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Identifying the 50 statistically-most-concerning derelict objects in LEO

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A R T I C L E I N F O

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A B S T R A C T

This paper describes a process for identifying the intact objects in orbit that (a) pose the greatest debris-generating potential risk to operational satellites or (b) would reduce the risk the most if they were removed or prevented from colliding with each other (i.e., remediated). To accomplish this, a number of diverse, international space organizations were solicited to contribute their lists of the 50 statistically-most-concerning objects. The results of the multiple algorithms are compared, a composite ranked list is provided, and the significance of the consolidated list is presented including critical assumptions and key factors in determining this "hit list." It is found that the four primary factors used in these processes are mass, encounter rates, orbital lifetime, and proximity to operational satellites. This cooperative international assessment provides a useful ranking of the most hazardous massive derelicts in low Earth orbit as a prioritized list for remediation to (1) enhance space safety and (2) assure long-term space sustainability. This will hopefully catalyze international action in debris remediation.

1. Introduction

While development of space debris mitigation guidelines began in earnest in the 1990s and space traffic management (STM) activities are accelerating, substantive operational debris remediation efforts have been slower to materialize. The reticence of the space community to execute debris remediation activities is primarily due to four issues: 1. the cost of debris remediation alternatives is uncertain, but probably expensive, and their performance is unproven; 2. ownership and access rights to physically manipulate and remove objects registered to other states are uncertain and potentially contentious; 3. the objects most needed to be remediated have not been identified clearly in a multinational forum to enhance space safety and assure long-term space sustainability; and 4. the attempt to remove or nudge a massive derelict (i.e., remediate) does pose the potential for unanticipated debris

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Acronyms/Abbreviations

Active debris removal (ADR)
Low earth orbit (LEO)
Payload (PL)
Rocket body (R/B)
Statistically-most-concerning (SMC)

generation.

This paper addresses the third issue, identifying a prioritized list of objects for debris remediation that was created by a multi-national group. This will hopefully motivate organizations to develop a range of remediation options that are both effective and reasonably-priced while encouraging governments to fund projects to jump start debris remediation. The aerospace community is actively discussing space traffic management (STM) and debris mitigation, providing a foundation to minimize the creation of space debris and collision risk. Nonetheless, there is a need to remove from orbit some of the millions of kilograms of intact derelict mass because of their debris-generating potential. This hardware has been deposited in orbit either due to non-compliance with established debris mitigation guidelines or abandoned before mitigation guidelines were established.

As a result, debris remediation concepts must be be developed, tested, and deployed quickly to remove some of this hardware. One means to motivate this process is to develop an internationally-derived "hit list" of the statistically-most-concerning (SMC) objects in low Earth orbit (LEO) with the greatest potential to disrupt space activity. While active debris removal (ADR) is often proposed, debris remediation alternatives, such as "just-in-time" collision avoidance (JCA), long-term debris management (LTDM), and nano-tugs, can also be applied to the list compiled in this paper [1]. A JCA system would simply nudge one of two derelicts that are on a collision course to prevent that imminent collision. The impulse could be delivered by a physical cloud (such as an upper stage rocket plume or a puff of talc from a ballistic trajectory) or by a laser (possibly either ground-based or space-based). LTDM is a system that whereby a space-based laser system will provide multiple small impulses to derelicts to maintain their spacing to avoid collisions or even close approaches. A nano-tug is a small satellite that could be attached to a massive derelict to provide it with attitude control, collision avoidance, and position determination capabilities. There may be a safety benefit to "remediate in orbit" objects that are very massive and, as such, will likely pose a significant ground and aviation impact hazard upon reentry.

As early as 2009, NASA identified the objects that would need to be removed to curtail space debris growth [2]. There are nearly 1300 massive derelict objects in LEO that comprise over 2,000,000 kg of mass distributed in clusters in altitude and inclination, creating pockets of high debris-generating potential [3]. These objects average over 1800 kg in mass, with one cluster of 36 objects centered around 850 km averaging over 6000 kg each. Most of these objects were abandoned before 2000, but due to poor mitigation compliance since then, derelict mass continues to accumulate as depicted in Fig. 1.

