



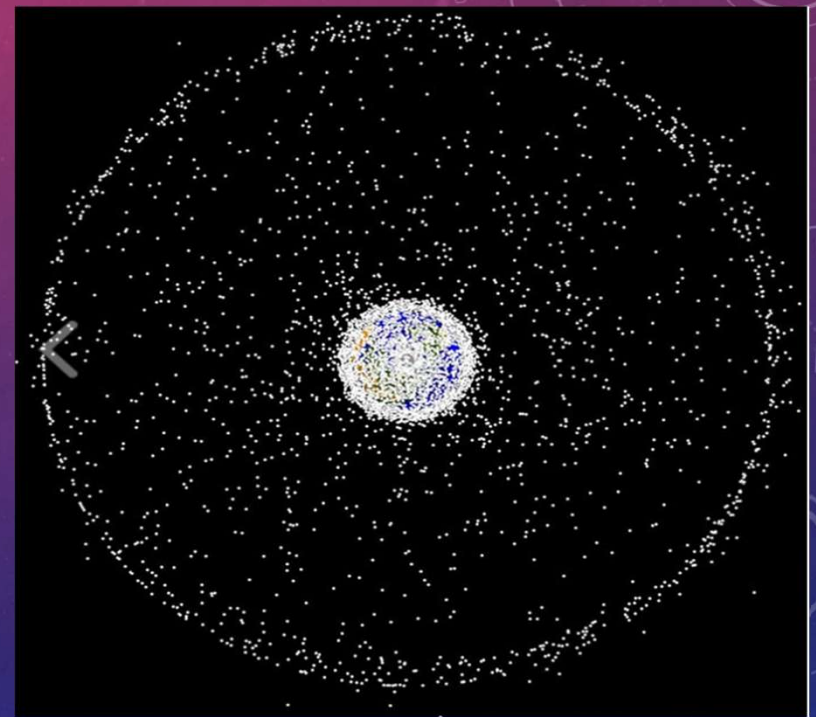
COST DRIVERS FOR IN-SPACE LOGISTICS OF RECYCLED SPACE DEBRIS

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INTRODUCTION

Imagine if space debris becomes a valuable in-space resource for on-orbit materials processing and re-use

- Space debris problem
- Steps to recycling space debris
- Cost-drivers for different steps
- Trade-off scenarios
- Trade-Off scenarios Cost-Drivers
- Space Capsule Mailing Service
- Conclusions



Courtesy: NASA ODOPO, [ARES](#) | [Orbital Debris Program Office](#) | [Photo Gallery](#)
([nasa.gov](#))

SPACE DEBRIS CHALLENGE – PART I

	<u>Rockets launched</u>	6.380	(100%)
	<u>Rockets still in Space</u>	1.990	(31%)
	<u>Satellites launched</u>	15.430	(100%)
	<u>Satellites functioning</u>	7.600	(49%)
	<u>Dead Satellites in Space</u>	2.690	(17%)
	<u>Space objects mass</u>	10.800	<u>tonnes</u>
	<u>Frangmentation events</u>	640+	
	<u>Debris tracked</u>	32.070	
	<u>Debris >10 cm</u>	36.500	
	<u>Debris 1 -10 cm</u>	1 <u>million</u>	
	<u>Debris 0.1-1cm</u>	130 <u>millions</u>	

source ESA updated at March 2023

	<u>Rockets launched</u>	7170	
	<u>Satellites launched</u>	25 170	
	<u>Satellites functioning</u>	14 200	
	<u>Space objects mass</u>	15 800	<u>tonnes</u>
	<u>Frangmentation events</u>	>650	
	<u>Debris tracked</u>	44 870	
	<u>Debris >10 cm</u>	54 000	
	<u>Debris 1 -10 cm</u>	1.2	<u>million</u>
	<u>Debris 0.1-1cm</u>	140	<u>millions</u>

Source: ESA Space Environment report January
2026

SPACE DEBRIS CHALLENGE – PART II

- Current satellites are not built to be serviced or recycled
- Diverse ADR concepts -nets, harpoons, robotic arms, grippers, magnets, tethers, etc. With different TRL and complexity
- Small debris 1-10 cm lethal high speed, difficult to track, destroy s/c, damage critical sub-systems, penetrate s/c shield
- However, space debris contains valuable materials- titanium, aluminum alloys, copper, stainless steel, etc.
- Imagine if it is possible **easy to collect the smaller space debris and recycle it?** what do you do with the collected space debris arises?

