Space Sustainability
A Complex Systems Perspective

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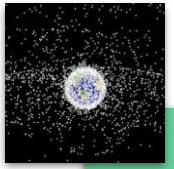
Three Pillars of Space Sustainability

Wilson, R. A. and Vasile, M. *The Space Sustainability Paradox*, Journal of Cleaner Production, 2023, Volume 423, 15 October 2023, 138869, https://doi.org/10.1016/j.jclepro.2023.138869

Sustainability from Space

Space for Sustainable Development

- EO data for climate monitoring
- EO data for urban development
- EO data for fair trade
- EO data for equity and justice
- Energy from space



Sustainability in Space

Sustainable use of Space

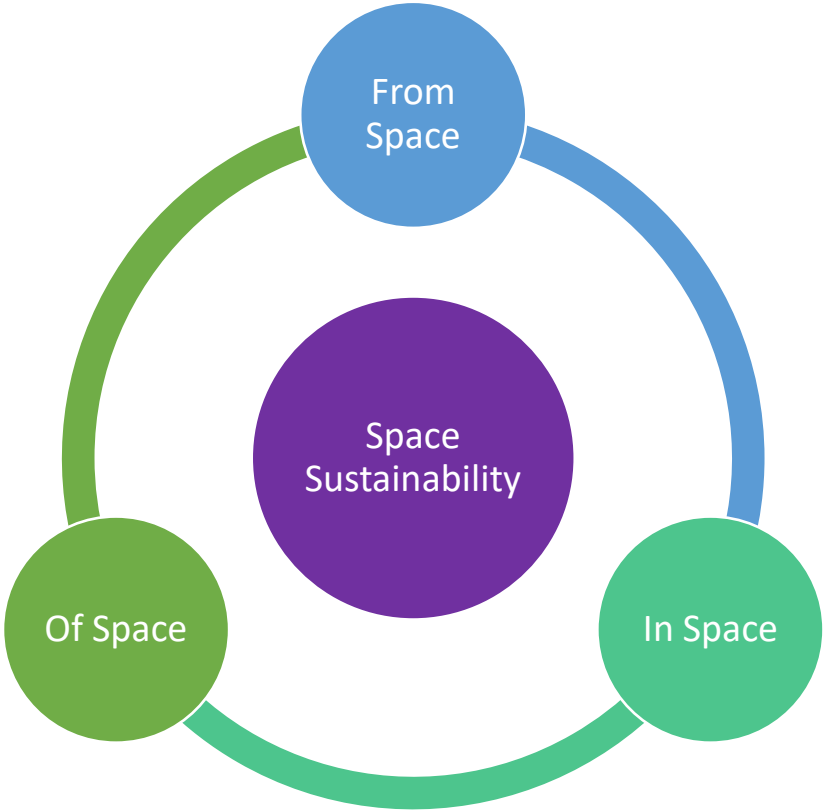
- Space safety
- Space environment management
- In orbit servicing
- In orbit manufacturing
- In orbit recycling
- Sustainable use of space resources
- Re-entry and demise
- Regulatory and legal aspects

Sustainability of Space

Sustainable Space Sector

- Life Cycle Engineering
- Eco-design
- Environmental impact of manufacturing, launch, disposal
- Environmental impact of data processing and exploitation
- Sustainable use of Earth resources
- Supply chain sustainability
- Socio-economic impact

Complex Dynamic Interaction



- The three pillars are tightly connected
- Dynamic relationship between each of the elements of space sustainability
- An integrated approach is required

What do we do about it?

- Space sustainability roadmap
- Satellite data for sustainable development
- Support the UK delegation to the Inter Agency Debris Coordination committee (IADC)
- **SOLERO** – space environment impact of large infrastructures
- **PERSEO** – long term sustainability of space activities
- **U-Life** – Eco-design of space systems