The international experts who contributed their "top 50" lists each (1) explain their process for selecting their SMC objects in LEO and (2) provide their list as of the time of the publication of this paper. All non-operational objects in the on-line Space-track.org catalog are eligible for consideration, and all contributed lists have focused on LEO objects, due to their larger collision velocities and higher spatial density.

These 11 methods generate different results based on diverse hypotheses and approaches. Some of the approaches focused on short-term space safety (e.g., McKnight, Witner, Nicolls, etc.) while others scrutinized long-term sustainability (e.g., Lewis, Letizia, Rossi, etc.). However, Baranov/Grishko is the only team that focuses largely on efficiency of removal. Space safety metrics are likely linked to immediate collision risk while sustainability may focus more on the accumulation of the debris population over time. Nevertheless, they are globally coherent in the identification of the subset of the statistically-most-concerning derelict objects in LEO. Indeed, this paper applies the diversity prediction theorem that states the combination of a series of reputable but different decision schema provide a superior aggregate model than trying to determine the "best" of the available models [4].

This paper, thus, describes and integrates a variety of methods to evaluate the criticality of derelict resident space objects (RSO). The consideration of these results, as an absolute listing, is limited by the completeness of the database provided by Space-track.org. While there is currently no better database of on-orbit objects, it is known that there are some sensitive military and intelligence community satellites excluded from Space-track.org.

2. Approaches for identifying objects to Be removed from LEO

A short description for each approach used to determine the top 50 SMC objects is provided below; please refer to identified references for full descriptions of these approaches.

<u>McKnight, US, Centauri</u>: The Massive Collision Monitoring Activity (MCMA) has monitored and characterized the encounter dynamics of massive (*i.e.*, greater than 700 kg) intact derelict objects in LEO over the last five years [6,7]. This activity currently scrutinizes nearly 1300 objects that comprise over 2,300,000 kg in a series of clusters that are identified by the altitude of the center of each cluster (e.g., C975 contains objects that are roughly centered at 975 km). The SMC

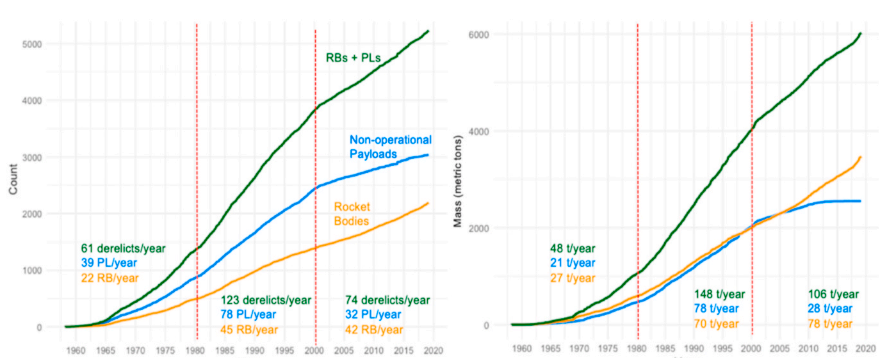

Fig. 1. The accumulation of massive derelicts in number (left panel) and mass (right panel) in Earth orbit has progressed unabated, but the 1980–2000 era is still the most responsible for the current population of abandoned hardware – rocket bodies, non-operational payloads, and their sum. The figures above include all objects in Earth orbit; the small region of LEO contains about half by number and mass of all Earth-orbiting derelicts [5].

objects are selected from this population by determining the potential risk as the product of probability and consequence of collision.

This list will change over time as actual encounter dynamics are used to calculate the SMC rank. The equation is:

$$\begin{aligned} \text{SMC} &= [\text{probability}] * [\text{consequence}] \\ &= [\ \text{CR} * \text{AR} * \{ (\text{E5}/25) * (5*\text{E1}) \}\ ] * [\ \text{MF} * \text{PE} * \text{SPDO}\ ] \end{aligned} \quad (1)$$

Where *Probability Factors*:

CR = annual collision rate of the MCMA cluster within which the object resides;
AR = area (m^2) of the object which is determined by multiplying its mass, in kg, by 0.005;
E5 = encounters less than 5 km per year, divided by 25 to reduce its effect;
E1 = encounters less than 1 km per year, multiplied by five to amplify its effect.

