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KTH ROYAL INSTITUTE OF TECHNOLOGY

Experiences from ESA Clean Space Training Course 2021

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A little bit about me – Greta Tartaglia

- From Italy, born in 1998
- BSc in Aerospace Engineering at Politecnico di Milano
- Currently enrolled at KTH, MSc in Aerospace Engineering, space track
- Involved in the student project MIST

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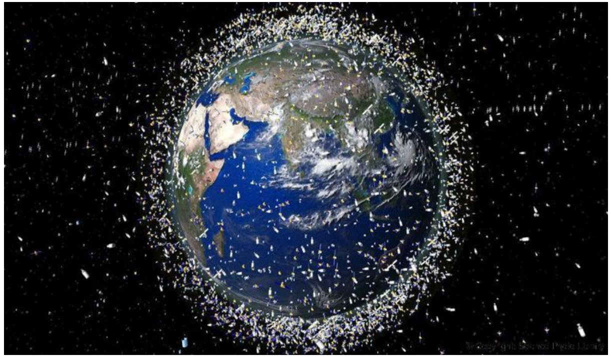
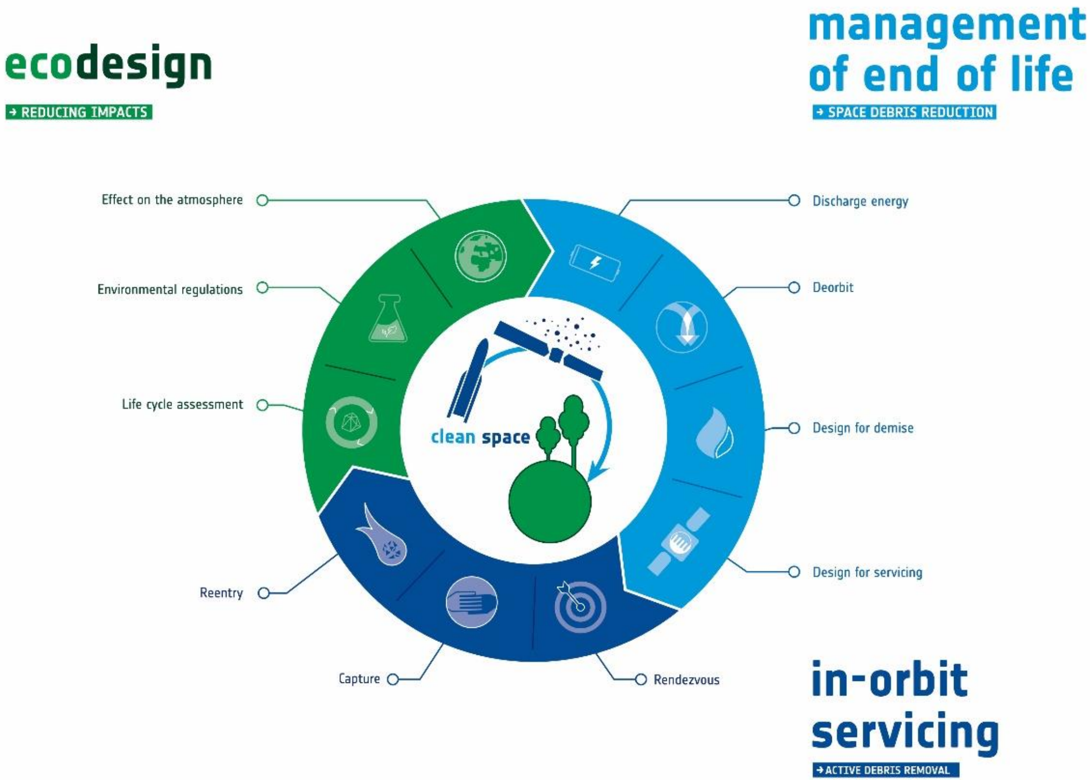
What is Clean Space?

- ESA initiative started in **2012** to analyse the environmental impacts of ESA activities both on Earth and in space
- Space industry has an important role in developing **sustainable energy technologies** and understand **climate change**
- Same moral must be used while approaching space missions
- Being “clean” in space is not optional anymore → number of debris increasing exponentially



Luisa Innocenti – Head of ESA Clean Space Office

Clean Space overview



Source: ESA Clean Space Office

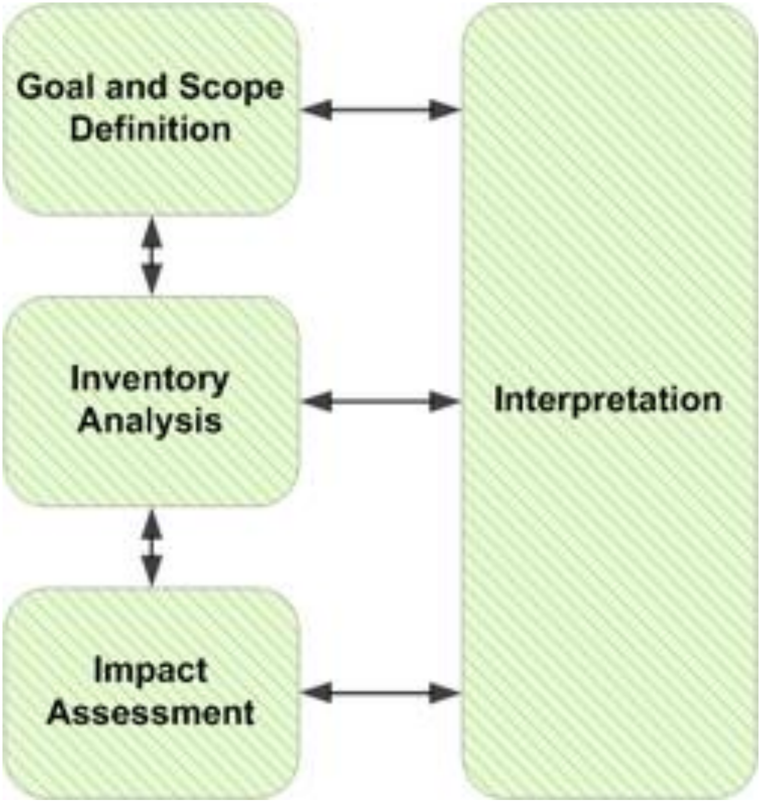
Political and social context

- International context
  - **Paris Agreement** → increase in the global average temperature must be below 2°C above pre-industrial levels
- European context
  - **European Green Deal**
    - > *No net emissions of greenhouse gasses by 2050*
    - > *Economic growth is decoupled from resource use*
    - > *No person and place is left behind*
  - **European Climate Law** → e.g. reducing greenhouse gasses emission by 55% by 2030
- Space sector
  - Non-binding requirements from the UN and non-specific legislations from Europe
  - National laws → **French space law** mentions impact assessment (art. 8)

