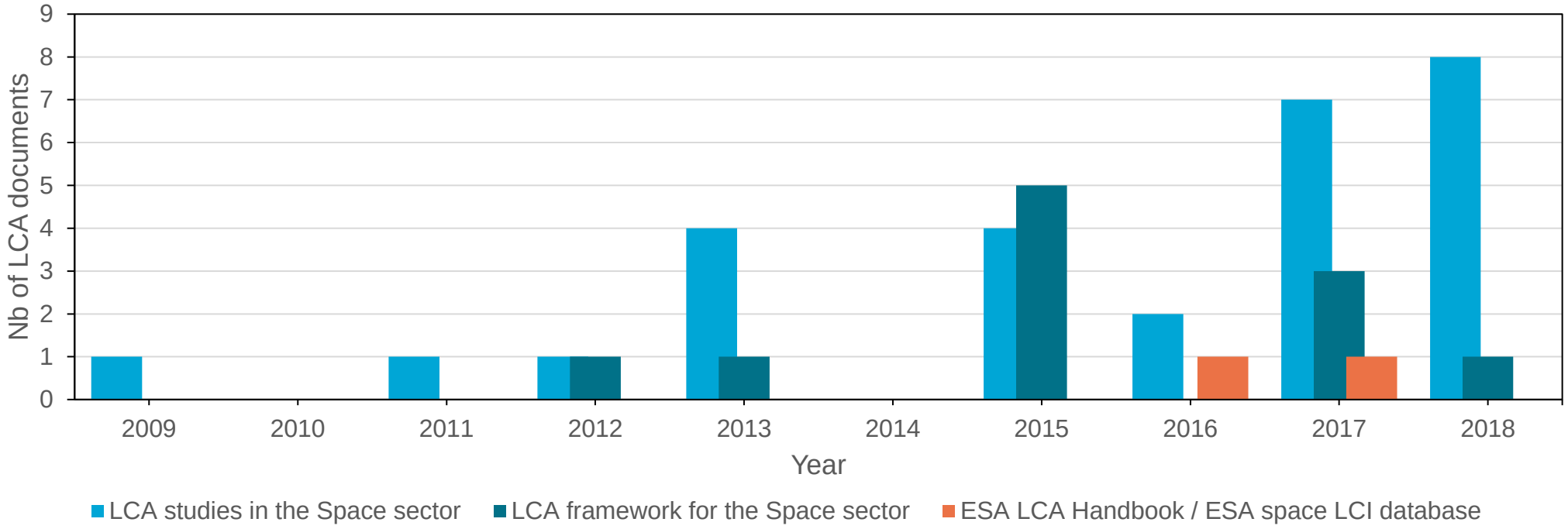
Increase in the use of LCA

- Growing international interest
- The space sector sees more use of LCA
- Europe is leading, with developments around the world



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Modified from: T. Maury et al, "*Application of environmental life cycle assessment (LCA) within the space sector: A state of the art*", 2019, DOI: 10.1016/j.actaastro.2020.01.035

Goal of the survey

Understand which aspects of sustainability are the most critical according to the space sector as a whole

Get the industry's opinion on **which impact categories** of a LCA are **important** per **mission type**

Obtain a **preliminary consensus** on the weights for a **single-score**

Understand the **main reasons** to do, or not to do, a space LCA

Get opinion on **SSR's rating system** with a **LCA module**

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Survey Structure & DELPHI Method

Questionnaire 1:

- Individual Background
  - General field of expertise
  - Experience in Sustainability
  - Experience with LCA
- Identifying **highest environmental impacts**
  - Between life-cycle phases
  - Between Segments
  - Between midpoint indicators
  - Between endpoint indicators

Feedback

Questionnaire 2:

- General Information:
  - **Drivers** and **inhibitors** in doing LCA
- More detailed **ranking of impact categories**
- Additional questions, based on feedback

Feedback

Questionnaire 3:

- General information:
  - Implementation of LCA in the **Space Sustainability Rating modules**
- Final **rating of the impact categories.**
- Additional questions, based on feedback