Consequence Factors:

MF = mass factor, derelict mass (in kg)/1500;
PE = persistence, lifetime of an intact object at the center of the cluster;
SPDO = spatial density of operational satellites (#/10^9 km^3) within 150 km of each cluster, #/km^3.

Every object that is considered has a foundational risk based on the cluster within which it resides and its physical size (i.e., CR * AR) that is then weighted by the 5 km and 1 km miss statistics, with more emphasis placed on the 1 km misses. The consequence for each object is a combination of its mass, as this drives the number of objects likely to be released in a collision, modulated by the persistence of the debris (how long this debris will remain in orbit) and the number of operational satellites that are near an SMC object. The SPDO effect has been "softened" since debris liberated at higher altitudes (e.g., 850 to 1500 km), where there are currently fewer operational satellites, will eventually decay through the lower altitudes, and, in the future, a significant number of satellites will be launched into these higher altitudes.

Witner, US, North Carolina State University: Risk posed by massive derelict objects is framed as consequence times probability.

Consequence is the sum of three components: combined mass of the objects, approximate persistence of debris at the conjunction altitude, and number of operational satellites nearby. This algorithm treats these three as being of equal importance. Combined mass contributes to consequence, since the amount of mass involved in a conjunction is directly proportional to the amount of debris that is expected to be produced by a collision. Persistence is based on orbital lifetime using altitude-dependent atmospheric density and coefficient of drag. The persistence function was developed by using discrete lifetime for debris objects (A/M = 0.1 m^2/kg) using Desmond King-Hele [8] is shown in Fig. 2. If a collision occurs near where many operational satellites reside, the debris is more likely to pose a collision risk to those satellites. Thus, for each conjunction, the spatial density of operational satellites at that altitude is applied.

The probability component is based on the miss distance of each conjunction, the smaller the miss distance the greater the probability. In general, risk increases exponentially as miss distance reduces.

However, due to the uncertainty inherent in the use of two-line element sets (TLEs) for miss distance estimation, this trend does not hold for misses that are reported to be under ~1 km. The margin of error for these miss distances is so significant that it is not fair to conclude that a 0.05 km miss is exponentially riskier than a 0.5 km miss. Thus, the probability component is quantified by dividing consequence by 10 to the power of the miss distance, if miss distance is greater than 1 km; otherwise, dividing consequence by 10. For example, consider the consequence component of a conjunction is 300.

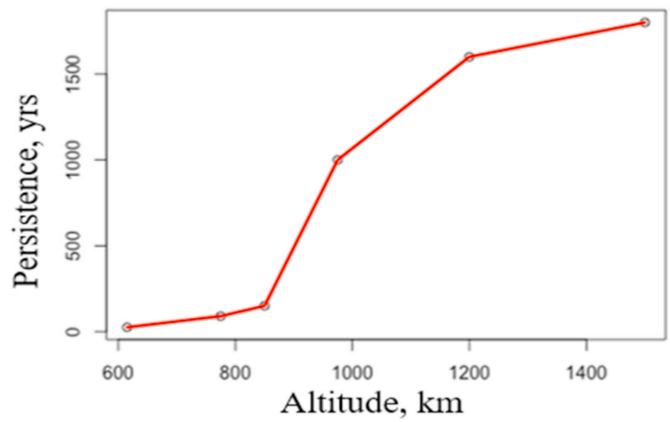

Fig. 2. Persistence of generated debris gets larger at higher altitudes.

Table 1 shows the "risk" for various miss distances but it should be noted that this is merely a scaled qualitative risk and not a true probability of collision. This demonstrates that conjunctions under 1 km contribute exponentially more to risk than conjunctions greater than 1 km. After calculating the risk of each conjunction, risk is summed over each object to get the total debris-generating risk that each object poses. The cumulative risk thus continuously increases as the number of close and highly consequential conjunctions accumulates over time. While this approach is advantageous as it is based on real conjunction data it is biased to the observation period used which might differ from actual long-term collision statistics for these derelict objects.