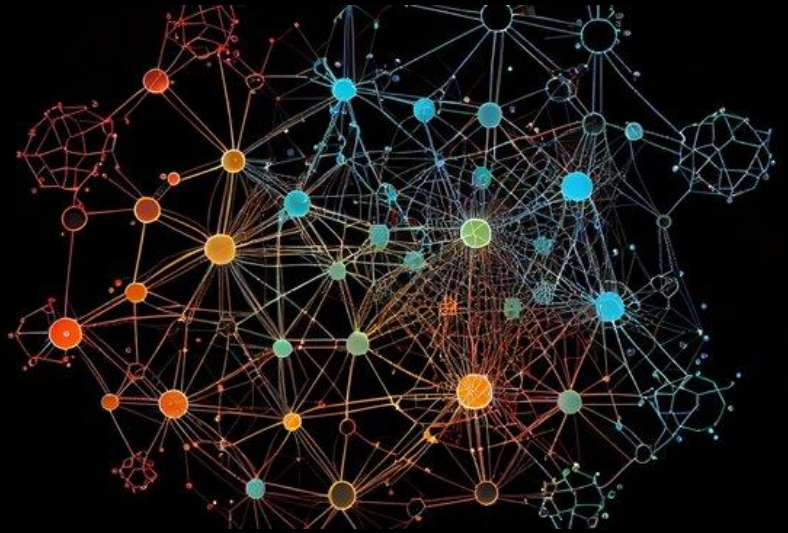
Project - PERSEO

Wang, Y., De Marchi, P., Vasile, M. A Stochastic Dynamic Network Model of the Space Environment, Advances in Space Research, 2025.
https://doi.org/10.1016/j.asr.2025.08.051

From Physical Space to Network Abstraction

Physical space

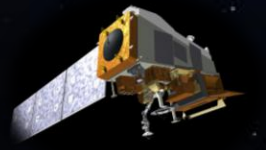
Equivalent network



Defunct Objects

Different species

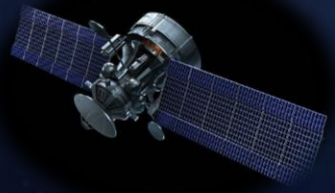
Rocket Bodies



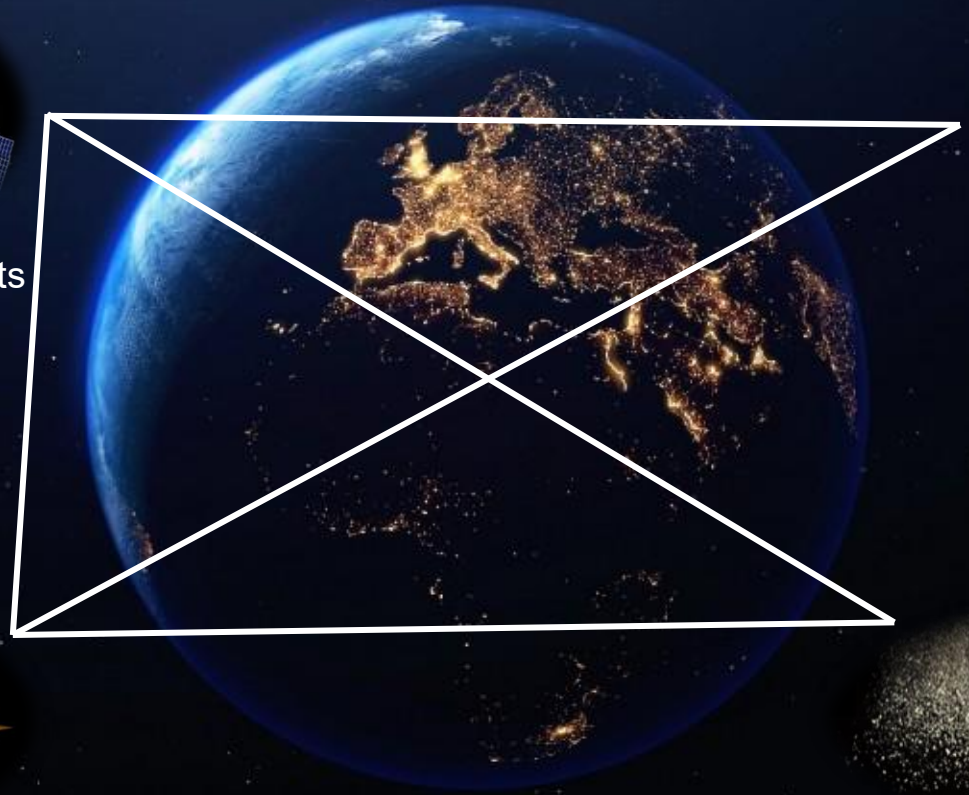
Satellite Constellations

Debris clouds

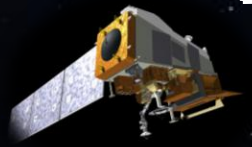
How are they connected and related?



