Conceptual model for a profitable return on investment from space debris as abiotic space resource

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Abstract
Space debris presents an emerging "tragedy of the commons", posing hazards to the access, use, exploitation and exploration of space. We recommend a model addressing this issue and qualify debris as abiotic space resources and argue that it can be recycled and converted into fuel for other space ventures such as producing metal for on-orbit 3D printing. This could produce a commercially viable solution for incentivizing debris removal. We acknowledge mandatory property insurance and absolute third party liability insurance, both in orbit, to fund such operations through insurance salvage clauses facilitating title claim and sustain return on investment.

1. Introduction

"We the mortals touch the metals,
the wind, the ocean shores, the stones,
knowing they will go on, inert or burning,
and I was discovering, naming all these things:
it was my destiny to love and say goodbye."
Pablo Neruda

Outer space, which includes Earth orbits, constitutes a **collective natural resource**. A "**tragedy of the commons**" exists when many actors use and benefit from a collective resource whilst no actor has an incentive to bear the burden of maintaining it. Hence, orbital space debris present an emerging "tragedy of the commons", posing an imminent **hazard** to the access, use, exploitation and exploration of near-Earth space. Moreover, the international surge in small satellite constellation deployments creates the potential for an exponential growth in **orbital debris**. While the adverse impact of orbital debris on the continual access to and the use, exploration, and exploitation of space has generated much talk and discussion, there is a noticeable **absence of meaningful action** among space actors to actively engage in orbital **debris removal**. Current proposals are **too costly**, and the compliance level to mitigation rules is still low. The **lack of an incentive** for space actors to engage in orbital debris removal appears to be a fundamental reason for the approaching "tragedy of the commons".

An **interdisciplinary** modelling priority is needed to include both space debris and mechanisms to **incentivize return on investment (ROI)** for space **active debris removal (ADR)**. This paper aims to provide a commercial and profitable model for incentivizing orbital debris removal by qualifying orbital debris as an "**abiotic in-situ space resource**". It is submitted that most structural parts of space objects are **metal-based**. This presents an economic opportunity, as the current state of the technology exists, allowing for the **recycling** of such metals into **fuel rods** (fuel generation), or into a source material for **3D printers** to fabricate parts and objects within the space environment. In this paper, we convey an innovative perspective of yet another type of resources: in-situ resource utilization of space debris – a renewable, non-depletable, consumable type of resource, fitting supply and demand dynamics, and taking in account their strategic juncture in the sustainability of space. Accordingly, a new legal regime is proposed for the exploitation of these resources.

The paper analyses such technological capability and affordance, in conjunction with resource prospecting needs, followed by **legal issues** on orbital debris extraction. We argue that recycling "abiotic in-situ space resources", as well as defunct and decommissioned satellites, will effectively **constitute in-situ space resource utilization** (ISRU) which can produce **commercially viable space industries**. Pursuant to it, within our model, we **acknowledge mandatory**

first party (property) insurance and **absolute third party liability insurance, both in orbit,** in order to **stabilize the yet volatile space insurance industry** and to provide a commercial incentive for recycling debris by claiming title and benefits derived from **salvage clauses**.
This model leverages the status of resources, anchored in engineering, economical and legal aspects which further the establishment of a foundation for empowering the future of **sustainable** space development.

1.1. Overcoming Obstacle 1: Finding an economic incentive to fighting the Kessler syndrome

We submit that most structural parts of space objects are metal-based. This presents **an economic opportunity**, as the current state of the technology exists, allowing for the recycling of such metals into fuel rods (fuel generation), or into a source material for 3D printers to fabricate parts and objects within the space environment. The technological ability to transform a decommissioned satellite into a fuel source provides another activity for an **on-orbit service** (OOS) facility. In addition to serving as a "gas station," and a "repair garage," an OOS platform can also be a "hospice" for decommissioned satellites having reached the end of their life by facilitating the assets' transition into a fuel source or by transformation into a 3D printable material. Such a **transition** presents an efficient orbital **debris mitigation process** as it allows for recycling of a satellite rather than burial in a graveyard orbit. It is our opinion that the commercial viability of on-orbit platforms recycling satellites into a fuel source will depend on **standardization** mechanism e.g. "hooking" which will allow for "hooking" and retrieving aged satellites. Standardization is not unusual in the space industry as it exists in spacecraft docking mechanisms. An industry standard for a satellite retrieval mechanism is just as important for **Space Traffic Management (STM**) purposes, as a common docking mechanism for rescue purposes and cooperative space ventures, such as the International Space Station. The standardization of a retrieval mechanism associated with recycling satellites can be achieved by industry consensus, market, or governmental fiat. Without some form of standardization, however, commercial recycling of satellites will be a **haphazard** enterprise, instead of a vibrant orbital debris mitigation process. A unified standard or competing standards will commercially emerge only if governmental STM regulations mandated satellite recycling, instead of the two most common practices which are: (1) parking a satellite in a graveyard orbit, upon a satellite being decommissioned or reaching the end of its operational life or (2) relying on "cremation" which is depending upon the Earth's atmosphere to consume the satellite upon its re-entry and descent toward the terrestrial portion of the planet.