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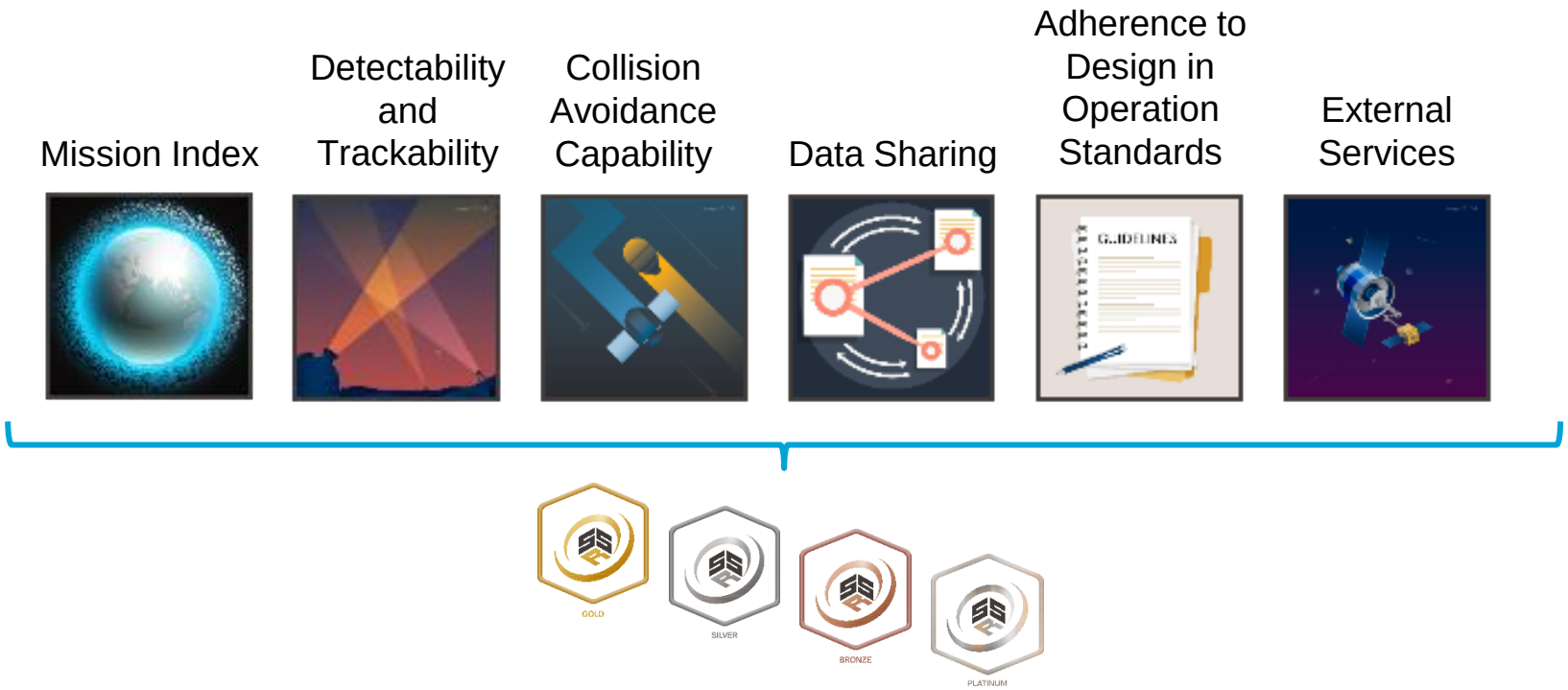
Sustainability rating: Space Sustainability Rating



Images taken from: https://spacesustainabilityrating.org/

Sustainability rating: Space Sustainability Rating

Mission Index

Detectability and Trackability

Collision Avoidance Capability

Data Sharing

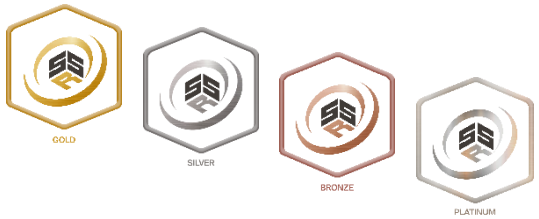
Adherence to Design in Operation Standards