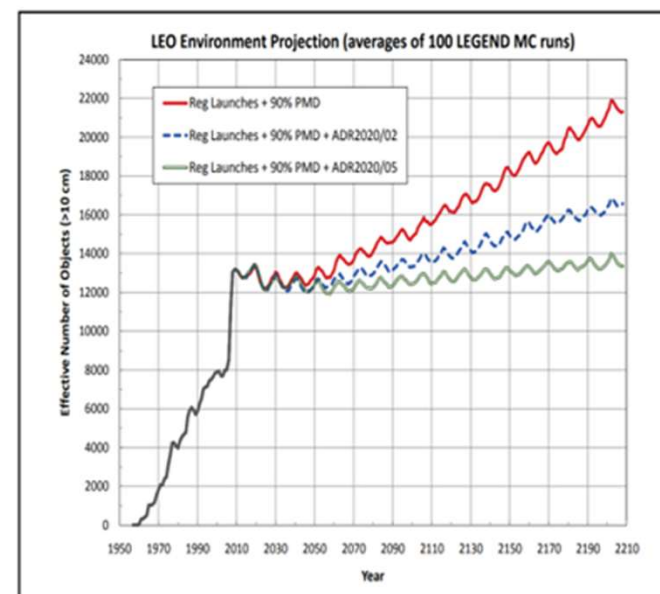


Figure 4. The evolution of trackable debris in LEO over a 200-year timescale. Each line assumes that PMD compliance has risen to 90 percent. The red line assumes that no debris removal occurs. The blue and green lines assume that 2 and 5 large debris objects are removed per year, respectively. Source: (NASA ODPO 2011)

1 FEASIBILITY STUDIES



- Technical feasibility
- Economic analysis
- Legal & regulatory assessment
- Risk assessment
- Mission concept & technology evaluation

2 SPACE-BASED SSA – SD VALUE



- Space Situational Awareness (SSA)
- Detect, track & characterize debris
- Assess material composition & quantity
- Determine Space Debris (SD) value & priority targets

3 RPO (Rendezvous & Proximity Operations)



- Orbit determination
- Rendezvous planning
- Safe approach
- Relative navigation & proximity operations

4 COLLECT SPACE DEBRIS



- Capture mechanisms (robotic arm, net, harpoon, magnetic or other)
- Stabilize & secure debris
- Prepare for next phase

5 TRADE-OFF SCENARIO



- Evaluate options based on:
- Value vs. cost
 - Technical feasibility
 - Mission risk
 - Environmental impact
 - Time constraints
 - Strategic objectives

6 RECYCLING



- Process & recycle materials
- Recover usable resources (metals, alloys, materials)
- Produce new components or propellant
- Support future space missions & economy