To better understand the technology we refer to, "think of this space recycler as an **on-orbit refinery**, powered by that amazing source of **energy** in space called the sun", as one member of industry pointed out [1]. The mechanism would use the heat generated by the sun to **melt down the captured debris**, mostly consisting of metal (aluminium), and either literally vaporizing it or recycling it through 3D-printing it into new components **for in-space assembly** or fuel rods. On one hand, in-space assembly could help trigger a **new space-driven market economy** based on the "**cotsification**" of a **space-based supply chain**, with notable **revenue streams** to be considered. Fuel rods, on the other hand, can represent another important revenue stream disrupting the space **accessibility** sector as the launchers industry remains significantly challenged by the heavy costs of propellant-related resources and propulsion technology. This return on investment represents a **major potential**. However, the space community observes a **lack of economic incentive** towards building such recycler:

> "…right now there is no financial incentive to get rid of space debris (...) that's why we should develop this or similar concepts as a nation. If we can figure out a way to convert dead satellites from **a waste product into an economic benefit**, recycling in space will happen [2]".

This reiterates the **Defense Advanced Research Projects Agency (DARPA)** stance on space debris as space resource: *"If this program (PHOENIX) is successful, space debris becomes space resource* [3] ". Several public and/or private entities are aiming at this **nascent market** and according to some authors, only space policy and legal limitations prevent opening wide the floodgates to a "**space junk rush**".

1.2 Overcoming Obstacle 2: Finding the legal nexus

Indeed, new technological initiatives evolving around ADR confirm the possibility of recycling space debris and transforming them into fuel. Such initiatives come from, among others, the **public sector** (e.g. DARPA), **spin-offs** such as Russian Space Systems stemming from public agencies, which announced successful developments earlier in 2019, and the **private sector**, such as the Australian start-up Neumann Space, which is among the first actors to look into the technology from a **business model** angle. Policy and legal **limitations** include, but are not limited to, the fact that space debris, regardless of their partial or total **dysfunctionality**, are under the **jurisdiction** and **control** of the **State** having **registered** it (registry or mon commonly referred to as the launching State [4]). **Registry State jurisdiction and control can only be transferred to another State, not to a private entity**. Indeed, **Article VIII** of the **Outer Space Treaty of 1967 (OST)** decrees that the nationally registering launching State retains "jurisdiction and control" of any launched spacecraft or component part. Article VIII reads, in relevant pat, as follows:

> "A State Party to the Treaty on whose registry an object launched into outer space is carried shall retain jurisdiction and control over

> such object, and over any personnel thereof, while in outer space or on a celestial body. Ownership of objects launched into outer space, including objects landed or constructed on a celestial body, and of their component parts, is not affected by their presence in outer space or on a celestial body or by their return to the Earth [5]".

Under Article VIII, the owner (**operator**) of a satellite or space object retains its **ownership rights at all time** [6]. Likewise, **title** to a satellite as well as any component part of a satellite always remains with the owner **as space law does not provide for any divesting of title**. Therefore, no actor other than the Registry State or owner has the right to *rendez-vous* a decommissioned satellite or consent to the extraction or recycling of each particular piece of space debris. This circumstance **bars the rush** to space debris and lessens the expectations of economic incentives in that respect. Other policy limitations include the perceived or real **dual nature** (civil and military) of ADR and consequently a **reluctance** from the **Department of Defence (DoD)** to facilitate/enforce military ADR which might add **tensions** to the already **"congested, contested and competitive**" space domain. Furthermore, policy was adopted by no other than **NASA** to **limit** its own ADR capacity for several reasons, budget being one of them:

> "While these small research and development grants are a step in the right direction, NASA has also decided to set strict limits on its investment in carrying research and development of ADR technologies forward. In June 2014, NASA formally adopted a policy to limit its ADR efforts to basic research and development of the technology up to, but not including, on-orbit technology demonstrations. It is believed that the main reason for this limitation was an unwillingness by NASA to take on a potentially costly major new initiative without additional funding from Congress [7]".

Our paper will try to **reconcile** these **divergences** and propose a **model** taking into account **legal**, **policy** and **economic** needs, all the more since the **Technology Readiness Level (TRL)** seems to take a **maturing path**. The stakes reside into boosting the **Demand Readiness Level (DRL)**, still on the rocks, by ensuring a constructive, prosperous and thriving market, especially at a time when cleaning space is becoming an **emergency** for maintaining the security of critical space infrastructure [8]. Our model will essentially rely on the **space insurance (both property and liability) as the nexus for an innovative solution** from the legal, policy and economic standpoints. Our **rationale** is to **upgrade**, from a **top-down approach**, the **on-orbit property insurance regime from optional to compulsory**, and the **on-orbit liability regime from fault-based to absolute** (or strict as in environmental law), getting thus rid of the **difficult burden of proving fault in orbit**, which is still required within the **Convention on International Liability for Damage Caused by Space Objects of 1972 (Liability Convention)**. As of now, property and liability insurance are **required** in some States only at the **launching phase**. Since all objects launched into space are under the ultimate liability of the Registry or "launching" State in case of harming a third party, some States require further liability insurance caps. However, currently, on-orbit property insurance remains only optional and liability kicks in if fault is established and proven, which is difficult, which may **deter** OOS efforts and ADR initiatives such as recyclers.