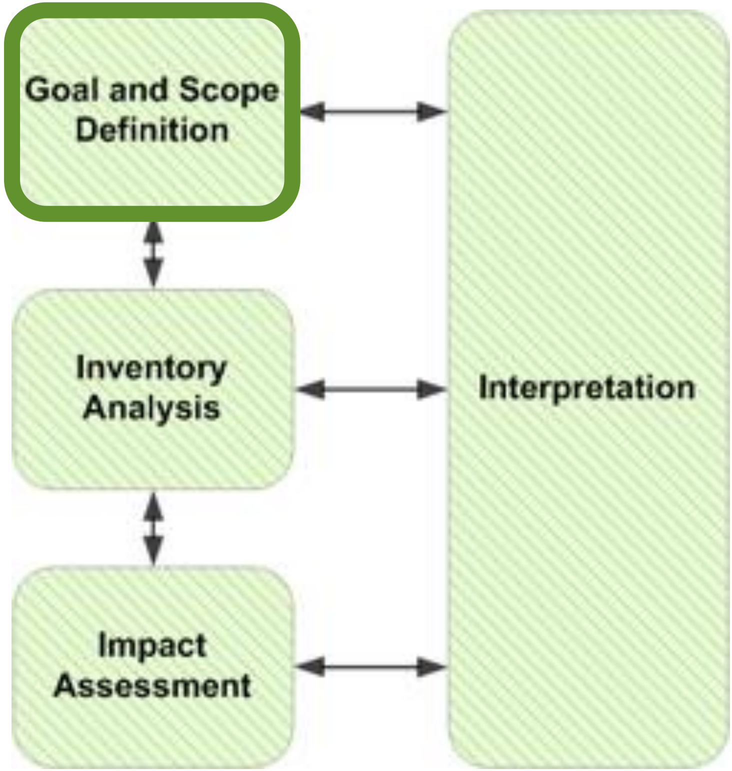
Life Cycle Assessment

- **Environmental impact** → a change in the environment, negative or positive, resulting partly or totally from a human activity, product or service (ISO 14001)
- To decrease the environmental impact:
  - Change the behaviour of individuals and society
  - Reduce the consumption of goods
  - **Produce differently**
  - **Prevent the environmental impact**
- The **Life Cycle Assessment (LCA)** is a tool used to measure the environmental performances of goods and services
  - Compiles and evaluates the inputs, outputs and the potential environmental impacts of a product or system throughout its life cycle (ISO 14 040/44)
  - Multi-step and multi-criteria process → avoid **burden shifting**