TRADE-OFF SCENARIO OPTIONS

A. RECYCLE IN ORBIT



Process debris in space into raw materials or components

B. DEORBIT TO EARTH



Bring debris to Earth for processing, recycling or disposal

C. DIRECT REUSE IN SPACE



Use components directly for construction, refueling or infrastructure



SUSTAINABLE SPACE FUTURE



Reduce Debris in Orbit



Lower Costs & Create Value



Enhance Safety & Security



Protect Environment & Resources



Enable Long-Term Space Exploration

STEPS TO RECYCLING SPACE DEBRIS

1. Feasibility Studies – Value vs Cost, Trade-off scenario benefits, TRL, potential end-users& applications



2. Space-based SSA & Debris Value – detect, descibe and analyse the value of space debris



3. RPO (Rendezvous & Proximity Operations) - IOS



4. Collect Space Debris – ADR

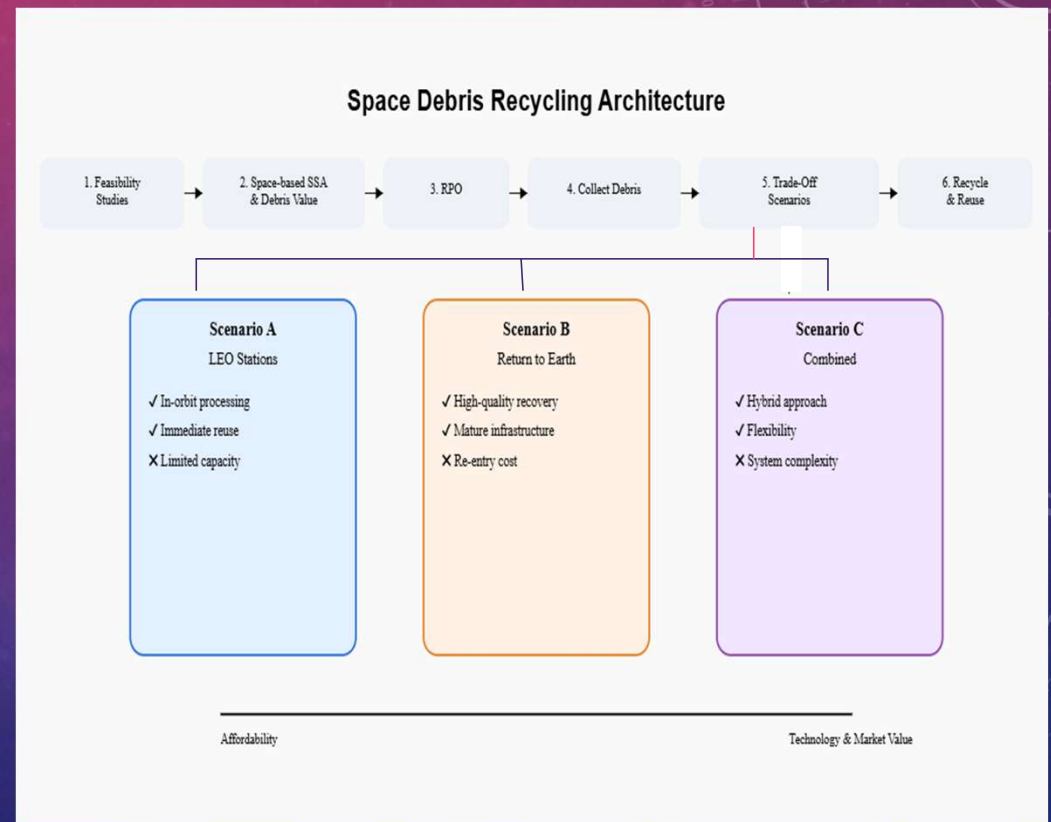


5. Trade-Off Scenarios



6. Recycle & Reuse – ISAM, 3D printing, ISRU

VARIOUS COST DRIVERS DURING DIFFERENT STEPS TO BE ASSESSED



COST DRIVERS DURING DIFFERENT STEPS

- **Size of Space Debris - STEP 1 Feasibility Studies**
Assess object size to estimate capture, handling, and storage needs.
- **Value of Collected Space Debris - STEP2 – Space Based SSA-SD Value**
Estimate the value of recoverable materials and their contribution to mission economics.
- **Launch Cost - STEP 3 -RPO**
Show cost of launch vehicle
- **Recycler Cost- STEP 3 - RPO**
Show cost of recycler, payload mass, etc.
- **Recycling Mission CONOPS – STPES 3 RPO , STEP4 COLLECT SD &STEP 6 RECYCLE - Rendezvous → Capture → Recycle**
Mission design drives operational complexity and cost.