1.3 Overcoming Obstacle 3: Finding the bridge between OOS and On-Orbit Compulsory Property Insurance (OOCPI) & On-Orbit Absolute Liability Insurance (OOALI)

As is, the space insurance market is **unsustainable** and **volatile** [9]. It finds itself into too much of **a tight spot** to offer ***bonus/malus*** incentives: *"…lacking a robust market for liability insurance, insurers have **less leverage** over the on-orbit activities of satellite operators that could promote best practices and safer behaviour* [10]." Consequently, some insurers look into ways to **adapting** to **market dynamics**, such as **mergers and acquisitions** (M&As) or **innovation strategies** such as **policy aggregation**. For instance, Caitlin XL (acquired by AXA in 2018), proceeded to such aggregation:

> "We have developed this coverage based on our review and monitoring of the space industry as well as on feedback from clients and brokers. With the **proliferation of new, small satellites and launch vehicles, a single, standardized product** will provide easy access to insurance throughout the development and deployment lifecycle of satellites and launch vehicles (...) The policy is a game changer for the aerospace industry which traditionally has had to secure separate Policies for each portion of the process. Now we can insure all aspects and phases under one single policy... [11] ".

Other insurers, **undisclosed** at the moment, work with start-ups, such as **Astroscale** [12], on **new ADR insurance** contractual clauses. Orbital insurance is **necessary**. For instance, the risk of satellite **failure** is almost equally **distributed** between the launch phase and life in orbit (45% during launch, 42% during the first two months in-orbit and 13% between three and twelve months in-orbit [13]). Consequently, from 1968 to 2014, of all insured claims, **72% of them addressed in-orbit failures** (power, altitude control and telemetry), almost equally divided between the separation and initial test phases, first year in orbit and, after two years in orbit [14]. We therefore consider that introducing a new model for space insurance will not only help stabilize the yet volatile space insurance market [15], by making on-orbit premiums mandatory, but also incentivizing the OOS market by securing **a standardized property and liability insurance cover**. Indeed, according to our model, since property insurance [16] will become mandatory on orbit, OOS will be covered *de facto* in terms of property damages. However, it might be argued that since the **OOS client/plaintiff consents to OOS services,** this consent might **exempt** the OOS service provider of property damages undue to *inter alia* gross negligence or misbehaviour. Furthermore, since liability would be compulsory and absolute, both the OOS client and provider will be **protected against third party damages** because liability [17] would apply **automatically**, regardless of fault (with some **exceptions** [18] for either provider or plaintiff in case of gross negligence, wilful misconduct, non-compliance, etc.). This is especially important at a time when orbits become overcrowded, as in the case of **Low Earth Orbit (LEO)**, where **dozens** of projected **mega constellations** consisting of hundreds to thousands of small satellites, will **compete** for both **space** and **spectrum**, for different **service-oriented** configurations such as **5G, Earth Observation (EO)**, etc. Needless to say, the development of a **cislunar economy** with the advent of **the Lunar Gateway** will add to the **traffic**, with potentially more crewed missions. Therefore, the argument based on the fact that, according to the Liability Convention, liability is to be absolute only if the launch causes damages during launch (on the **Earth surface**) or during lift-off (**in the air**) because the **risk** to human life, private property and the environment are highest**, no longer applies**. First, spacefaring nations are not yet equal in terms of technological capability to prove fault and therefore the **burden of proof** might become **discriminatory** towards certain spacefaring nations [19]. Second, technology evolves and space tech merges with air tech in some cases (**spaceplanes**). Moreover, such **distinction is obsolete** as **stratospheric** activities increase and the legal community is still divided upon its jurisdiction **(spatialists** *vs* **functionalists**). One harmonized regime of liability must prevail, and it must be absolute. Third, though required in domestic law, fault and causation are **not required** in **international law**: *"Every internationally wrongful act of a State entails the international responsibility of that State* [20]*"*. Since space law is considered international law, we observe here a **discrepancy**. Therefore, international law should be followed as space includes gradually more **non-space actors**. International **environmental** law is also a relevant field of law to dig into in terms of absolute liability. All the more since in environmental law we find principles related to sustainability such as the **intergenerational equity**, which advocates **resilience** and we consider, along with several other space actors (see table 2) that OOS is a source of resilience. We must insure this source of resilience because OOS operations pose a **higher risk ratio**. Upgrading the insurance standard can be perceived as a drastic measure, but an efficient and timely way to help fight the **Kessler syndrome** [21]. The insurance industry might prove to be an excellent **buffer** between States, satellite owners or operators and the private industry specializing in OOS, by **outsourcing** OOS/recycling contracts but retaining the **benefits** in order to generate and optimize ROI.