Life Cycle Assessment

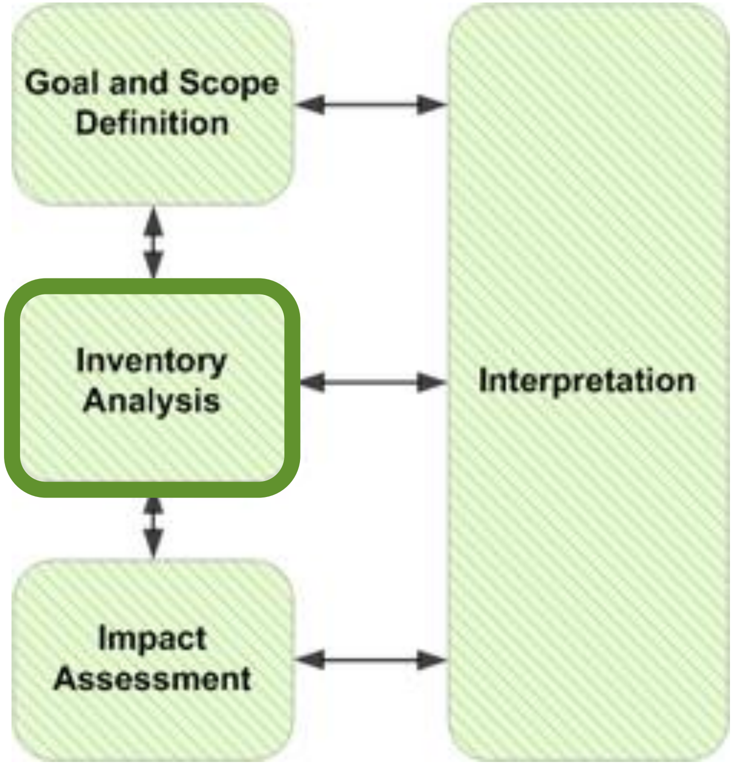


Life Cycle Assessment



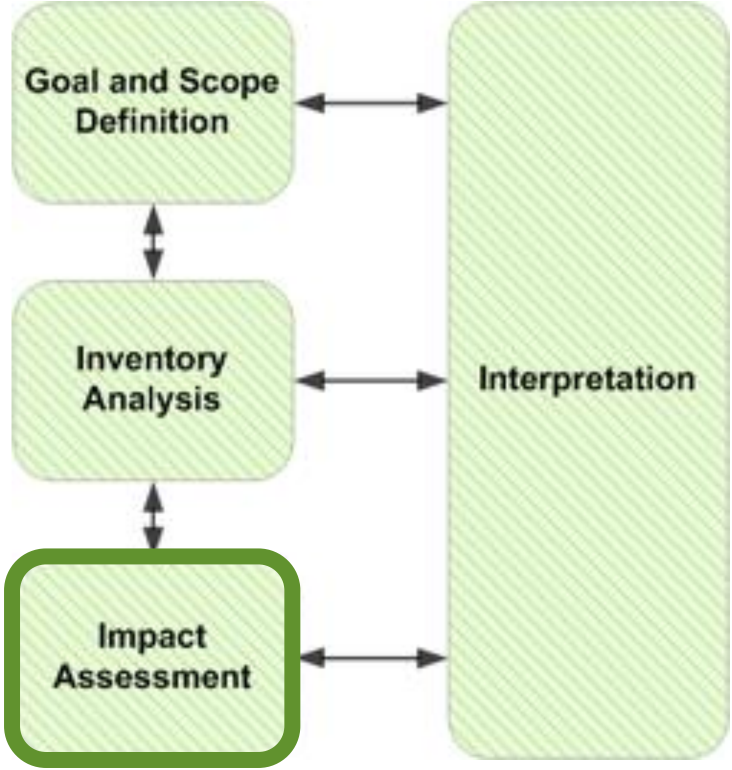
- First step → definition of the **objectives** of the study and the **system** to be studied
- **Functional Unit** → reference value depending on the function of the product
  - Measurable → used to compare multiple scenarios
  - All flows depend on it
- **System boundaries** → all activities that contribute to complete the functional unit
  - **Cradle-to-gate**
  - **Cradle-to-grave**

Life Cycle Assessment



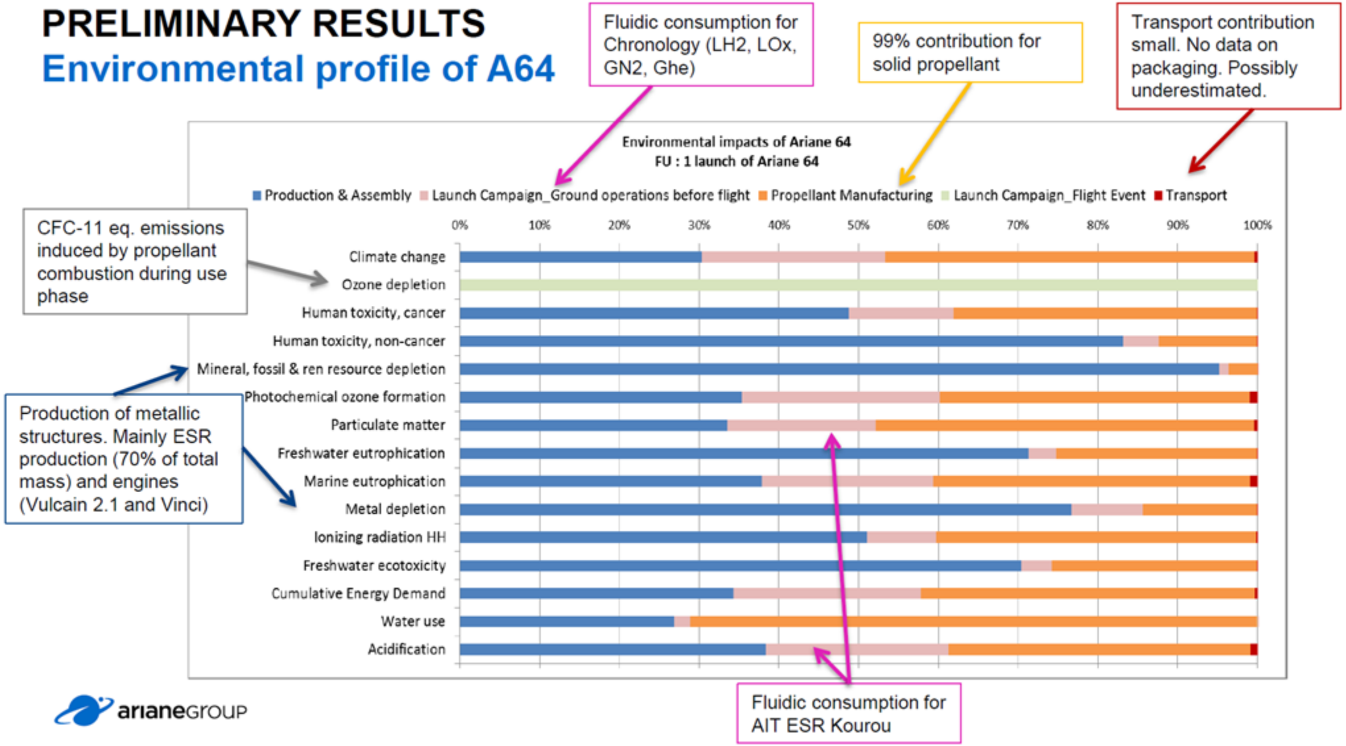
- Compiling all **elementary flows** in and out of the system to fulfil the function unit → exchange of **matter and energy**
  - Resource extraction
  - Emissions to air, water, soil
- For complex systems, items with a negligible percentage with respect to the final product can be disregarded
- **Databases** are needed
  - Ecoinvent
  - ILCD, European commission
  - **ESA LCA Database**