External Services

LCA Module

Launch Vehicle Sust. Rating

Dark & Quiet Skies



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Images taken from: https://spacesustainabilityrating.org/

Origin of highest impact according to survey participants

Launch Segment

Arguments for Launch segment:

- Mass of launcher vs payload
- Manufacturing of launcher and propellant
- Emissions in the higher atmosphere

Phases C+D and E1

Arguments for C+D:

- Length of design phase
- Manufacturing of space-specific material/propellant

Argument for E1:

- Emissions during launch

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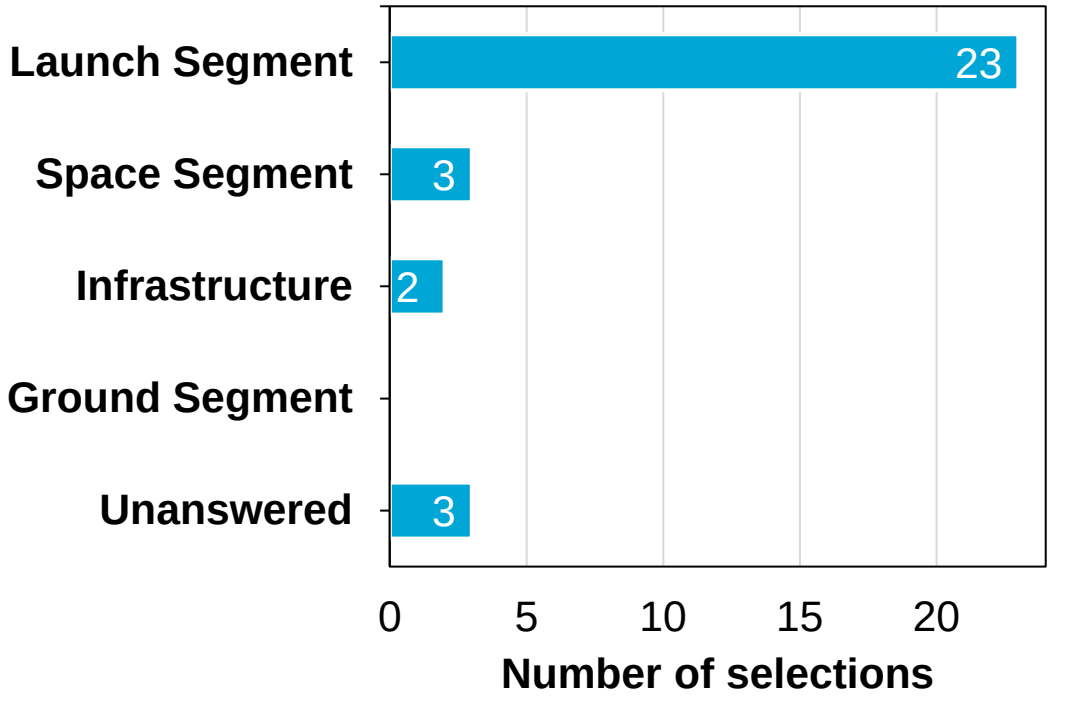
Segment of highest impact according to survey participants



n=29 answers

Arguments for Launch segment:

- Mass of launcher vs payload
- Manufacturing of launcher and propellant
- Emissions in the higher atmosphere