Table 1: Comparison between Space Insurance

Regime	**Third Party Liability Insurance (for spacecraft operations)**	**Property On-Orbit Insurance**
Nature as is	*(+/- Mandatory)* *Several States require licensed or registered operators to provide in orbit third party liability insurance*	*Optional*
Function as is **Coverage in case of damage caused by a space debris to a satellite**	*It covers the damage to third parties caused by the owner/operator of the satellite, at the origin of the debris, due to the space activity of the insured*	*It covers "all risks" of the victim (operator of the satellite)* *(burden of proof falls upon victim)*
ON-ORBIT STATUS PROPOSAL	***MANDATORY ABSOLUTE***	***MANDATORY***
INSURED OOS OUTCOME	***SECURED*** ***OOS PROVIDER AND CLIENT PROTECTED DE FACTO***	***INCENTIVIZED*** ***OOS CLIENT CONSENT EXEMPTS PROVIDER UNLESS EXTRA PROPERTY INSURANCE***

1.4. Overcoming Obstacle 4: Taming constellations

Within the current evolution of the space market (**privatization, commercialization, miniaturization, democratization, service-oriented space market**, etc.), and the advent of mega constellations, it remains all the more important to provide for a clear and standardized space insurance regime in orbit, since less than **5% of commercial satellites in LEO are insured today** [22]**.** The danger here resides in the market-driven reluctance to insure **smallsats** in orbit since easily **replaceable**, especially within the context of (mega) constellations which will constitute an increasing source of risk. Currently, there are dozens of mega constellations projected on paper with *circa* 20 000 smallsats. There is much speculation as to whether they would all become sustainable or remain "***paper sats***", however the risks remain and the reluctance towards insurance as well. The following list summarizes the risks:

1. Heightened debris **collision.** Mega constellations are being launched into littered debris areas, which lead to LEO congestion; this congestion makes it more difficult to re-manoeuvring around operational assets, entailing collision, damage, and debris-generation loop. The collision risk is a significant additional consideration for insurers;
2. Decrease of orbit utility due to higher risk of collisions;
3. **Accumulation of risk**. Mega constellations need multiple launches and launchers to replenish and refresh the constellation architecture; this means that a total launch failure is likely to have a material impact on the operations of the overall constellation;
4. **Varied risk**. Constellations are made up of multiple smaller satellites and these smaller satellites may incorporate new technologies, manufacturing processes and space operations and may be built by new entrants to the market, which introduces new and different risks that insurers must evaluate. Change in space systems and new operations augment the likelihood of errors and accidents; on the other hand, new operators less familiar with good practices, still learning lessons, might create additional risk;
5. **Shorter orbital lifetime** (5 to 7 years), smallsats more quickly replaceable;
6. **CubeSats** irregularities plagued with physical capacity issues related to failures, battery backup constraints (latency, anomalies and unknown attitude dynamics);
7. De-orbiting and re-orbiting become practice;
8. **Risk to the sustainability** of space missions, as the current guidelines allow for a 10% failure rate, which does not cope with the present orbital debris environment;
9. **Aggregated insurance policies *per* constellation.** The constellation operator may not require coverage for each and every satellite lost, as they may have planned redundancy in orbit or on the ground or some other contingency which allows some form of loss retention even in the event of a total loss during launch. With risk quantification for large infrastructures, space operators will move towards aggregated insurance policies (*per* constellation);
10. Extended coverage for **constellation performance**. Insurers will seek coverage for overall constellation performance, irrespective of the underlying losses of individual satellites part of the constellation;
11. Citizens **more dependent on non-resilient space systems**, which are ubiquitous to **commerce** [23].

Indeed, operators of these mega constellations consisting for the vast majority in **commercial-off-the-shelf (COTS)** technology readily available out there or 3D printable, consider their assets "resilient": the constellation is resilient as a whole **(service as a whole**) and if one component (smallsat) becomes inoperable, or damaged goods, it shall either be **deorbited**, burned into the atmosphere, or become space debris. Cutting back on investing in insurance premium would, in no measure, prove profitable. Even if such reasoning is understandable from the operator's point of view, it is unacceptable in terms of space debris, as it only adds up to the Kessler effect. Mandatory insurance would imply **wider coverage** and therefore help **reduce premiums** even more so **and help fund OOS** initiatives to clean space and recycling. Furthermore, the absolute liability will cover damages if the smallsat causes damages to a third party in orbit. All these factors will constitute a resilient constellation because right now, as is, they are not. Indeed, **redundancy** is only but one of the four main aspects of resilience. The **four Rs** known for **Robustness**, **Redundancy**, **Resourcefulness** and **Rapidity** [24]. There are initiatives underway for increasing resilience within constellations. For example, one of DARPA's projects dedicated to resilience called **PHOENIX** is developing a concept, in partnership with **Aerospace Corp**, start-ups and spin-offs such as **NovaWurks** and **Arkisys**, in which small satellites ("*satlets*") will **congregate** in space according to different configurations based on mission/market requirements. These satlets will function similarly like organic cells in a body ("**biologically inspired**", "**self-healing**", etc.), embracing resilient features both **internally** (by design) and **externally** (by OOS accompanying the configuration and ensuring maintenance, etc.). Another DARPA program dedicated to resilience and OOS was the **Space Infrastructure Services (SIS)** spin-off, in partnership with **SSL**. However, this particular program was frozen due to SSL's withdrawal based **on MAXAR's corporate transformation** and strategic shift towards dedicating more efforts on EO services (DigitalGlobe legacy). Experts agree though that this withdrawal does not significantly impact the OOS market and that DARPA is actively searching for **other** partners. There is competition from NASA with **Northrop Grumman through its Space Logistics Services (SLS)** spin-off. The case of SIS is interesting for it had already secured future **clients** such as **Societe Europenne des Satellites (SES)** for in-orbit "**roadside assistance**'' and this service was to be **insured** (**payment not due until successful service completion**). All in all, once OOS technology matures, it will prove a suitable means for ensuring mega constellation resilience. Smallsats, as a constellation component, should be taken into account according to their **capacity/service**, not on size and therefore insured accordingly.