Life Cycle Assessment

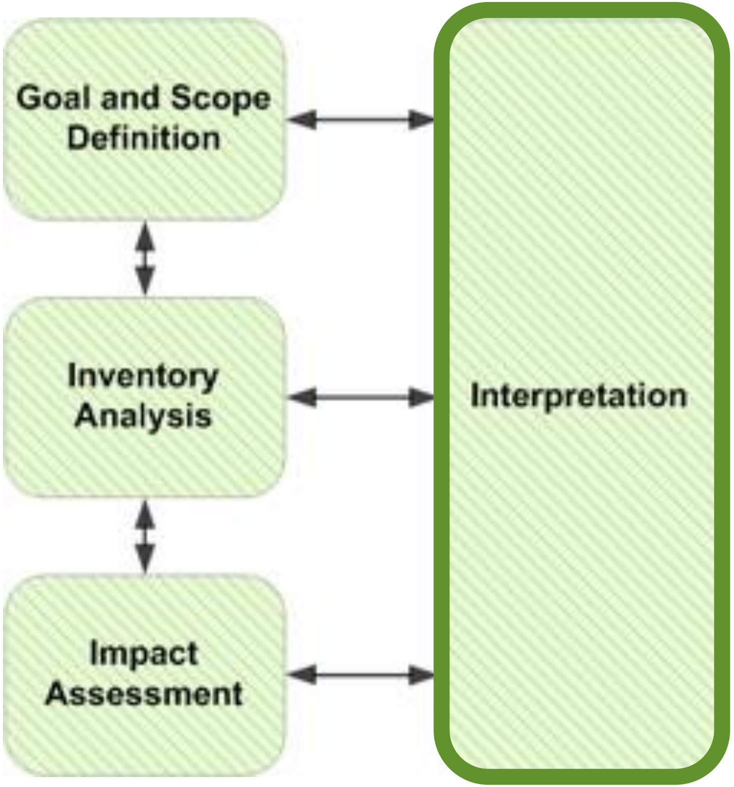


- Elementary flows are linked to environmental mechanisms → visualized through **impact indicators**
  - Climate change
  - Ozone depletion
  - Acidification
  - Eco-toxicity
  - Human toxicity
  - Abiotic depletion
- Impact indicators are then linked to the various life cycle phases to better understand how to improve the system

Life Cycle Assessment



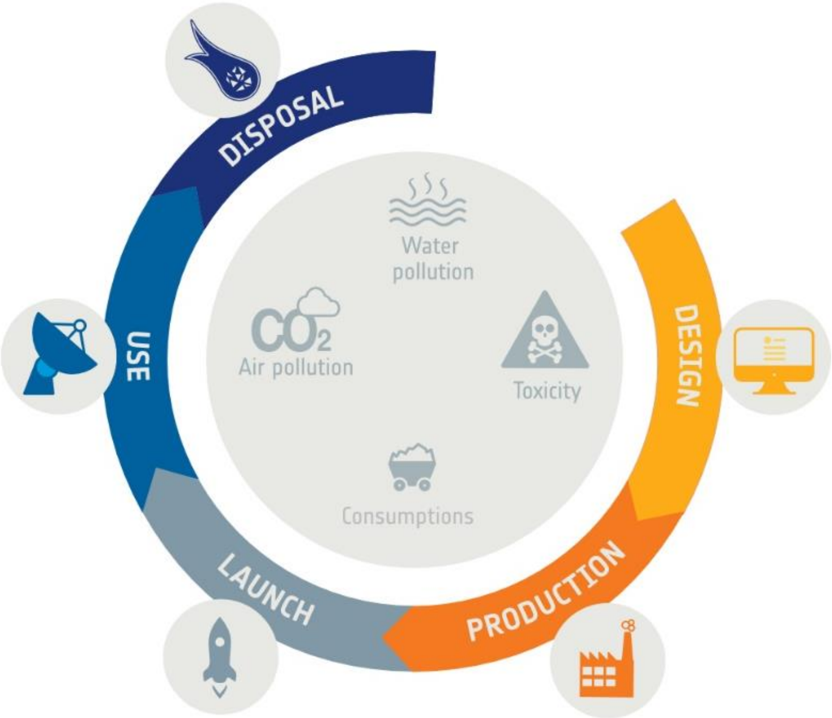
Life Cycle Assessment



- **Hotspot analysis** → identification of principal stages that contributes to the impact

- Limitations
  - Difficult to better all environmental impacts with one solution
  - **Uncertainties** in the model
  - **Choice influenced** by politics, product priorities