Anselmo & Pardini, Italy, ISTI/CNR: In order to evaluate the environment criticality of objects abandoned in LEO, several criticality indices were developed at ISTI [7–12]. The most complete "full" (F) approach is the "normalized" (N) "ranking" (R) index R_N developed in 2014 (RN-F-ISTI-2014) [9,13–15]:

$$R_N \equiv \frac{F}{F_0} \cdot \frac{l}{l_0} \cdot \left(\frac{M}{M_0}\right)^{1.75} \cdot \frac{LD50}{LD50_0} \cdot \frac{z}{z_0} \quad (2)$$

where *Probability Factors*:

F = orbital debris flux able to induce a catastrophic fragmentation of the object to be ranked, assuming a kinetic energy threshold, in the impact center of mass, of 40,000 J/kg;
l = lifetime function of the object to be ranked;
M = mass of the object to be ranked.

Consequence Factors:

$M^{0.75}$ = potential of a given mass to generate fragmentation debris (as per NASA Standard Breakup Model);
$LD50$ = time needed for the decay of 50% of the fragmentation debris ≥10 cm generated by a potential catastrophic fragmentation of the object to be ranked;

Table 1
Risk varies exponentially with miss distance.

Miss distance (km)	Risk
5	$300/(10^5) = 0.003$
3	$300/(10^3) = 0.3$
2	$300/(10^2) = 3$
1	$300/(10) = 30$
0.3	$300/(10) = 30$
0.05	$300/(10) = 30$

z = ratio between the flux of debris able to induce a catastrophic fragmentation at the orbital inclination of the object to be ranked and the flux at zero inclination; it was introduced to take into account that high inclination orbits can interact with more objects then equatorial ones and, therefore, any new sizable debris released into a high inclination orbit has worse potential consequences compared with a new debris released at low inclination.

Normalization is obtained by computing the same factors for a reference object (with zero subscript in the equation), representing the average intact object in LEO in mid-2013, with $M_0 = 934$ kg, placed into a circular sun-synchronous orbit at 800 km. Trying to avoid weighting objects too much due to their extremely long lifetimes, i.e., greater than ~230 years, appropriate upper limits are applied to l and $LD50$, so that $l/l_0 \equiv 1$ when $l > l_0$, and $LD50$ stops rising above 1250 km.

Letizia & Lemmens, ESA: ECOB (Environmental Consequences of Orbital Breakups) is a risk indicator, built from the general expression Risk = Probability x Severity, where the Probability term (p) captures the likelihood that an object is involved in a fragmentation event and the Severity term (e) quantifies the consequences of such an event. Specifically, p represents the probability of collision with objects large enough to trigger a catastrophic collision where enough energy is released that the parent object is destroyed.

The availability of collision avoidance capabilities can be captured by removing those objects that are large enough to be tracked with current surveillance systems and can be avoided with collision avoidance maneuvers from the computation of collision probability. The term e quantifies the effect of such fragmentations as the increase in collision probability for operational satellites. This is done by defining a set of representative objects of the population of operational satellites and computing the collision probability for those objects due to the simulated fragmentations. The focus on operational satellites is clear and meant to incentivize operators to consider how their future operations are affected by current decisions. More details on the approach used to model the probability and severity terms can be found in Ref. [16].

The risk metric so-defined (I) is not computed only at a single epoch, but rather evaluated along the mission profile of an object to capture two key elements: the implementation of disposal strategies at the end of mission and the evolution of the environment in the time frame when the object is in orbit [17]. The first aspect is addressed by considering the possible paths of evolution of the trajectory depending on the success rate of the disposal strategy (α), so that the index computation becomes

$$\mathrm{ECOB} = \int_{t_0}^{t_{EOL}} I\mathrm{d}t + \alpha \int_{t_{EOL}}^{t_{fD}} I\mathrm{d}t + (1-\alpha) \int_{t_{EOL}}^{t_{fND}} I\mathrm{d}t \quad (3)$$

The second aspect is addressed by updating the parameters depending on the environment status such as, for example, the debris flux. In this way, by design, the long-term implications of collision risk among inactive objects are captured such that the inherent risk of object clusters and graveyard orbits feed back into the risk of catastrophic collisions.

Rossi, Italy, IFAC/CNR: For a given object with mass M abandoned in space, the *Criticality of Spacecraft Index* (CSI) can be written as [19]:

$$\Xi = \frac{M}{M_0}\frac{\rho}{\rho_0}\frac{L}{L_0}f(i) \quad (4)$$

where.