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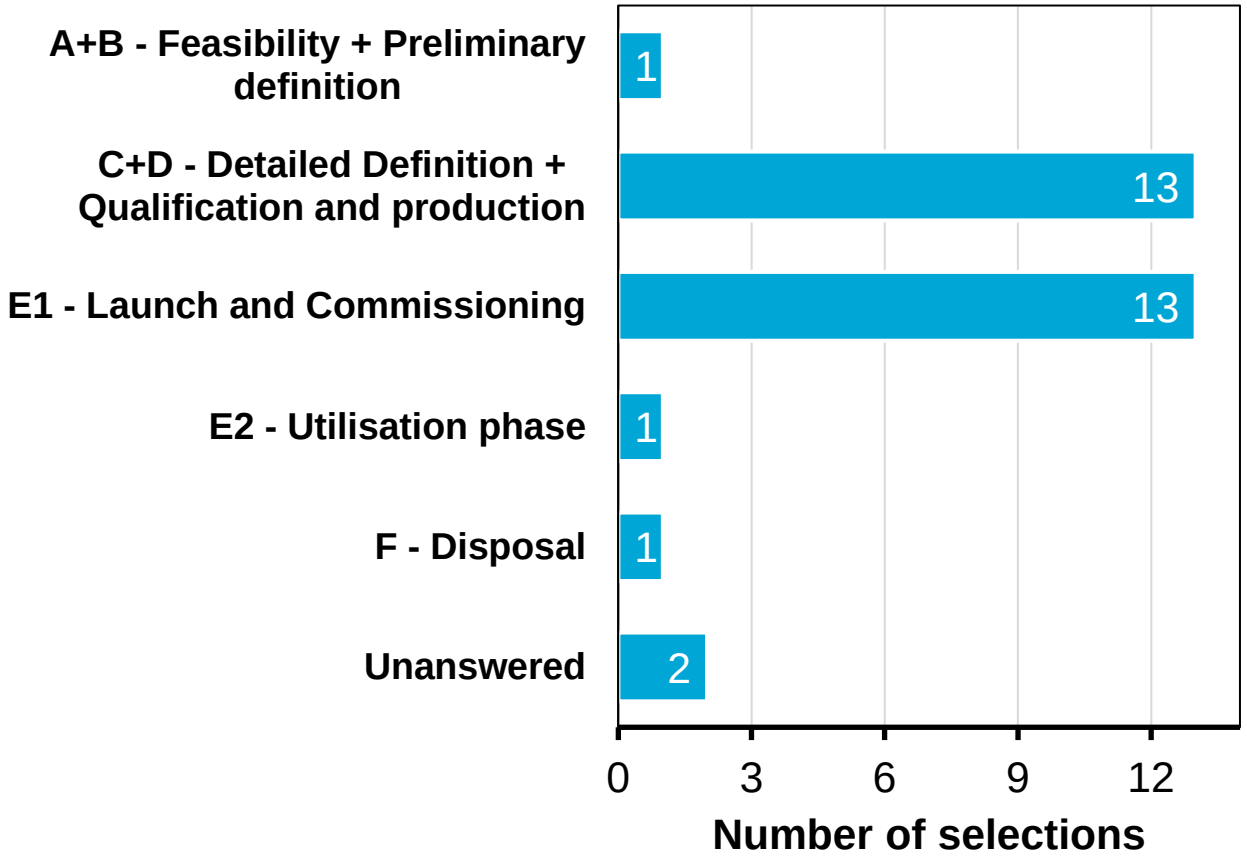
Phase of highest impact according to survey participants



n=29 answers

Arguments for C+D:

- Length of design phase
- Manufacturing of space-specific material/propellant

Argument for E1:

- Emissions during launch

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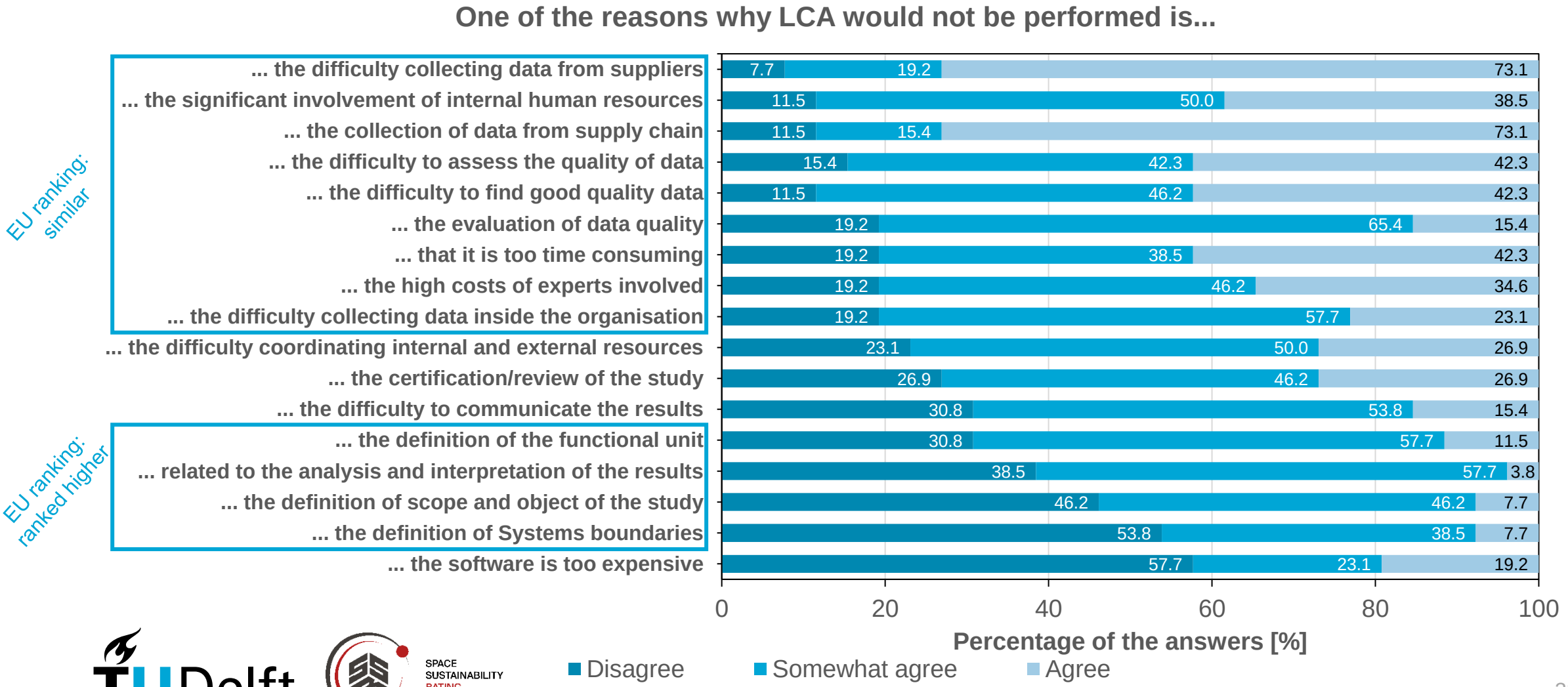
Inhibitors of space LCA



Source for the general EU industry ranking: F. Lupiáñez-Villanueva, P. Tornese, G. A. Veltri, and G. Gaskell, "Assessment of different communication vehicles for providing Environmental Footprint information, Final report," European Commission. Directorate General Environment., Directorate A-Green Economy, Env. A, 2018. [Online]. Available: https://www.oneplanetnetwork.org/sites/default/files/from-crm/2018_pilotphase_commreport.pdf (visited on Jul. 10, 2023).

Weight of midpoint indicators (before robustness factors)