LCA applied to the space sector



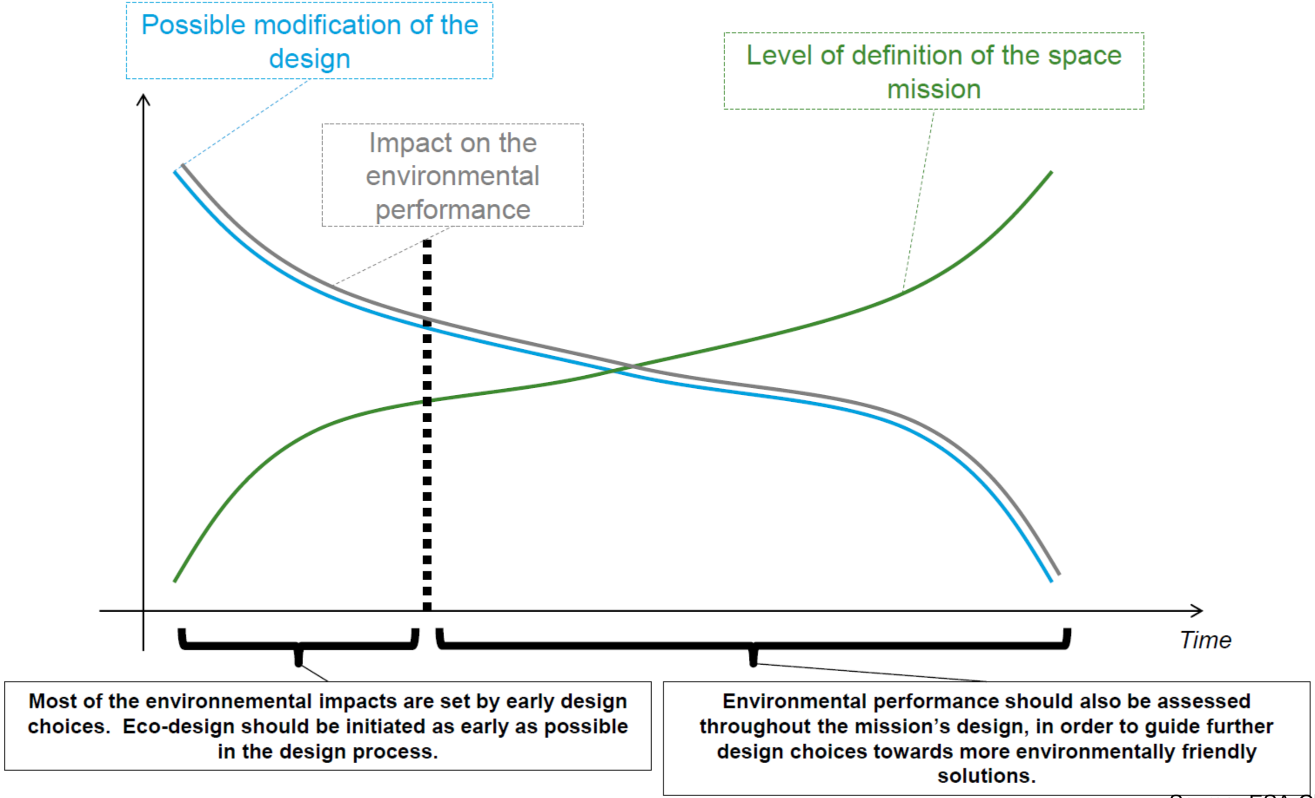
Source: ESA Clean Space Office

- LCA for the space industry is difficult:
  - More **complex system**
  - Specific materials and components
  - Costly and massive manufacturing at low rate
  - **Emission in different layers of the atmosphere**

EcoDesign

- Aims to **improve the environmental performance of products** and services assessing their environmental impact at the **design stage**, without reducing their **quality or performance**
- EcoDesign must be applied if:
  - The targeted system has **significant environmental impacts** in the whole life cycle of the mission
  - The modifications applied to the system determines **good environmental gains**
- In the future, ESA aims to implement LCA and EcoDesign different projects:
  - **Ariane 6**
  - **Copernicus Program**
  - **Earth Explorer**
  - **Galileo**

EcoDesign



Source: ESA Clean Space Office

Space Debris Mitigation requirements

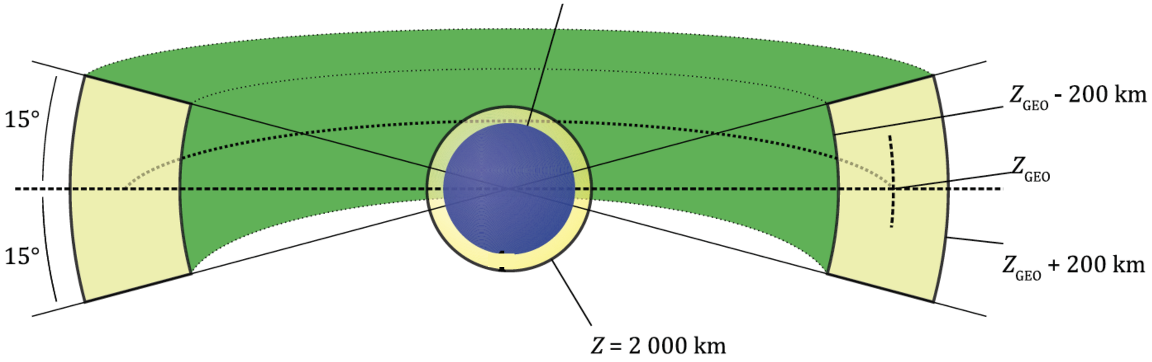
End-Of-Life measures

- Satellites in LEO must **exit the protected region (< 2000 km)** within **25 years** from the end of the mission
- For controlled and uncontrolled atmospheric re-entry, **casualty risk** on ground must not exceed 10^{-4}
- Satellites in **GEO** must be removed from the zone after the end of the mission → **graveyard orbits**
- The probability of **successful post mission disposal** (PMD) must be at least **0.9**
- At the end of life, the satellite must permanently deplete or make safe all stored energy → **passivation**

Re-entry strategies

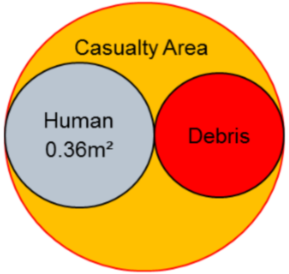
Protected zones

- **LEO →** under 2000 km → **re-entry strategy**
- **GEO →** graveyard orbit **~300 km higher**



Source: ESA Clean Space Office

Re-entry strategies



Casualty risk:

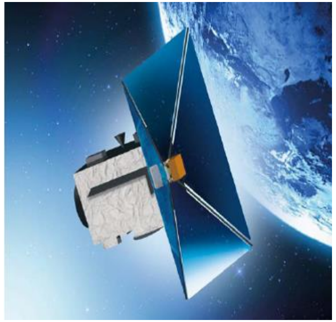
- Defined as the **probability of serious injury or death**
- An object is considered deadly if it has an energy of **15 J**
- Casualty area is the **total area impacted by a debris**
- Mean population density → depends on year and orbit of the debris

→ **Casualty risk = casualty area** (for > 15 J debris) **x mean population density**

- The requirement of casualty risk < 10^{-4} is very constraining

Uncontrolled re-entry

- Casualty risk must be < 10^{-4}
- Natural decay
  - Satellite is slowed down by **atmospheric particles**
  - Decay velocity depends on altitude → ~ 25 years for 600 km altitude
  - **Easiest way** → low impact on satellite and mission
  - **No control** over fallout zone, **no collision avoidance manoeuvers**
- Deorbiting system
  - **Drag sails** → increase in area, increase in drag
  - **Deorbiting tether** → uses magnetic field to generate currents and create drag
  - **Low impact** on satellite and **low cost**
  - Little control, **no collision avoidance manoeuvers**
  - Needs **detumbling** after deployment