M = mass of the object;

ρ spatial density associated with the orbital shell where the object is residing in a given year computed by evolving a reference scenario of the space debris environment with SDM 4.2 [20];

L = lifetime of the object at the altitude corresponding to the shell; and

$f(i)$ = function of the orbital inclination i, reflecting the fact that the typical flux of debris on an almost equatorial orbit is 60% of the flux in polar orbit. Moreover, high inclination orbits can lead to very high mutual inclinations (and, therefore, high impact velocities) due to the differential precessing orbital planes. These high impact velocities imply not only an increased collision probability (which is a function of the relative velocity) but also an increased possibility of catastrophic collisions.

The terms M_0, ρ_0, and L_0 are normalizing factors. The criticality index can be computed also for a given shell of space in the LEO region, for a given year, by summing up the contributions of the single objects residing in that particular shell, as:

$$\Xi_{LEO} = \sum_{i=1}^{N}\sum_{j=1}^{p(i)}\Phi_{i,j}\Xi_j \quad (5)$$

where $p(i)$ is the number of objects moving through the shell, and $\Phi_{i\,j}$ denotes the percentage of the orbital period spent by the object j in the shell i, which is a function of the semi-major axis a and the eccentricity e of the object [19]. Finally, a specific index is developed for the quantification and the quick evaluation of the collision risk for the forthcoming large constellations of satellites in LEO [21].

Baranov/Grishko, Russia, KIAM/BMSTU: The approach for identifying objects to de-orbit in an ADR mission using the “collision risk probability” criterion does not consider key operational features of de-orbiting operations. While creating a list of the most critical derelict objects to be removed from orbit, logistical costs of these missions must be examined carefully. The cost of de-orbiting a single object is high.

At the same time, the orbits from a “risk-based” list do not consider the location of these objects with respect to each other in both altitude and inclination. Here it is relevant to note that the change of orientation of orbital plane is the most expensive part of a maneuver in terms of required ΔV.

As a result, a geometrical approach is proposed. This approach creates a list of objects based on the principle of cost-effective transfers between them during an ADR mission. Derelict objects are prioritized by their large mass (i.e., potential consequence) that reside in highly populated orbits (i.e., poses high risk). Therefore, though this approach considers removal efficiency it also accounts for short-term safety concerns of large debris-generating events.

The objects are classified into five groups as shown in Table 2, and the specific orbits for these objects can be found on pages 119–123 in Ref. [22]. The first fifty in this list are provided as the Top 50 list for this paper. Since the orbital inclination is constant within each group of derelict objects, one needs to correct only the differences in the Right

Table 2
The objects most important to be removed from orbit are in five general families.

Group	# objects	Incl., deg	Interval of semi-major axes, km	Typical mass of an object, kg	Types of objects
1	23	70–71	7193–7281	Up to 9000	18 Zenit-2 (2nd stages), 3 Thor Agena (2nd stages), and 2 Proton (4th stages)
2	11	74	7122–7152	1435	Kosmos-3M (2nd stages)
3	28	81	7211–7262	1100	Vostok-2M (3rd stages)
4	52	83	7318–7358	1443	Kosmos-3M (2nd stages) & Tsyklon-3 (3rd stages)
5	46	97–100	6973–7500	820 to 9000 (typically 4000)	Various

Ascension of the Ascending Node (RAAN) in order to change an orbital plane. These RAAN deviations (up to tens of degrees) can largely be eliminated using the RAAN drift caused by the Earth's oblateness. Starting a transfer from one passive object to another, an active spacecraft lowers its orbit and the RAAN drift increases [23,24].

The parameters of a drift orbit depend on the value of corrected $\Delta\Omega$ and the flight duration [25]. The transversal components are also responsible for the rendezvous solution. In order to determine the sequence of transfers between objects in a group, the RAAN deviations' evolution should be used. This approach results in a significant decrease of lateral components of velocity impulses (*i.e.*, out of plane maneuvers) in all transfers within a group of objects. For sun-synchronous orbits, it doubles the mission efficiency [26] compared with other related papers. With the consolidated list of critical derelict objects taking into account their collision risk and spatial distribution of their orbits, it is possible to single out the sub-groups with similar inclinations. A model of transfers between objects in these sub-groups using the RAAN precession will ensure minimal costs of ΔV, and will permit the evaluation of the quantity and technical parameters of the retrieval spacecraft.