Table 2: Nexus between OOS and Insurance

Institutions	Positioning
Aerospace Corporation (Reesman, 2018)	*"The opportunity for on-orbit servicing to have a unique symbiotic relationship with the insurance sector could provide ample assurance to this risk-averse base. (…) The ability to fix anomalies or extend service life for aging satellites can change the way the industry views risk and develops mission plans. (...) Still, the technology carries inherent risks and it will take time to build confidence among stakeholders* [25]*".*
Marsh SA. (Gaubert, 2012)	*"Insurance underwriters have paid out some $700 million in claims for satellite failures caused by propulsion-leak issues or due to the satellites being placed into too-low orbits. In either case, on-orbit servicing could have sizable appeal to operators or underwriters* [26]".

Samson et al. (Samson, 2018)	*"New actions like on-orbit servicing or satellite refuelling could serve to extend the lifespan of many satellites. These changes to expectations of satellite longevity could significantly upset the space insurance market* [27]*".*
Space Infrastructure Services, (SIS 2018)	*Space Infrastructure Services (SIS) offers the world's first on-demand robotic service spacecraft available for missions in 2021 and beyond (...) With SIS, satellite operators can improve **on-orbit resilience** and have unprecedented flexibility for satellite fleet management. (...) **Services are insured** (...) and your satellite continues to operate during most SIS on-orbit robotic servicing procedures* [28]*".*
SSL MDA Holdings Inc. (MDA 2017)	*"Both commercial and government satellite operators are looking for flexibility in managing capital expenditures and better ways to incorporate **resiliency** into their fleets (…) On-orbit satellite servicing will provide operators with the ability to enhance the existing use of space assets through life extension, inspection, and repair. In addition, satellite servicing provides a capability to perform partial assembly in orbit, either **augmenting existing satellites, replacing elements from modular satellites or constructing larger satellites freed from the mass and size constraints of launch*** [29]*".*
David Belcher, Scott Freese et al., IAC (Belcher, 2014)	*"**OOS operations are fairly new**, they do not have the historical data required by insurance companies to assess adequately the risks of OOS activities. Such insurance would cover not only indemnification against liability for damages to a third party, but also the possibility of damage to the client and servicing satellites. Lack of data and experience with the risks of in-orbit operations makes **procuring insurance difficult**. Solutions: Technical demonstrations should be continued in order to gather technical and operational data necessary to adequately assess the risks of OOS activities, and an assessment of the actual costs of an eventual accident* [30]*".*

1.5 Overcoming Obstacle 5: Finding Salvation

This would be made possible by insurance clauses such as the **salvage clause**, originally stemming from **maritime law** and which made its way into space insurance contracts. UNIDROIT defines it as:

> "Salvage' is a legal or contractual right or interest in, relating to or derived from a space asset that vests in the insurer upon the payment of a loss relating to the space asset [31]".

Although mostly unheard of within the larger space domain, in comparison with maritime bounty hunters or spectacular salvage operations, clauses allowing for salvage do exist in space insurance contracts. However, legally speaking, private entities proceeding to such rescue might not, according to space law, obtain title (jurisdiction and control), as mentioned earlier. Indeed, Registry States are **responsible** for "their" space objects:

> "Layered on top of the launching State concept is the mandatory "**authorization and continuing supervision**" provision, contained in Article VI of the OST, making every State involved in a space activity **bear international responsibility for national activities, including those carried on by non-governmental entities.** As a result, a State which is not considered a launching State under the OST may still be **held liable if the owner or operator** of a space object is a national of that State. Thus, while the registry is a useful tool for identifying relevant space actors, it is only the beginning of the inquiry as to what nations may be impacted in a salvage mission [32]".

However, through salvage clauses, **ownership**, and ultimately **title to generated profits**, but not of the *spacecraft per se* [33], may be **transferred**, to insurers, if so written in the insurance contract and if the insurer thereof chooses to exercise the right of salvage.

> "Salvage, though usually provided in space insurance contracts, as stressed by the insurers, is rarely enforceable in practice. It may be applied in situations where the satellite still operates, even if in a limited scope, after being declared totally lost. It is possible in practice to carry out the salvage right in the case of TCL (for total constructive loss), as in the case of total loss, the **satellite usually no longer operates** (or no longer exists). The salvage right has a practical significance in the early states, where the satellite lifespan is still long, and, in spite of malfunctioning, it may **generate some revenue over a longer period**. At this state, the satellite may still be of a potential significant value. That is why insurers, when compensating the damage of the insured, are **entitled to that value as salvage**. I should be noted that the salvage right of the insurer may be in conflict with the right of the investors expecting a revenue on the space project, especially if it concerns "comsats". Most conflicts in this area occur in the case of a partial loss or TCL), where the satellite life is shortened [34]".