Midpoint impact indicator	**PEF weights before robustness**	Questionnaire 1: **Generic mission** (n=31 answers)		Questionnaire 2: **Single satellite** (n=26 answers)		Questionnaire 2: **Constellation** (n=17 answers)		Questionnaire 3: **Single satellite**, impacts/mass of sat (n=21 anwers)		Questionnaire 3: **Constellation**, impacts/mass of sat (n=11 answers)		Questionnaire 3: **Generic mission**, impacts/mass of sat, **No Launch Segment** (n=16 answers)	
		Avg Score	Computed Weight [%]	Avg Score	Computed Weight [%]	Avg Score	Computed Weight [%]	Avg Score	Computed Weight [%]	Avg Score	Computed Weight [%]	Avg Score	Computed Weight [%]
Climate change.	12.9	95.6	9.3	87.4	8.29	91.1	8.28	95.3	6.33	92	6.06	81.6	5.94
Ozone depletion.	5.58	89.6	8.72	87.2	8.27	90.9	8.27	90.3	6	87.2	5.75	48.3	3.51
Human Toxicity - cancer effects.	6.8	65.7	6.39	65.2	6.18	52.6	4.78	65.7	4.37	58.3	3.84	67.9	4.94
Human Toxicity - non-cancer effects.	5.88	60.4	5.88	56.5	5.36	49.9	4.54	57.3	3.81	44.2	2.91	56.2	4.09
Particulate matter.	5.49	63.9	6.22	63.5	6.02	63.8	5.8	67.6	4.49	63	4.15	56	4.07
Ionizing radiation - human health.	5.7	58.3	5.67	53.7	5.09	60.4	5.49	55.7	3.7	52.8	3.48	53.4	3.88
Photochemical ozone formation - human health.	4.76	53.7	5.23	45.8	4.34	53.4	4.86	54.4	3.62	43.5	2.87	47.1	3.43
Acidification.	4.94	55.1	5.36	46.1	4.37	50.1	4.56	44.3	2.94	36.5	2.41	41.2	3
Eutrophication - terrestrial.	2.95	48.2	4.69	42.7	4.05	44.5	4.05	38	2.53	33.3	2.19	37.8	2.75
Eutrophication - freshwater.	3.19	49.5	4.82	41.5	3.94	43.9	3.99	38.5	2.56	32.9	2.17	38.9	2.83
Eutrophication - marine.	2.94	48.9	4.76	40.2	3.81	44.1	4.01	37.6	2.5	36.5	2.41	41.3	3
Ecotoxicity - freshwater.	6.12	61.8	6.01	50.4	4.78	47.9	4.36	44.5	2.96	39.5	2.6	44.9	3.27
Land use.	9.04	55.8	5.43	53.1	5.04	48.6	4.42	45.5	3.02	47.1	3.1	44	3.2
Water Use	9.69	60.1	5.85	NA	NA	NA	NA	58.1	3.86	64	4.22	46.4	3.38
Resource use: metals and minerals.	6.68	82.7	8.05	84.3	8	92.4	8.4	83	5.52	87.5	5.77	77.7	5.65
Resource use: fossil fuels.	7.37	78.2	7.61	80.4	7.63	83.6	7.6	75.8	5.04	72.6	4.78	61.9	4.5
Mass left in space	NA	NA	NA	79.8	7.57	96.9	8.81	73.7	4.9	99.1	6.53	79	5.75
Al2O3 emissions in air	NA	NA	NA	76.6	7.26	85.5	7.78	84	5.58	91.9	6.06	44.8	3.26
Orbital resource depletion	NA	NA	NA	NA	NA	NA	NA	77.9	5.18	97	6.39	79.6	5.79
Critical raw material use	NA	NA	NA	NA	NA	NA	NA	69.7	4.63	75.6	4.98	69.1	5.03
Re-entry smoke particle generation	NA	NA	NA	NA	NA	NA	NA	61.1	4.06	66	4.35	67.9	4.94
Cumulative energy demand	NA	NA	NA	NA	NA	NA	NA	66.1	4.39	66.8	4.4	63	4.58
Total mass disposed in ocean	NA	NA	NA	NA	NA	NA	NA	54.5	3.62	56.5	3.72	55.9	4.07
Restricted substance use	NA	NA	NA	NA	NA	NA	NA	66.2	4.4	73.5	4.84	70.9	5.16

SSR Module

	SSR's Weights	Jury's weight of current modules excluding External Services (n=18 answers)	Jury's weight of current modules including External Services (n=18 answers)	Jury's weight with future modules (n=16 answers)
Mission Index	50	22.9	20	12
Detectability, Identification, and Trackability (DIT)	16.5	18.7	16.4	9.3
COLision Avoidance Capabilities (COLA)	16.5	19.7	17.2	10.7
Data Sharing	12	18.6	16.2	8.5
Application of Design and Operation Standards (ADOS)	5	20.1	17.5	10.6
External Services	Bonus	Bonus	12.7	7.1
LCA Module	NA	NA	NA	12.2
Launch Vehicle Sustainability Rating Module	NA	NA	NA	10.6
Dark Skies Module	NA	NA	NA	9.6
Quite Skies Module	NA	NA	NA	9.5

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Calculation of the single-score weighting factors