TRADE-OFF SCENARIOS

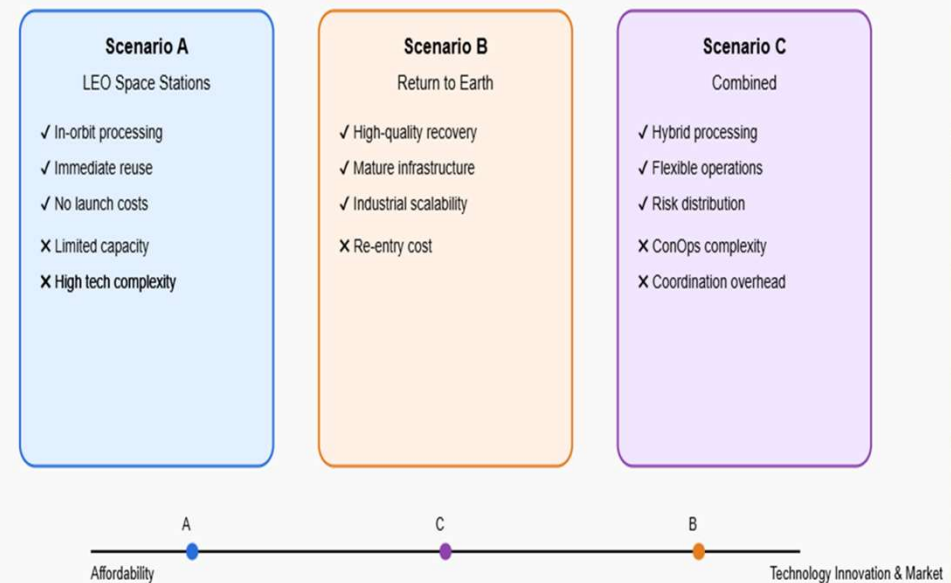
H1 -In the long run there will be space debris collectors and recyclers of small space debris.

- Scenario A: Transfer capsule to LEO Space Stations – for metal powders from aluminium or titanium for metal 3D printing - Cost Drivers – Value of Space Debris, Recycler Cost, Recycler Mission CONOPS
- Scenario B: Return to Earth –Value of Space Debris, Recycler Cost, Recycler Mission CONOPS, Re-entry Capsule Mission Cost
- Scenario C: Combined - first dock to LEO space station and return to Earth only sorted materials not useful for 3D printing - Value of Space Debris, Recycler Cost, Recycler Mission CONOPS, Re-entry Capsule Mission Cost

Initially analysis of the Cost-Drivers under the proposed scenarios will need to be performed

Trade-Off Scenarios for Recycling Space Debris

Debris Collection → Recycling Decision



LOGISTICS SCENARIO - A

Dust and Space Debris



Debris Collector



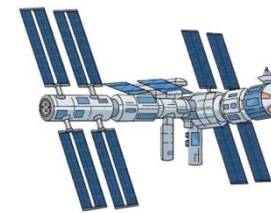
Dust and Small Debris Collector



Launch of Automated Collectors

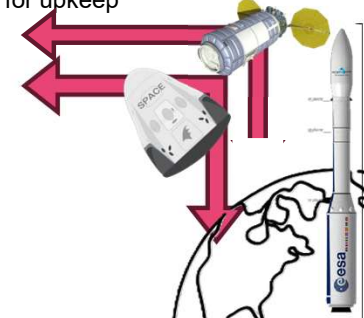


Collectors stay in orbit and are refuel at the station. At EOL refurbished/Recycled at station.



Crewed Space Station with Re-cyclers and Manufacturing

Space station logistic chain for upkeep



LOGISTICS SCENARIO – B & C

Dust and Space Debris



Debris Collector



Dust and Small Debris Collector



Launch of Automated Collectors



Collectors stay in orbit and are refuel at the station.
At EOL refurbished/Recycled at station.