Defunct Objects



Rocket Bodies

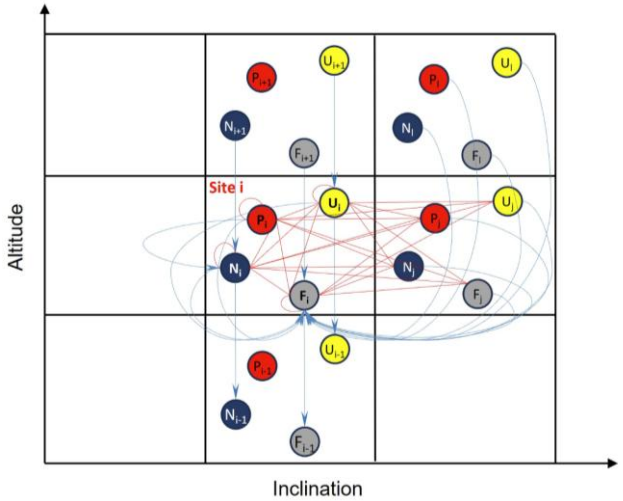


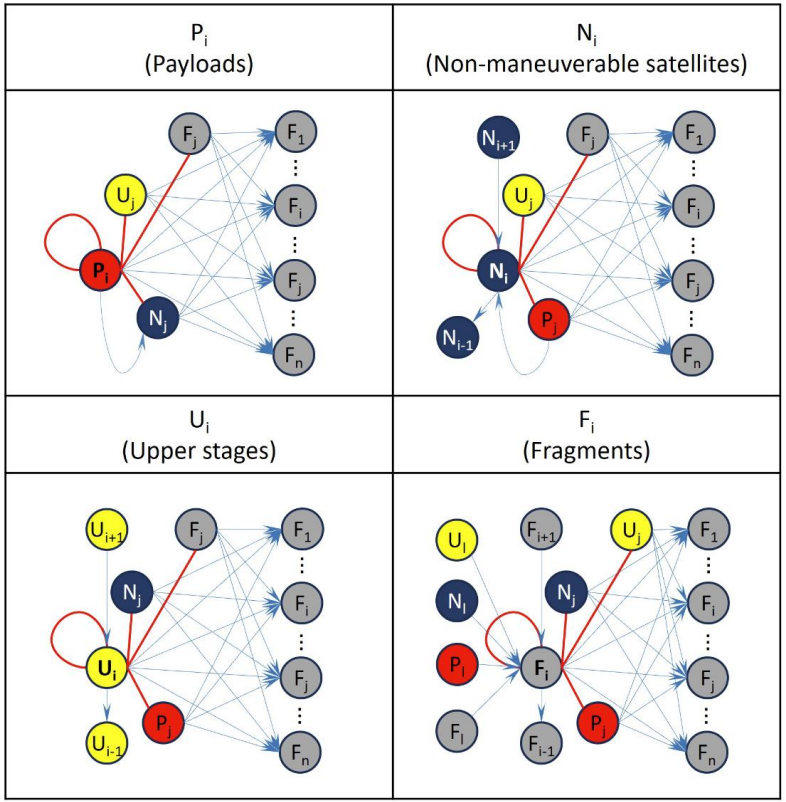
Satellite Constellations

Debris clouds

Network model for Space Sustainability (NESSY)

- Divide space environment in **orbit sites**.
- Define **nodes representing species of objects**
- **One mode can be an object or a group of objects.**
- Define **relationships among objects and sites**



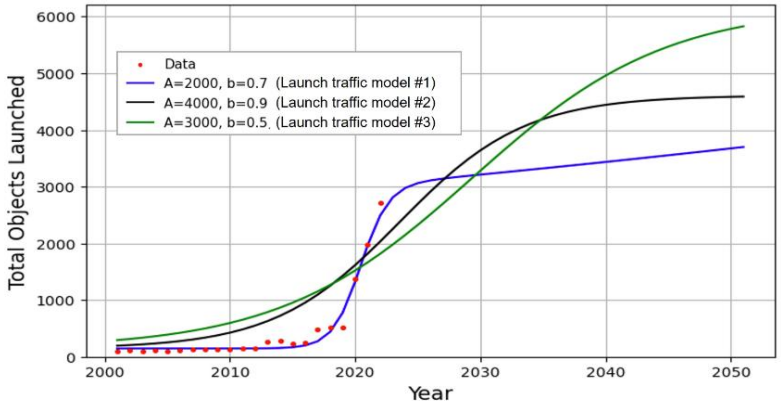


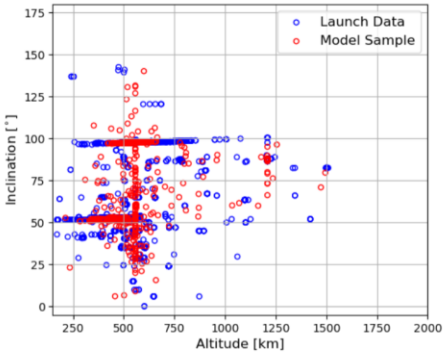
A Network Model of the Space Environment