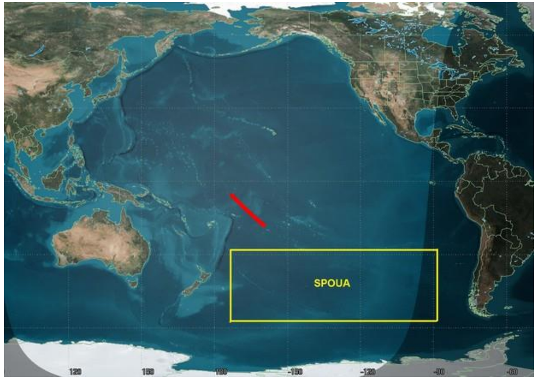


Source: ADEO, ESA

Source Emxys

Controlled re-entry

- If casualty risk > 10^{-4}
- Target specific areas → South Pacific Ocean Uninhabited Area (**SPOUA**)
- Requires fuel to lower the altitude and **high thrust engines** for steep re-entry angles → combination of efficient electric engines with high thrust for the last burn
- Ensures a **fast re-entry** with respect to the uncontrolled passive decay
- Difficult to assess the **reliability** of the system at the end of life
- **Higher costs** and more **complex system**



Design for Demise

- Design for Demise (D4D) is to intentionally design a space hardware such that it will **disintegrate during re-entry**
- Necessary for **mid and large systems** → casualty risk requirements cannot be achieved → with D4D the 10^{-4} threshold can be reached
- Multi-level approach
  - **System level** → configuration to allow higher exposure of equipment to heat flux
  - **Equipment re-design** → aims to reduce the heat load necessary to demise the item
- <u>Critical elements</u>
  - **Propellant tanks**
  - **Reaction wheels, magnetic-torquers**
  - Large mechanisms
  - **Optical equipment**, lenses, mirrors
  - Batteries

Design for Demise

- Benefits and limitations
  - **Simpler system**, **less cost and mass** and more **robust** that planning a controlled re-entry
  - Sustainable
  - Compromise between D4D and performance, with today's technologies
  - Requires **re-entry simulations, on-ground tests and in-flight experiments** → uncertainties due to lack of knowledge
- Design for Demise techniques
  - **Minimise required heat** → lowering the mass, replacing the materials
  - **Maximise available heat** → higher ballistic coefficient, exothermic reactions
  - **Optimize heat transfer** → early break-up fragmentation through dedicated mechanisms or demisable attachment points
  - **Minimise casualty area** → keeping the fragments together
- A combination of techniques is usually required for full demisability

Passivation for power

- Passivation means **permanently depleting, deactivating or making safe** all on-board sources of stored energy capable of causing accidental break-up
- Power passivation is needed → at least 10 spacecrafts broke up due to battery and explosive failure modes cannot be excluded
- Battery break-up causes
  - **Over-temperature**
  - **Over-charge/over-discharge**
  - **Short circuit**
  - **Structural issues** or damage
- **Thermal runaway** → once reached the **onset temperature**, very fast increase in temperature and pressure → protection systems do not react in time
- To passivate, the battery must be discharged and isolated from the power source (solar array), then kept within an acceptable temperature range

Passivation for propulsion

- Propulsion system is the **main cause of spacecraft break-ups**
- Risks
  - **Propellant dissociation** → exothermic reaction that can lead to tank burst
  - **Hypervelocity impacts** → change in pressure can cause ignition
- Passivation through **thrusters** (requires power) and **valves**
- Equipment
  - **Shape-memory alloy valves** → can be deformed by force and get back to original form when heated
  - **Microperforators**
  - **Pyrotechnic valves**
- New equipment and methods are still under development → complex system

In-orbit servicing

- In-orbit servicing is an important tool for a clean space:
  - To solve issues with existing space objects → **repair**, debris removal
  - To increase the utility of existing space objects → **refuelling**, **life extension**
  - To develop new systems on-orbit → **manufacture** and **assembly**
  - To assist **human exploration**
- A paradigm shift is needed

→

Non-flexible and **dedicated design** of spacecraft

↓

Flexible systems with **adaptable equipment**

In-orbit servicing

Source: ClearSpace

ADRIOS: Active Debris Removal/In-Orbit Servicing

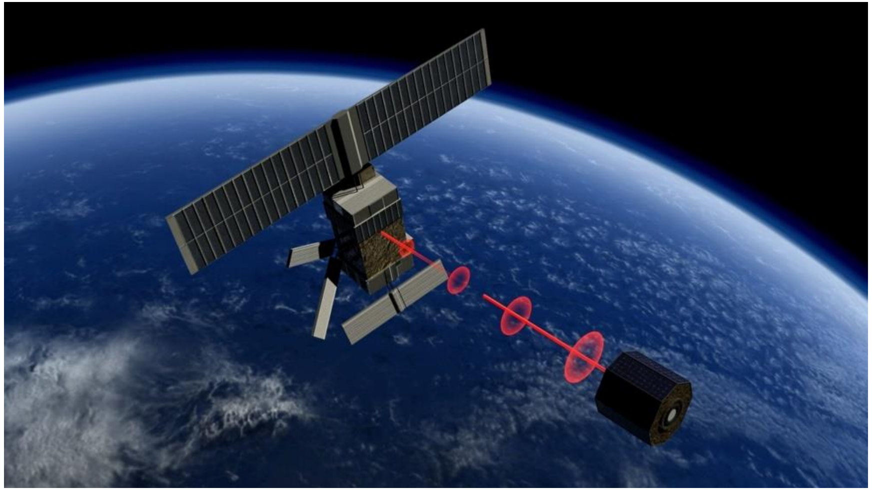
- Mission planned for 2025, part of **ClearSpace-1**
- Objectives
  - Remove ESA debris with a **mass greater than 100 kg** by 2025
  - Demonstrate **feasibility of critical technologies** for in-orbit servicing opportunities
  - Provide **business model** for in-orbit servicing beyond ESA
  - Comply with **space debris mitigation requirements**
- ADRIOS project will include **advanced guidance**, **navigation and control systems**, **vision-based AI** and **robotic arms** → chaser can safely approach and capture target