This last sentence means that recycling is less likely to be concerned by such conflicts as we discuss debris. Indeed, "*...once a satellite loss has been **compensated in full**, the insurer may be entitled to salvage in accordance with insurance contract clauses* [35]". What is of interest to us is that: "*according to the standard salvage clauses, if the insurer pays proceeds after a satellite loss, it **<u>is entitled to salvage in the form of title, sales, proceeds from or a percentage of the revenues generated from the malfunctioning, but still operating satellite</u>*** [36]". Here lies the **financial incentive** we are looking for and therefore we must assess the ROI from debris recycling and its ISRU sustainability and profitability. At this stage, we might stress the relevance of salvage in space to fight the threat of space debris similar to the "*the concept of special compensation beyond pure property salvage for **<u>preventing environmental damage</u>***", which was codified and expanded by the **International Convention on Salvage**, 1989 and which entered into force in 1996:

> "Article 14 of the Convention considers protection of the environment (even beyond oils spills) as part of salvage and therefore subject to reward if **contamination is prevented by the salvor**. Such reward, informally called **"liability salvage,"** is termed "**special compensation**" by the Convention, as opposed to compensation for property salvage [37].

The good news is that standardized **metrics** are put into place, since 1999, in the maritime insurance market with regards to salvage cases in terms of compensation (**Special Compensation Protection and Indemnity Clause or SCOPIC**) and only 9 out of approximately 330 cases have gone to arbitration [38]. Therefore, **transparency** efforts have proven successful towards salvage. Typical salvage clauses read as follows:

> "...if a covered loss leads to a reduction of the lifetime or operational capacity of the insured satellite below a threshold, typically set between 75 % and 90 %, it will be declared a 'constructive total loss', in which case the satellite will be totally indemnified by the insurers. (...) As a counterpart to such full indemnification, **insurers may be entitled to the sole rights of salvage, a concept originating in maritime law under which title to the satellite will pass to the insurers**, who are **free to sell it on**… [39]".

At this point, if the insurer would exercise the right of salvage, according to our model, the insurer would acquire the title, even though on the space registry the satellite would still figure under the ownership of the launching State in accordance to the space law liability requirements:

> "Since the authority to launch and operate a satellite is given specifically to the satellite owner/operator, the situation in a satellite salvage is more **complex** than a general one. This authority is not a transferable asset which can be acquired by insurers under any rights to salvage [40]".

This means that the insurer will **replace the operator but not the launching State**, not affecting thus the liability regime. This would result in the fact that the insurer might, among others, recycle or outsource the recycling of the "debris" to a third party and benefit from the benefits thereof generated (i.e. selling the in-orbit produced fuel, selling in-space assembled COTS, etc.). In-orbit assembled "*cotsification*" might, in the long run, or long "free fall", represent an appealing revenue stream. Salvage might indeed remain mostly unheard of today, however, it has been applied at least twice in the past. Indeed, in 1984, two spacecrafts, the **Westar VI** and the **Palapa-B2**, were left stranded in LEO and were **rescued** by the Space Shuttle before being left in storage until insurers would figure out what to do with them. Ultimately, they **sold** them six years later, respectively as **Asiasat-1** and **Palapa-B2R** [41]. The next step is to **enforce environmental salvage and incentivize recycling in-orbit**.

1.6 Overcoming Obstacle 6: Transforming risk (space debris) into opportunity (space resources)

Creating an incentive to help mitigating the proliferation of space debris, provide for cleaner orbits and facilitate recycling is all the more important by means on insurance as most insurers are reluctant to provide on-orbit third party liability insurance coverage for space debris per se as they present an increasing risk on the long term. A minority does offer it, but on the short term only, which usually means one year [42]. The lack of uniform definition of space debris in space law adds up to the puzzling guidelines. The expected growth of satellite constellations [43] will result in an increased number of space debris up to a complete congestion of LEO orbits [44]. In the face of the proliferation of space debris, the last two decades have seen the multiplication of guidelines encouraging States to respect their international commitments and the obligations that these commitments incur in their care, as shown in table 3.

Table 3: Positioning on debris

Stakeholders	Positioning
IADC Space Debris Mitigation Guidelines	*Prevention of orbital break-ups, removal of end of mission spacecraft and orbital stages, limitation of objects released during normal space operations.*
UNOOSA [45]	*Compendium of space debris mitigation standards adopted by States and international organizations.*
UNCOPUOS	*Working Groups on Space Debris; Long-term Sustainability of Outer-Space Activities.*
ESA and Airbus Study	*New constellations would need to de-orbit their old, redundant spacecraft within five years, or run the risk of seriously escalating the probability of objects hitting each other* [46].
Lloyd's Realistic Disaster Scenarios (RDS) [47]	*Adopted a number of Realistic Disaster Scenarios (RDS) with four potential risks, whereby collision with space debris is one of them (1-in-15 years).*
Hugh Lewis' team (working with ESA) [48]	*The study showed that even with high compliance to current space debris mitigation measures, the number of catastrophic collisions over the period could increase by about 50% if old practices are maintained. They propose reducing to five years.*
Brian Holz, CEO OneWeb/Airbus	*Stated his constellation was to set new standards in debris mitigation, adhering to a two-year commitment, using also refuelling and in orbit servicing* [49].