Wilson, C. J., Vasile, M., Feng, J., McNally, K., Antón, A., & Letizia, F. (2024). Modelling future launch traffic and its effect on the LEO operational environment. In *AIAA SciTech 2024 Forum* https://doi.org/10.2514/6.2024-1814

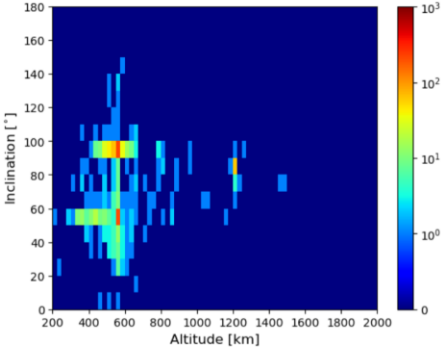
Launch traffic model

- The total number of objects launched in a certain year is given by an exponential logistic curve
- Fit to historical orbital and physical parameters distirbution





(a) Historical launch data and GMM sample.



(b) Number of objects added to example nodes.

Testing the Effect of Collision Avoidance Manoeuvres

Evolution of each species – mean over 200 runs

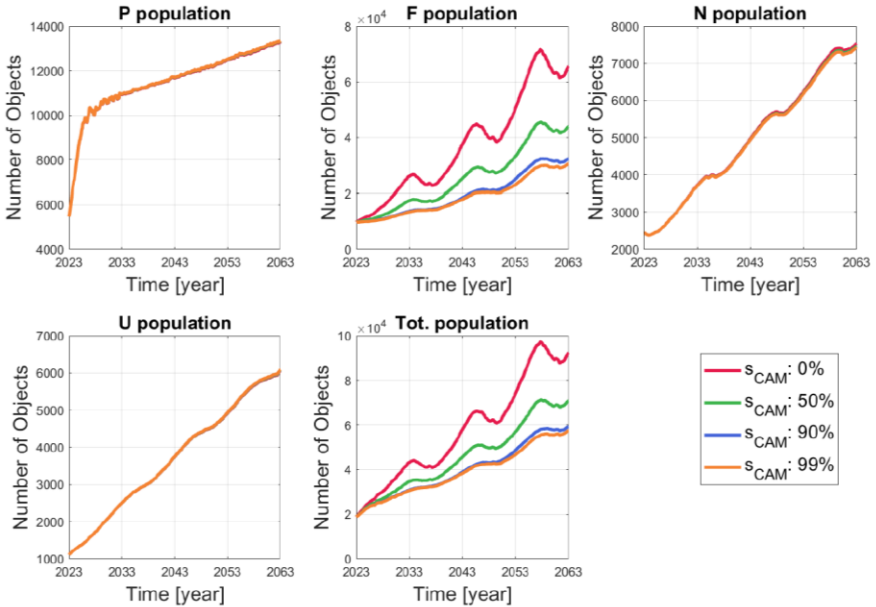


Fig. 16: Evolution of the environment based on different s_{CAM}.