Active Debris Removal

- Active Debris Removal (ADR) is a type of mission aimed at targeting a debris and removing it from the protected areas with the use of a chaser satellite
- Active debris removal has **never been done** yet
  - **Legal issues** → each nation is responsible of its own debris, the damages caused at re-entry and any in-orbit collision
  - Requires **new technologies** → many tests needed
  - **High costs** → no company dares to invest
  - No law obligates active debris removal
- <u>Benefits</u>
  - **Clean**
  - **Prevents liability issues** due to collisions or re-entry
  - **Prevents impacts** on services
  - Ensures access to space → there's the need to go against the **Kessler syndrome**

Active Debris Removal

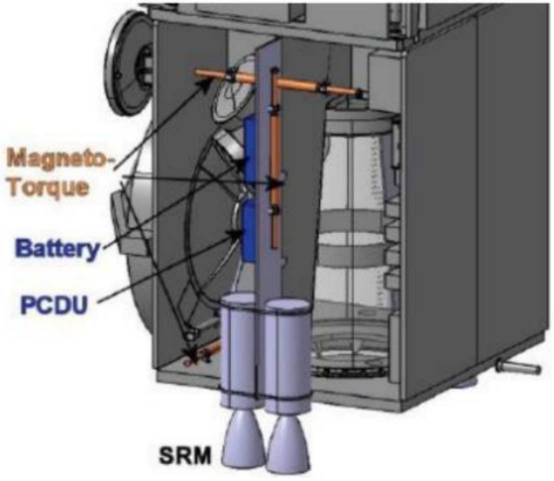
- Steps to perform ADR
  - **Monitor from ground** → determine attitude, spin rate and rotation axis of the debris
  - **Far range rendezvous** → line of sight and distance to target (**8 km to 1 km**)
  - **Close range rendezvous** → line of sight, distance to target and target attitude (**1 km to 2 m**)
  - **Capture** → track a capture point, approach safely the target and obtain a physical link
  - **Disposal** → support transfer of loads and the control of the thrust vector



Source: ESA

Active Debris Removal

- Removing **small debris** with propulsion → lower their orbit to re-enter in 25 years
  - **“Shuttle approach”** → the chaser catches the debris, brings it to a different orbit and releases it
  - **“Mothership approach”** → the chaser catches the debris, attaches a **de-orbit kit** and activates it → kit must include
    - > *Solid rocket **propulsion system***
    - > ***Attitude and Orbit Control Systems***
    - > *Power*
    - > *Sensors*
  - Some non successful tests have been carried out



Active Debris Removal

- Removing **large debris** with propulsion → controlled re-entry
  - The chaser must re-enter with the debris
  - Requires **high reliability**
  - Requires **high thrust** → lots of propellant

- <u>Technical problems when studying ADR</u>
  - Numerically simulate **touch dynamics** in space is extremely difficult
  - **Simulating 0 g on Earth** for enough time is impossible
  - Debris in space doesn't stand still → simulations with hanging systems are not reliable

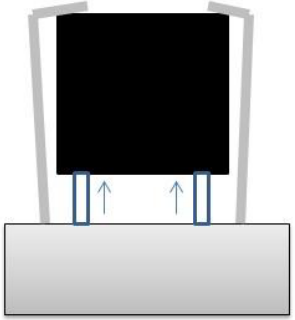
Capturing

- Capturing a debris is very different from docking or berthing in space
- The debris is **not necessarily cooperative** and has **dedicated capture points**
- Capture equipment can be both **rigid** or **flexible**
- Robot arm
  - **Complex** machine but **versatile** (can be used for in-orbit servicing)
  - Can be tested on ground
  - Allows for **re-tries**
  - Requires a **gripper** → can be changed for different targets

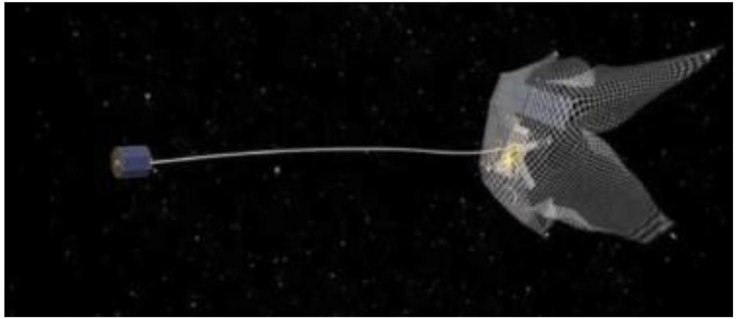
Source: NASA

Capturing

- <u>Clamping mechanism</u>
  - Less complex, similarities to docking system
  - Ensures **closing on the target before touch** → target cannot escape
  - Allows for **re-tries**
  - Centre of gravity of the debris must be aligned with the thrust force



- <u>Net</u>
  - **Independent from the shape** of the debris
  - Chaser can stay at **distance**
  - Complex GNC system to keep tether in tension
  - Cannot be tested on ground
  - Does **not** allow for **re-tries**
  - If debris is rotating, must stabilize it with thrust