Transfer and Return Vehicles
Crewed logistic chain for upkeep and down mass

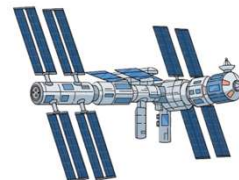
One way supply ships

Crewed return flights

Automated return flights

More frequent and fast turnaround

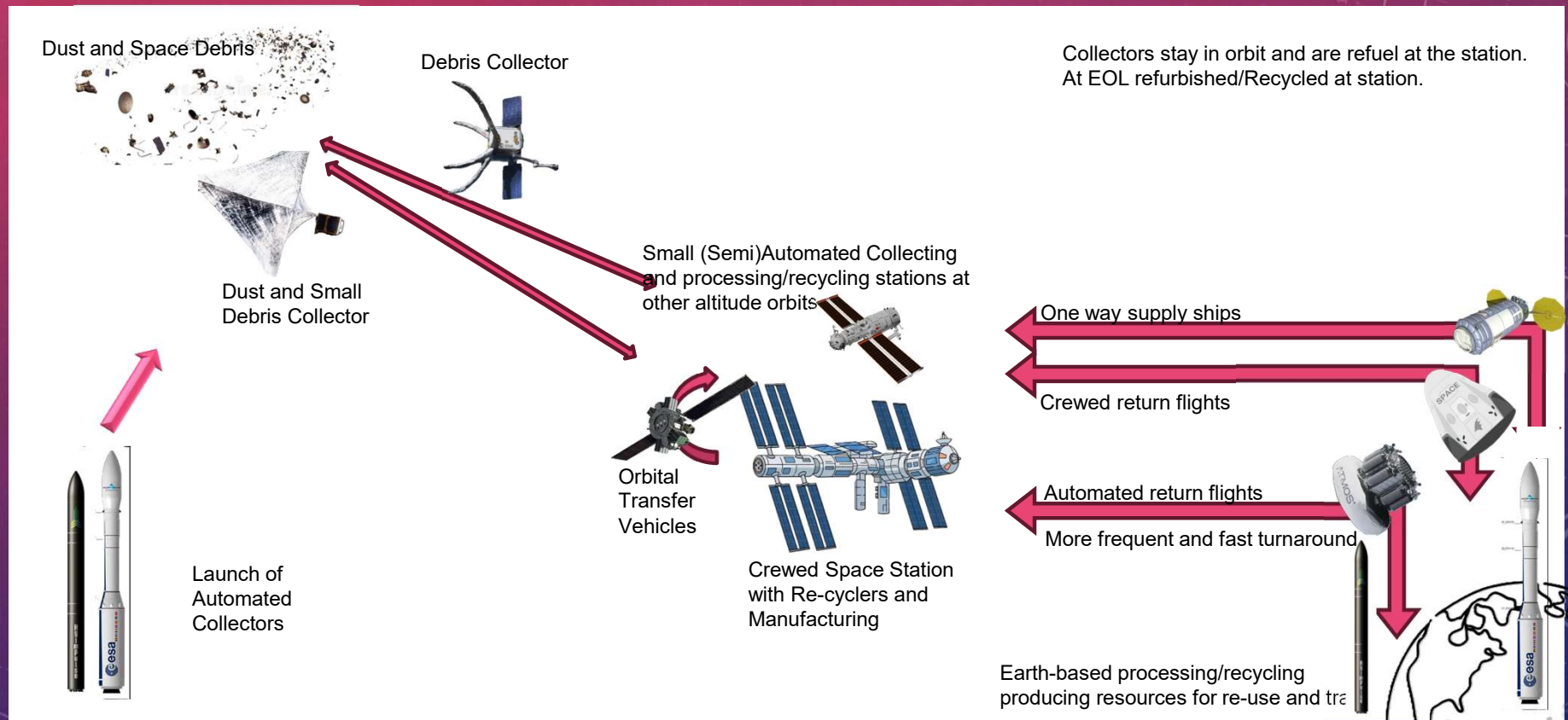
Crewed Space Station
with Re-cyclers and
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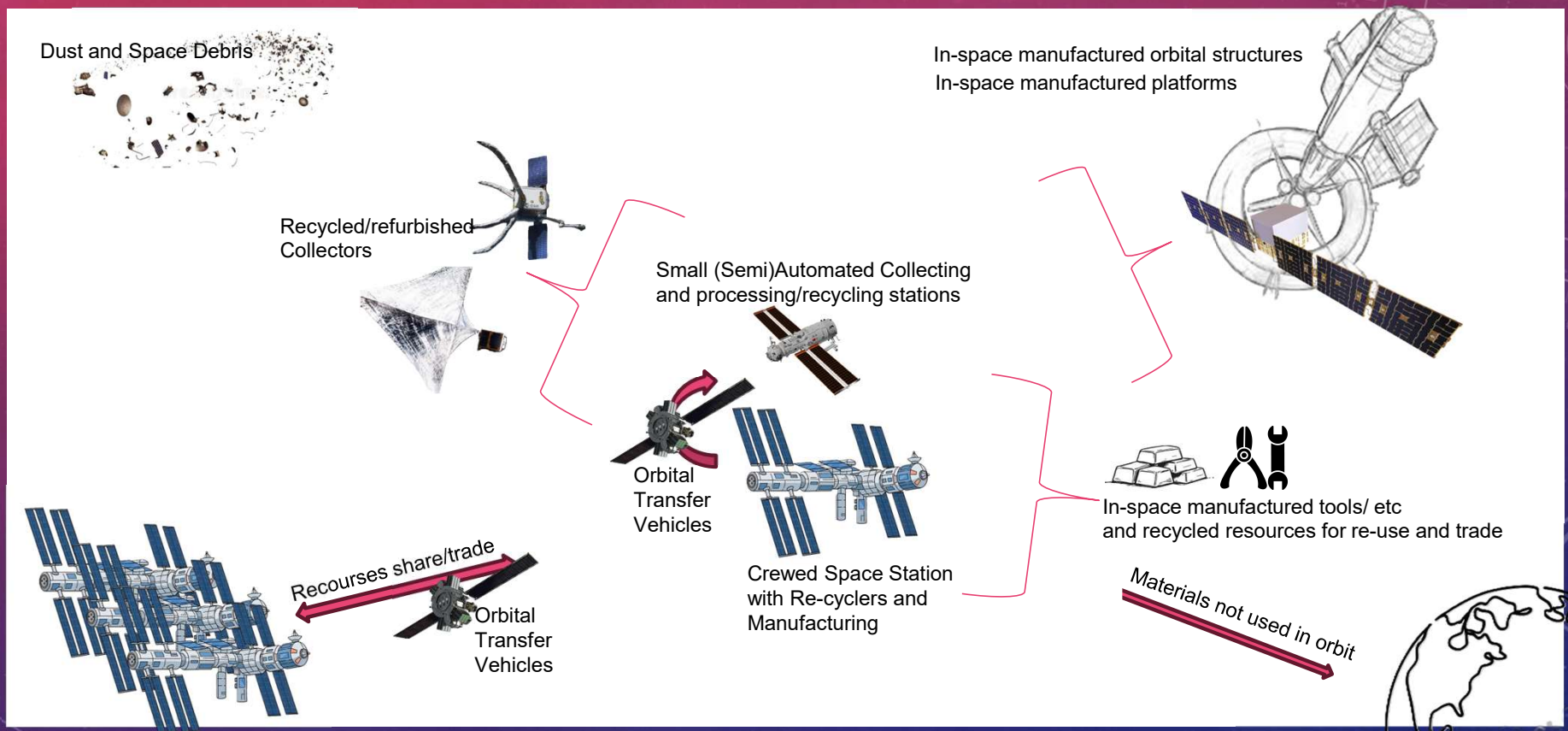
Earth-based processing/recycling
producing resources for re-use and tra