Midpoint impact indicator	Aggregated Weighting Set (A)	Robustness factor (B)	Intermediate Coefficients C=A*B	Final weighting factors (incl. robustness) C scaled to 100
Climate change.	9.66	0.87	8.41	**15.89**
Ozone depletion.	5.72	0.60	3.43	**6.49**
Human Toxicity - cancer effects.	8.04	0.17	1.37	**2.58**
Human Toxicity - non-cancer effects.	6.65	0.17	1.13	**2.14**
Particulate matter.	6.63	0.87	5.77	**10.90**
Ionizing radiation - human health.	6.32	0.47	2.97	**5.62**
Photochemical ozone formation - human health.	5.58	0.53	2.96	**5.59**
Acidification.	4.88	0.67	3.27	**6.18**
Eutrophication - terrestrial.	4.48	0.67	3.00	**5.67**
Eutrophication - freshwater.	4.61	0.47	2.16	**4.09**
Eutrophication - marine.	4.89	0.53	2.59	**4.90**
Ecotoxicity - freshwater.	5.32	0.17	0.90	**1.71**
Land use.	5.21	0.47	2.45	**4.63**
Water Use	5.49	0.47	2.58	**4.88**
Resource use: metals and minerals.	9.20	0.60	5.52	**10.43**
Resource use: fossil fuels.	7.33	0.60	4.40	**8.31**

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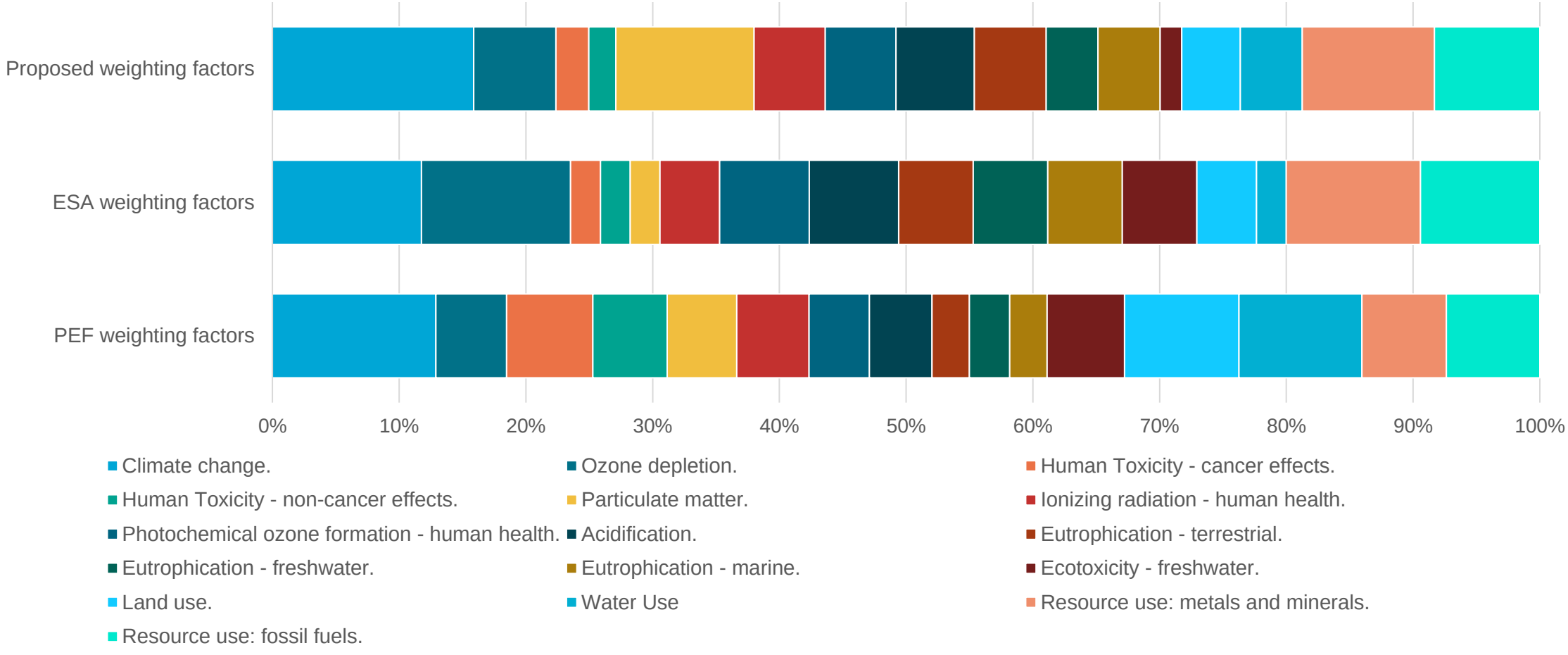
Proposed weighting factors