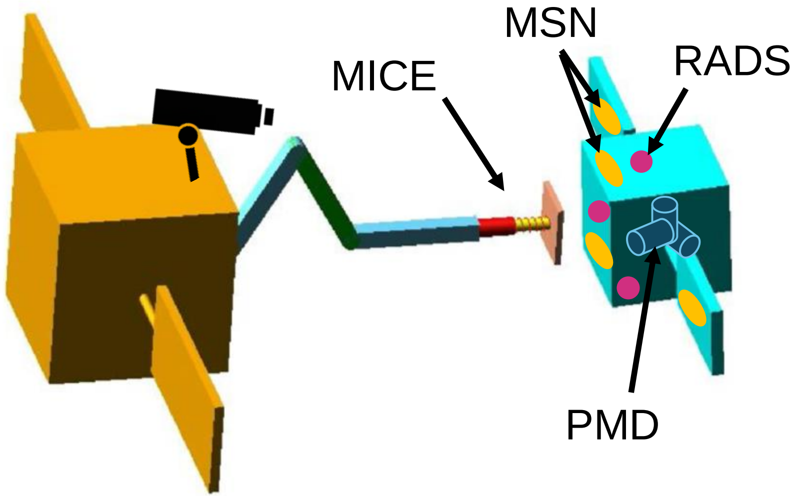


Capturing

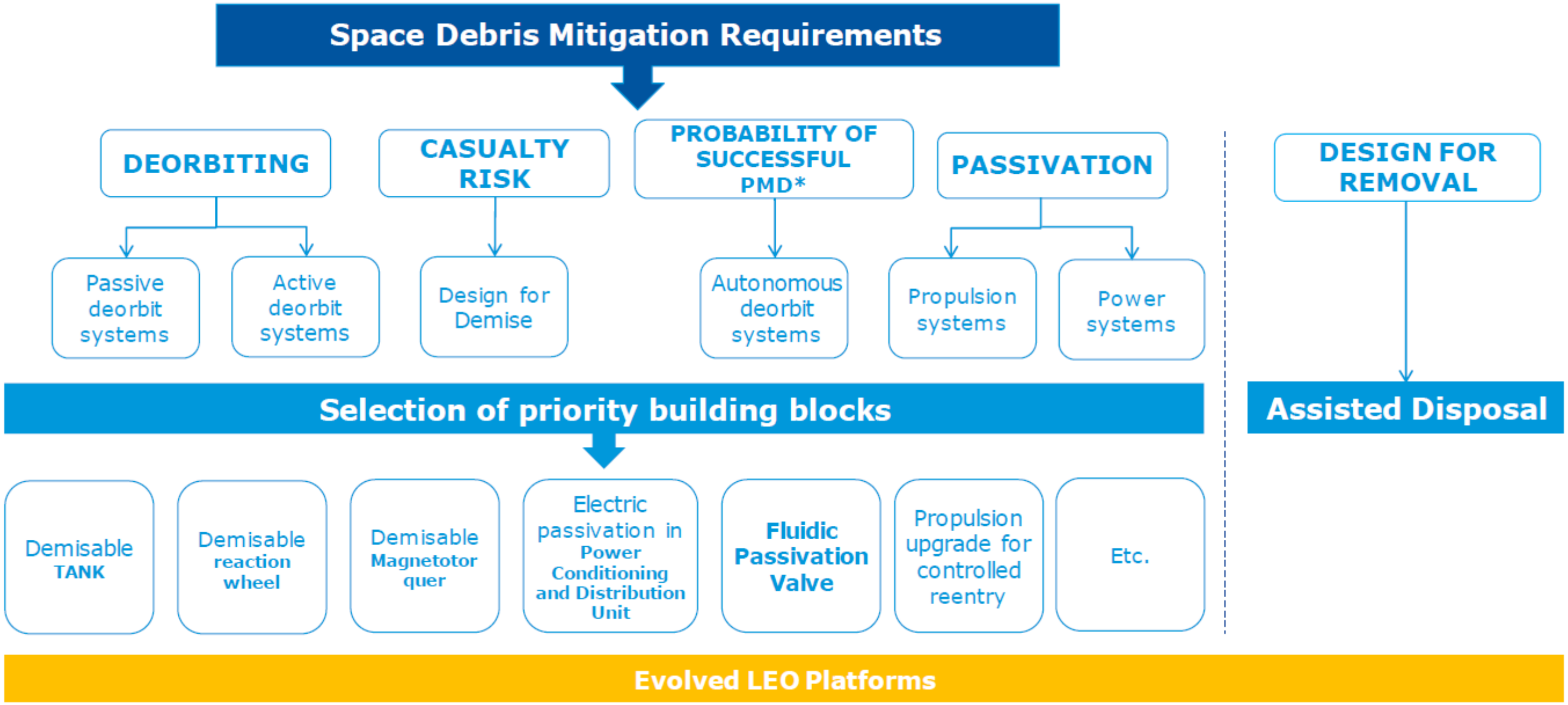
- <u>Harpoon</u>
  - **Mix** of robot arm and net
  - Chaser can stay at greater distance with respect to the robot arm but closer than the net system
  - Same tether problems as the net
  - Does **not** allow for **re-tries**
  - **Impact** with the debris could cause breakings or explosion
  - Successful capture test with harpoon in 2019 (RemoveDebris project)

Design for Removal

- Future targets and the chasers must be **designed so to ease ADR** → Design for Removal (D4R) technologies
- Chaser satellite must be designed together with the target satellite for what concerns the **capture interface**, even if its actual use is at the end of life of the target satellite
- D4D technologies
  - **Markers to Support Navigation** (MSN)
  - **Mechanical Interface for Capture** (MICE)
  - **Passive Magnetic De-tumbling** (PMD)
  - **Retroreflector-based Attitude Determination System** (RADS)



Clean Space techniques summary



Source: ESA Clean Space Office

Conclusions – what I learnt

- Making the space industry clean is **not an easy process** and **there is not one solution** to solve every aspect of it
- **Compromises** are needed to meet the Space Debris Mitigation requirements without affecting the performance of the missions
- There is still so much **unknown** in this area that we must continue studying to improve the space industry
- Space is awesome, but **we must act to protect it** as much as we need to do with Earth!

If you want to know more

- ESA Academy organises different courses every year aimed at Bachelor, Master and PhD level students → KTH is always promoting them so check out the announcements!
- Related links:
  - https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Clean_Space
  - https://www.esa.int/Education/ESA_Academy
  - https://www.esa.int/Education/ESA_Academy/Online_Clean_Space_Training_Course_2021_challenges_university_students_to_clean_a_Mega_Constellation
- Contact me: gretat@kth.se

Thank you for the attention!
Questions?

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