ESA	*ESA Debris Mitigation Handbook. Holger Krag, head of the Space Debris Office at ESA claimed current spacefarers do not comply with mitigation measures. "Forty percent of all missions fail to implement this today* [50]*".*
NASA ODPO's Large Constellation Study [51]	*Concluded that to prevent serious long-term debris problem, 99 % of the spacecraft must deorbit within five years after they complete operations.*

1.7 Overcoming Obstacle 7: Finding the right ISRU technology for recycling and 3D printing

Within the space community, there has been much **debate** over the status of space resources and whether they could be harvested. In 2015, the United States passed the **Commercial Space Act** [52] allowing US citizens to engage in the **commercial extraction of space and asteroid resources** [53] A space resource is defined as an *"**abiotic resource in situ in outer space**"* which includes but is not limited to water. *"* It is important to note that that U.S. legislation does not limit its application to natural resources. Indeed, it defines a *"space resource" to mean an "abiotic resource in situ in outer space"* and clarifies that the term **includes natural resources such as water and minerals**.

> This **broad definition** indicates that "space resource" extends beyond natural resources and can encompass resources which are of **artificial origin**. Indeed, space debris is abiotic as it is not alive and has never been alive. Thus, to the extent space debris can serve as a **fuel source**, it can be classified as a space resource within the definition of U.S. law and accordingly be subject to commercial recovery by a licensed United States citizen (…) **The ability to harvest or extract space debris for purposes of transforming it into a fuel source for other space ventures provides the economic incentive for cleaning up debris which has long been absent** [54].

However, the **commercial viability** of on-orbit recycling satellites into a fuel will depend on mechanism standardization. Industry is already working on the concept. Examples include the Australian start-up named **Neumann Spac**e which is developing an integrated solution. Indeed, it has patented a **solar-electric ion drive** which uses a solid fuel rod to power satellites, manufacturing thus fuel from "**nearly any metal**", in orbit [55].

> Most important, though, is **that aluminium is one of the metals that can be used to make the fuel rods**. Since most space objects are composed of aluminium, this means that existing space debris and aging satellites present an available fuel source *in situ* in outer space. Accordingly, the potential exists for space debris and for retiring satellites to be reincarnated as fuel rods. In other words**, debris and aging satellites can become a valuable space resource** [56].

As observed, the TRL of this concept is gathering **momentum** and critical mass. What remains to be clarified is the DRL and in order to facilitate its thriving, measures have to be taken to incentivize the market at the **governance** level.

1.8 Overcoming Obstacle 8: Framing the right governance model

Creating an environment adapted to such incentives requires work to be done at the legal and policy levels. There could be much discussion as to whether **soft law or hard law** would be better equipped to address these issues. There are *pros* and *cons* to both. **However, we might have reached a level where we already have tested the efficiency of soft law and self-regulation and can conclude that unless pushed harder, the industry won't budge much by itself. Especially the space insurance industry, and even more so with regard to environmental matters.** With so much at stake, hard law measures should be favoured, where **compliance would be binding** and not voluntary anymore. We passed this stage. Indeed, concerning space debris, at first the legal community created **guidelines** (e.g. **Inter-Agency Debris Committee Coordination** or **IADC** guidelines [57], etc.), but now, **national legislation**, such as France's case [58], requires **compulsory measures** for decommissioning satellites. This is the way to go for space recycling. International regulation should be drafted with the scope of harmonizing standards, metrics, etc., such as the SCOPIC in maritime salvage. Space salvage should be clearly defined in the context of space. Contractual clauses should incorporate this work within space insurance contracts and space insurance/liability has to be adapted following our **recommendations**. This scenario would be preferable as it would incentivize the private sector into assuming responsibility and not counting on classic principles such as "***polluter pays***", which in most cases means the State has to pay, and in the end the **taxpayer collects the bill**. Indeed, as space is increasingly becoming another service-oriented domain, increasingly so governed by **commercial interests**, and therefore **World Trade Organization (WTO) prerogatives surrounding the privatization of services and optimization of profit**, it is important to set into place **strict measures regulating the potentially immoderate** commercial interests in space. The OST of 1967 makes sure that space remains a sanctuary, but the **tragedy of commons foretells a rather bleak unfolding if clear legal beacons are not set in motion now.**

Appropriate and **action-oriented forums** for such discussion could include the newly created **Office for Space Commerce**, within the **US Department of Commerce (DoC)**, which has been granted authority on **STM and its commercialization guidelines** [59], along with the Department of Transportation (DoT). It could engage in a dialogue with consortiums such as the **Consortium for Execution of Rendezvous and Servicing Operations (CONFERS)**, put in place by DARPA, *"to establish '**Rules of the Road**' for On-Orbit Servicing of Satellites. It aims to help developing technical and safety standards for performance of in-orbit activities involving commercial satellite…"*, which is comprised of a majority of public and private **key players**. However, to bear fruit, this **dialogue** should be more **inclusive internationally** and counterparts should be identified at the international level (Europe, Asia, Africa, Latin America, etc.). An inaugural conference could be a start, following ICAO's example whose foundations were laid out during the Chicago Convention of 1944. The purpose of this **conference** could be, for starters, **amending proposals** to the Liability Convention of 1972 to include (some) of the mentioned recommendations, which would later on, when matured, be discussed at the UNCOPUOS. But to **accelerate the process**, the topic has to be backed by **consensus upstream**, before entering UNCOPUOS ground. From then on, governance models such as the **International Telecommunications Union (ITU)** could be looked into for its **efficiency dimension** and since it too copes with space resources (spectrum), and a blooming crisis (shortage), while channelling both public and private interests, at the international level and beyond.