Cumulative number of collisions

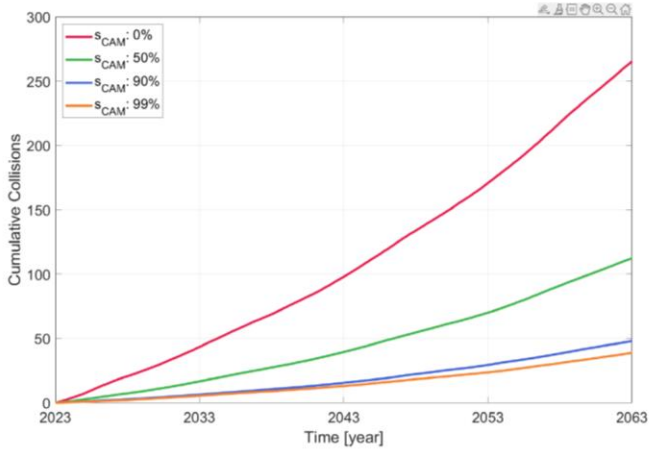


Fig. 17: Cumulative number of catastrophic collisions based on different s_{CAM}

Testing the Effect of Post Mission Disposal Manoeuvres

Evolution of each species – mean over 200 runs

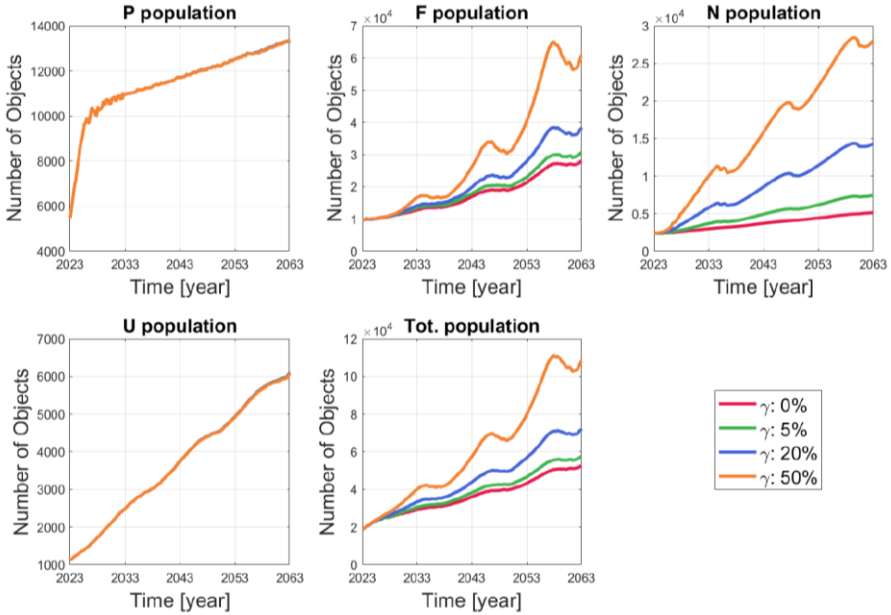


Fig. 18: Evolution of the environment based on different γ.

Cumulative number of collisions

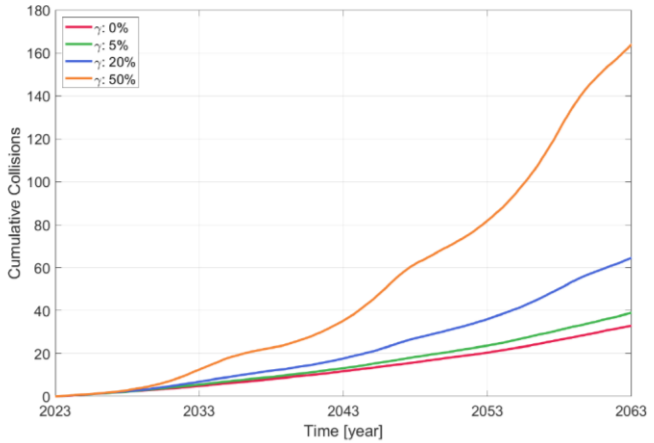


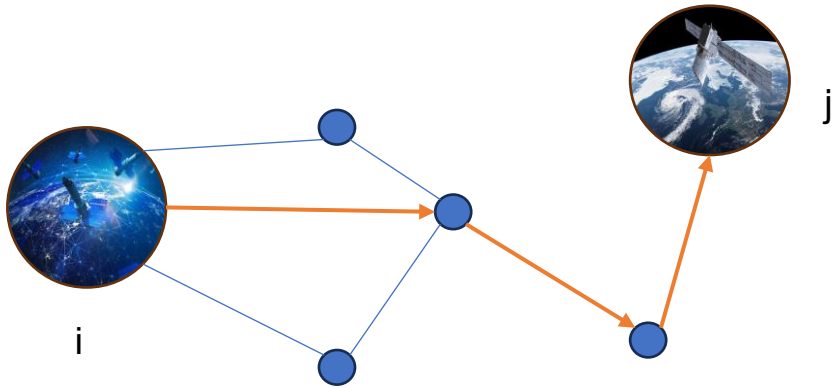
Fig. 19: Cumulative number of catastrophic collisions based on different γ.

What is the Global Impact of Space Activities?

Seen from the point of view of a complex network the questions is:

- How much launching a constellation in a given region of space affects the rest of the space environment?
- How much the design of the satellites affects the Earth and space environments?