LOGISTICS SCENARIO – next steps



re-use of collectables



Example

Cost benefit comparisons

	cost	Return value
One way Space Debris Collection and demise without recycling.	Costs per KG debris removed	e.g Les risk for current and future space assets
Space Debris Collection for recycling	Costs per KG debris removed and useful debris collected	e.g. Less launches needed for resources on-orbit. More on-orbit construction possibilities.
Tools/Structures/resources send from earth only	Costs per KG per launch	
Tools/Structures/resources made on-orbit from Space-Debris	Costs per KG reprocessed on-orbit	

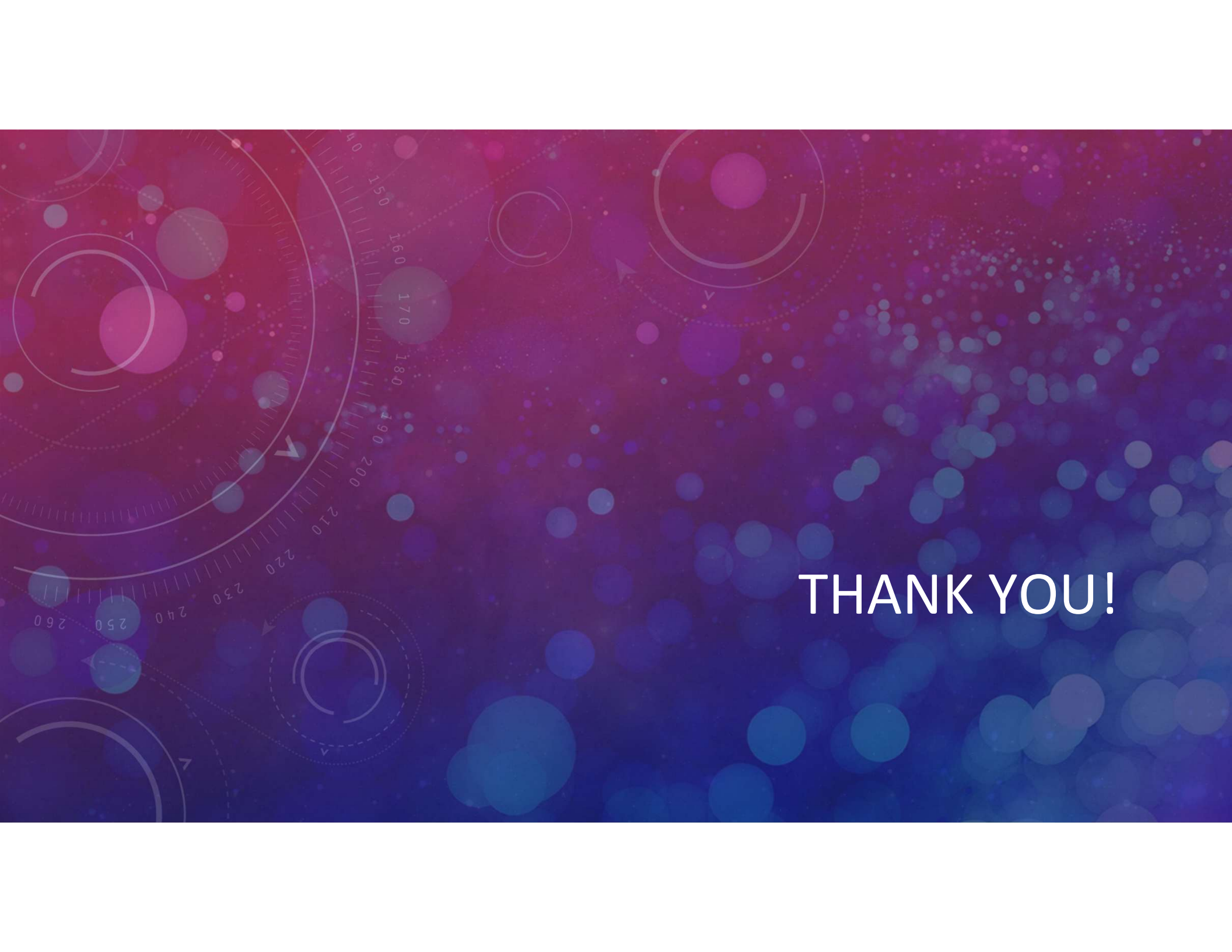
Example

Overview development and operational costs

	Debris-Collector	On-Orbit processing Recycling and Manufacturing	Return Capsules
Development	Phase 0	Large scale to be started	Already in progress
Re-builds			
Launch Cost			
Yearly operations costs – from ground			
Yearly operations costs - on-orbit			
On-orbit maintenance – refurbish – re-use			

CONCLUSIONS

- Diverse Cost Drivers that require trade-off cost scenarios to compare the various cost drivers for the proposed three scenarios
- On-board LEO space stations recycled space debris can be used for 3D printing material or tools needed. Capabilities beneficial for future in-space manufacturing.
- Recycling space debris can potentially generate benefits e.g. time and cost saving, contingency, space debris management, technology innovation partnerships, etc.
- Clear need for “space capsule mailing service” with trade-off scenarios assessed by an “user-driven analysis”
- Cost analysis to be performed identifying the direct (e.g. cost drivers, cost savings, safety, etc.) from the six Steps and the three scenarios
- Recycling space debris will be the first step to future In Space Assembly Manufacturing (ISAM) and future In Situ Resource Utilisation (ISRU).

The background is a gradient of deep purple and blue, filled with numerous out-of-focus circular light spots (bokeh) in various shades. Overlaid on the left side are several faint, white technical diagrams. These include concentric circles, arcs, and a large circular scale with numerical markings from 140 to 260 in increments of 10. Some of the diagrams also feature small arrows and dashed lines, suggesting a scientific or engineering theme.

THANK YOU!



Backup slides

LOGISTICS SCENARIOS