2. Discussion

Salvage remains a solution *in extremis*, when a satellite is beyond repair or becomes useless **--** space debris and waste to be recycled. It is to be applied when the situation is beyond the possibility of proceeding to corrective measures. Indeed, such contractual duty to correct defects lies mostly in unlaunched spacecraft or during early life in orbit (test phase, etc.) or the remainder or the in-orbit insurance, which as stated, usually lasts one or two years. Cross-waivers may however reduce their legal scope and so the problem remains unsolved. For this reason, salvage remains the ultimate option for transfer, since we need a legitimate buffer between States, operators and private salvors: (re)insurers. **Furthermore, different title transference scenarios could be drawn legally in the future that could lead to the potential creation of a commercial title registry market for items manufactured in space using debris**. For instance, title to the metallic space debris could be transferred to the on-orbit satellite recycling facility. **Otherwise,** under Outer Space Treaty Article VIII, ownership of the fuel rods and objects made from the metallic debris will **remain with the owner, whether it is the original owner or the insurance company that took title pursuant to a salvage clause**. This necessitates transference of ownership rights being a part of the on-orbit recycling agreement between the debris owner and the recycling facility. The recycling facility will then, in turn, transfer title to the purchaser of the fuel rods or objects made from the metallic space debris, if need be. If, in turn, this chain of actors proves to be too complex, **another solution** worth considering would the **expropriation** as a means of reducing the number of actors with rights or interests in space debris. This is **practical** in as much as launching remains liable for each piece of debris that was a part of a space object that it launched. If it is liable for space junk, it may as well have the ability to take title to it if necessary for ADR purposes. Nevertheless, it would **not solve** the defective proportion of the "polluter pays" ratio.

3. Conclusion

Our **rationale** is to **upgrade**, from a **top-down approach**, the on-orbit property and liability insurance regime, respectively from **optional to compulsory**, and from **fault-based to absolute**, getting thus **rid of the difficult burden** of proving fault in orbit. Creating an **incentive** to help **mitigating** the proliferation of **space debris**, providing for **cleaner orbits** and facilitate recycling are all the more important by means on insurance, as most insurers are reluctant to provide on-orbit third party liability insurance coverage for space debris *per se*, as they present an **increased risk on the long term**. The model takes into consideration that the Technology Readiness Level (TRL) is gathering momentum and critical mass. These proposals would incentivize the private sector into **assuming responsibility** in exchange of ROI, and not counting on classic principles such as "**polluter pays**" which, in most cases, means the State has to pay, and in the end, the **common taxpayer collects the bill**. The next step is therefore **to enforce environmental salvage** and investing in OOS and recycling through the appropriate governance forum and take action towards overcoming all the above-mentioned challenges. Our conception of space debris as space resources aligns with the dedicated purpose of ISRU: "*Harnessing and utilize space resources to create products and services which enable and significantly reduce the mass, cost, and risk of near-term and long-term space exploration* [60]*"*.

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[4] Article VII of the Outer Space Treaty of 1967 (OST) identifies four possible launching State categories: the State that launches the object or spacecraft; the State that procured the launch; the State from whose territory the object was launched; and the State from whose facility the object was launched.

[5] Outer Space Treaty of 1967 (OST)

[6] Article VIII further provides that the Registry State possesses jurisdiction and control over a satellite or space object registered by it pursuant to the Registration Treaty. A registry State possessing jurisdiction and control over a satellite or space object is not ownership. By analogy, think of ocean vessels. Ships have private owners, but the ship is subject to the jurisdiction and authority of its flag state. The flag State is not the owner. Title to the ship remains with the owner. This is essentially a similar concept. Therefore, no actor has the right to *rendez-vous* a decommissioned satellite.

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[14] Ibid, *supra* note 13.

[15] Kunstadter, *supra* note 9. Indeed, there is low frequency of losses, but these losses are characterized by high severity: it is a market where one launch can generate 10% of annual income, while one loss can obliterate the entire annual premium income. “The nature of this business is very volatile. You don't have many losses, but when you do, they're large".

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[17] Kunstadter, *supra* note 9. Third party liability insurance protects operators from claims from third parties for damage arising due to their space-related activities, whether during launch or in-orbit operations phases. Damage covered by third party liability insurance include third party claims resulting from: launch vehicle causing contamination; spent rocket parts returning to Earth or remaining in orbit as a collision risk; and damages caused by a satellite (belonging to the insured) as a result of a collision.

[18] Act of God in space should be redefined as we consider that, as is, this exclusionary clause avoids resilience measures by not pushing for stronger standards otherwise achievable, based on technological developments.

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