α^n - Spatial connectivity – how much *i* affects *j*

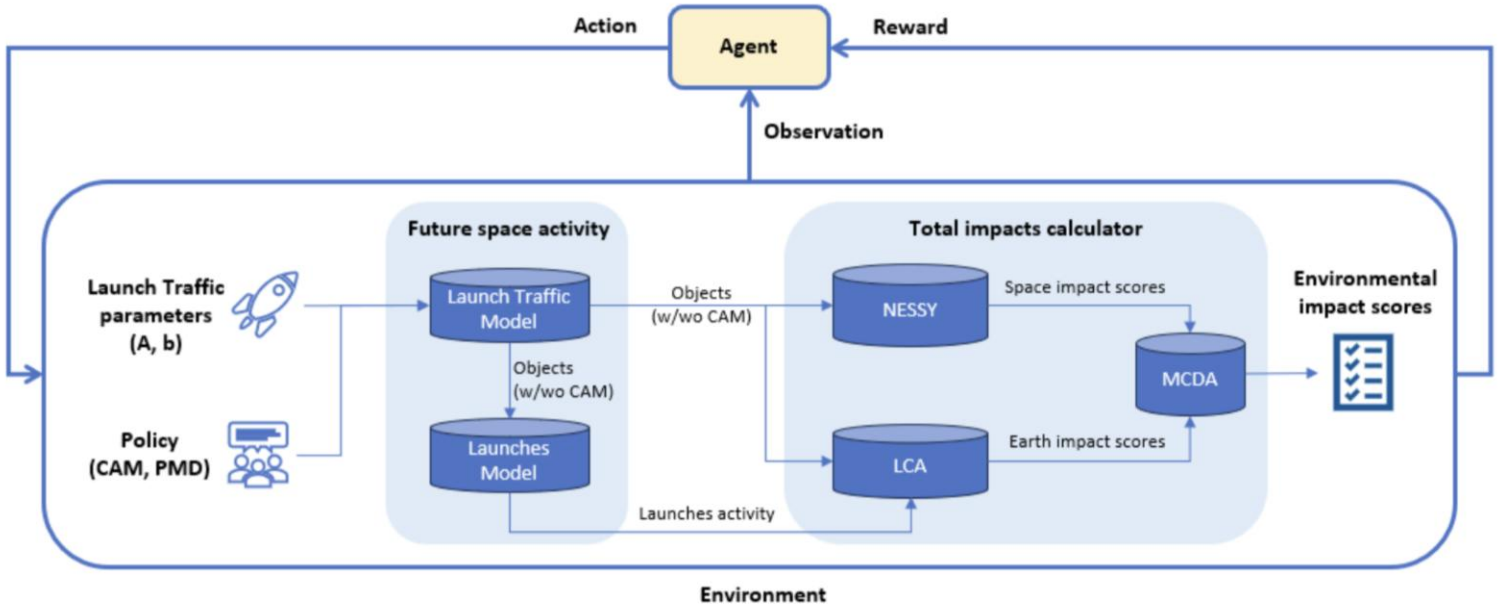


Project - ULife

Closing the Loop with LCSA

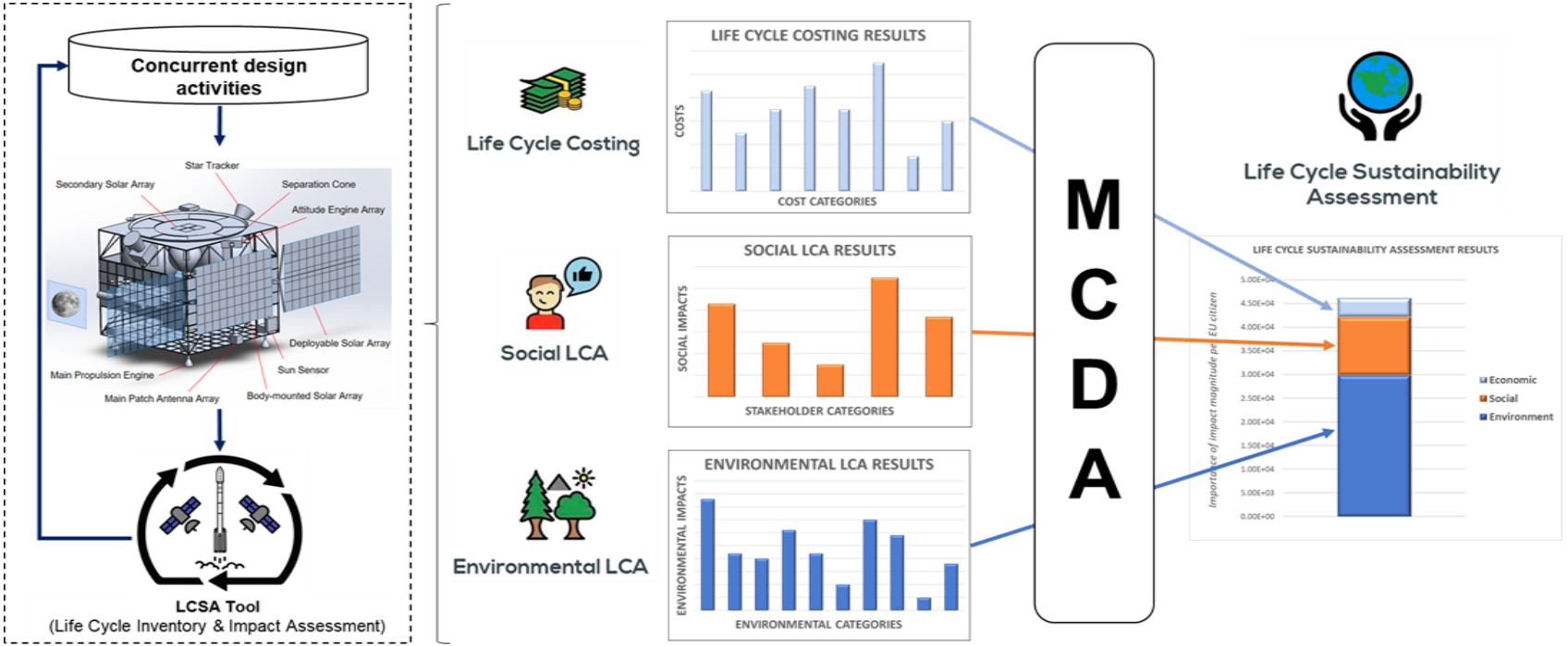
Yirui Wang, Andrew Ross Wilson, Callum Wilson, Massimiliano Vasile. Closing the Loop Between Space Capacity and Life Cycle Assessment: A Network-Theoretic Approach, 75th International Astronautical Congress (IAC), Milan, Italy.
https://www.researchgate.net/publication/384457703_Closing_the_Loop_Between_Space_Capacity_and_Life_Cycle_Assessment_a_Network-Theoretic_Approach