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SPACE SUSTAINABILITY RATING

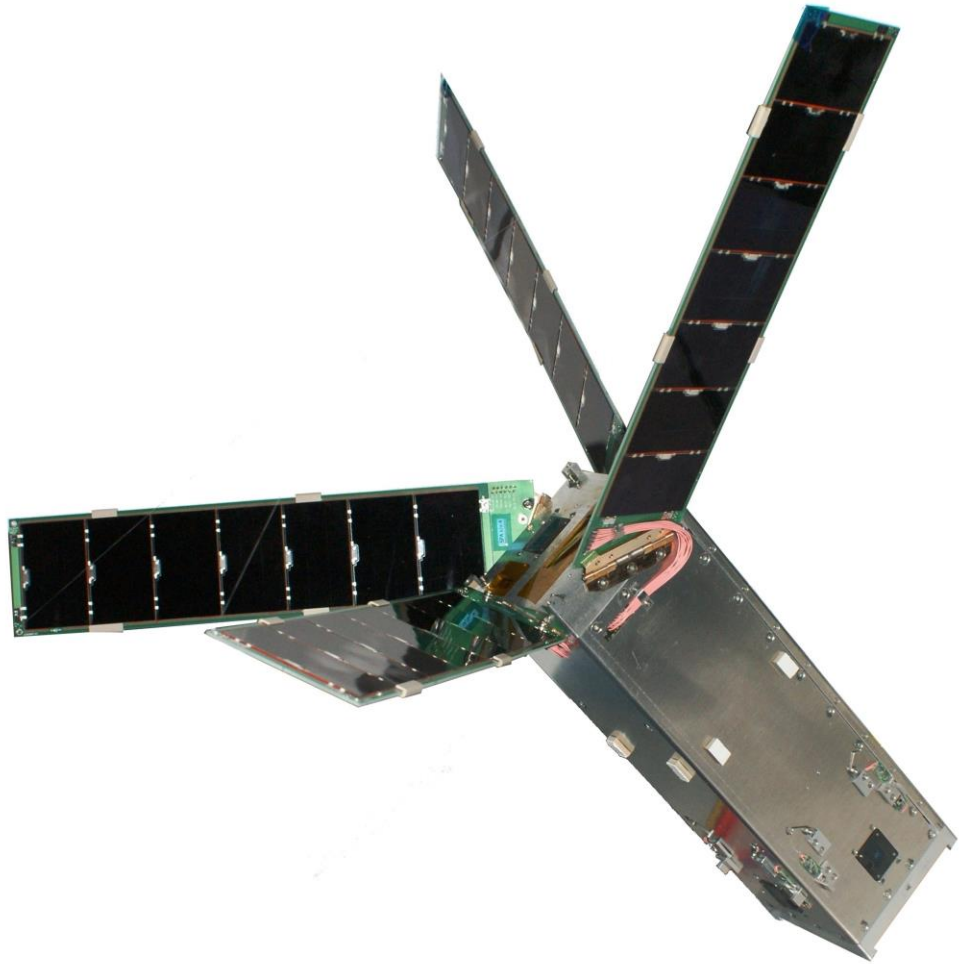
Delfi-n3Xt : TU Delft's second Cubesat

Key characteristics

- 3U-Cubesat (100x100x300mm)
- Mass: 3kg
- Launch date: 2013
- Operational for 2 months
- Loss of contact until a brief revival in 2021

Chosen for similarities to general cubesats

- ADCS (for demonstration)
- Micropropulsion (for demonstration)
- Battery



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