Dynamic Integration of NESSY and LCSA



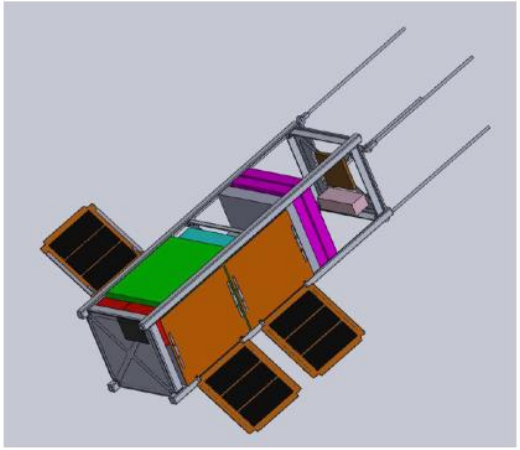
- NESSY sustainability indicators enter as impact categories in a comprehensive Life Cycle Sustainability Assessment
- LCSA uses a Multi-Criteria Decision Making Approach to aggregate Space, Earth and Socio-Economic Impacts

Life Cycle Sustainably Assessment



Constellation Configuration

- To demonstrate the approach, we investigate the environmental impacts of two constellation configurations.



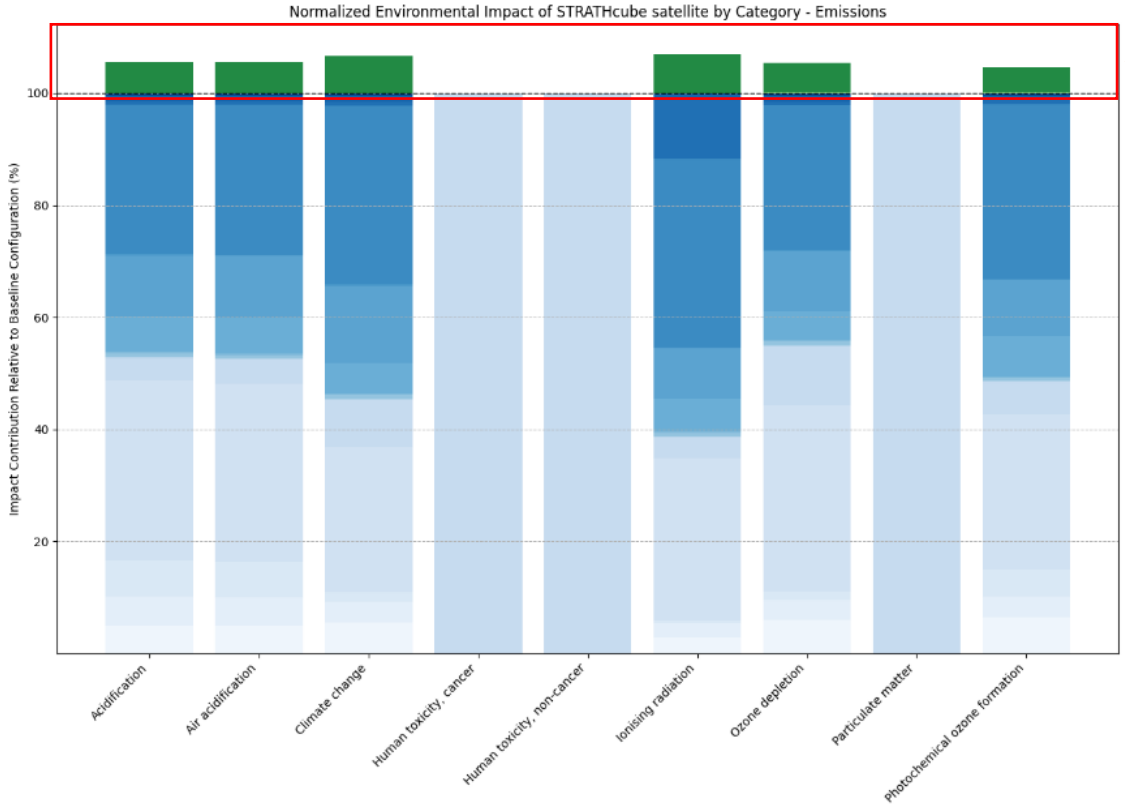
	Without CAM/PMD	With CAM/PMD
Altitude [km]	[600, 650]	
Inclination [deg]	[40, 60]	
STRATHcube number	1000	
mass [kg]	3.78	4.12
size [cm]	10	10
lifetime [years]	5	5
CAM success [%]	0	99.99
PMD failure [%]	100	5

- Two scenarios are considered:

Scenario 1: No further new launches after 2023

Scenario 2: Consider new launches after 2023

Mission impacts analysis based on LCA framework



Percentage increment in Earth environment impact due to the inclusion of CAM and PMD capabilities on each satellite.

The inclusion of CAM and PMD capabilities reduces the space environment impact by 56%.

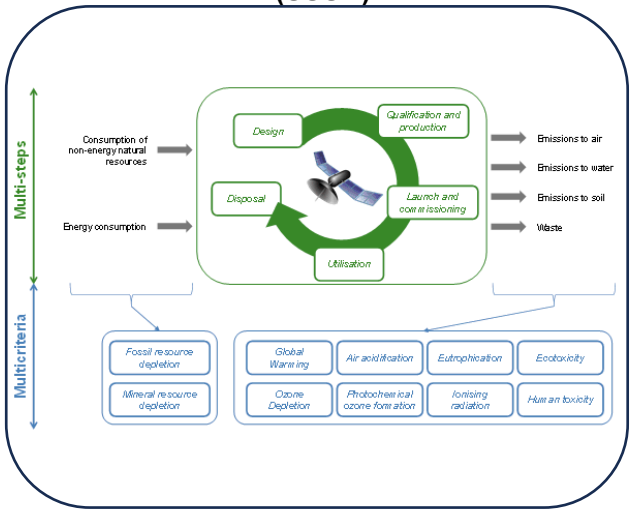
The inclusion of CAM and PMD reduces the risk of collision but increases the Earth environmental impact due to propellant and propulsion system.

No explosion risk is included in this analysis.

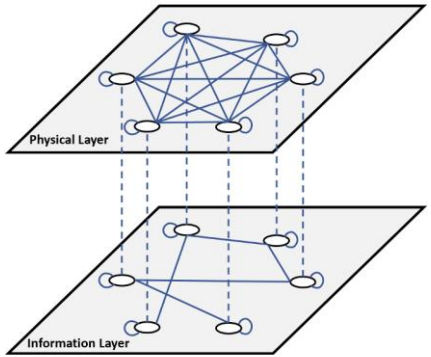
AI-powered Web-interface – Eco-Space Tools

- Allow the use of NESSY, MOCAT and LCSA tool in the same environment

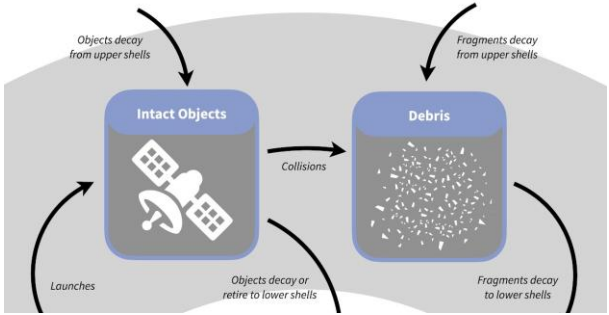
Strathclyde Space Systems Database (SSSD)



NEtwork model for Space SustainabilitY (NESSY)



MIT Orbital Capacity Assessment Tool (MOCAT)



AI Agents

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