Lewis, UK, University of Southampton: The Debris Analysis and Monitoring Architecture to the Geosynchronous Environment (DAMAGE) model was used to perform 220 Monte Carlo simulations of a 1000-year projection of the future debris population 10 cm or greater in LEO. The simulation parameters used for this study correspond to the parameters used for the current reference case adopted by the Inter-Agency Space Debris Coordination Committee (IADC) and full results are reported in Ref. [27]. DAMAGE is a high-fidelity three-dimensional physical model capable of simulating the evolution of future debris populations [28]. DAMAGE projections make use of the cube approach to simulate future collisions [29].

Within a 5-day projection time step, a random number is drawn and compared with the probability estimated for each pair of target and projectile objects found within 17 km. Collisions are simulated when the random number is less than the collision probability, with fragments generated using the NASA break-up model [30] and added to the simulated population.

Ten metrics were used to represent the hazard posed by every unique object from the initial (February 1, 2018) orbital object population involved in a collision:

1. The average number of collisions involving the object;
2. The average collision probability × mass of the object;
3. The average collision probability × the number of fragments generated;
4. The average number of collisions × mass of the object;
5. The average number of collisions × the number of fragments generated;
6. The average number of collisions involving the fragments of the object
7. The average collision probability of fragments of the object × mass of the objects impacted by the fragments;
8. The average collision probability of fragments of the object × the number of secondary fragments they generated;
9. The average number of collisions involving fragments of the object × mass of the objects impacted by the fragments;
10. The average number of collisions involving fragments of the object × the number of secondary fragments they generated.

The SMC score for an object is the sum of the ranking in each of the lists generated by the metrics above (with a lower rank score corresponding to a greater hazard), divided by the number of lists featuring the object. Objects in the top 50 featured in all 10 lists with the "worst" top 50 SMC score lower than 0.5% of the average score of the 10,000 objects from the initial population involved in collisions.

Kawamoto, Japan, JAXA: JAXA has been studying ADR targets using the Near-Earth Orbital Debris Environment Evolutionary Model (NEODEEM) jointly developed by Kyushu University and JAXA [31]. NEODEEM simulates the trajectories of all objects larger than 10 cm and determines debris collisions by considering the error spheres around those objects. We investigated the effect of ADR by continuously removing many debris objects according to a specific ADR strategy. One, three, or five debris objects are to be removed every year based on the debris indexes, such as collision probability multiplied by mass, the expected number of fragments generated, and the Criticality of Space Index (CSI) [18] as one example (Fig. 3).

Different ADR targets are selected using each index, but the overall trend was similar. Orbital lifetime and altitude have a significant effect on the effectiveness of ADR, thus, objects below 650 km were excluded. The case with expected number of fragments is slightly better for the short-term perspective, and the CSI is slightly better for the long term. Thus, we must decide whether to set priority for a short time span or a long time span. In this paper, we submit the top 50 objects with the highest expected number of fragments in the initial time period calculated in NEODEEM, although we do not consider that it is the optimum index. We consider that the ranking order is not important, as many objects need to be removed to suppress the increase of debris.

As Fig. 3 showed, the long-term space sustainability is not strongly sensitive to either the choice of metric to define objects for removal, and subsequently the choice of objects themselves. Neither is short-term space safety as it depends on the timing and will change soon. It is more important to remediate continuously, and to start remediation as early as possible [32].

The ranking order also changes over time – the top 50 objects of the initial year were not removed in the end if only a limited number of objects are to be removed every year. Note that the top 50 objects in this paper were chosen from the initial population data generated by JAXA, not from the data by ESA used in Ref. [30] and Fig. 3 since ESA's data does not include the Combined Space Operations Center (CSpOC) Satellite Number. This difference is not likely to affect the massive derelicts studied in this paper.

Nicolls, US, LeoLabs: LeoLabs tracks the vast majority of LEO objects greater than 10 cm in size, and is thus able to produce scoring based on individual event statistics. While this approach is advantageous as it is based on real conjunction data it is biased to the observation period used which might differ from actual long-term collision statistics for these derelict objects.

The two key factors in this calculation are (1) the consequence if an event occurs and (2) the likelihood of the event occurring. LeoLabs collision impact score is defined on an event by event basis as $CS =$

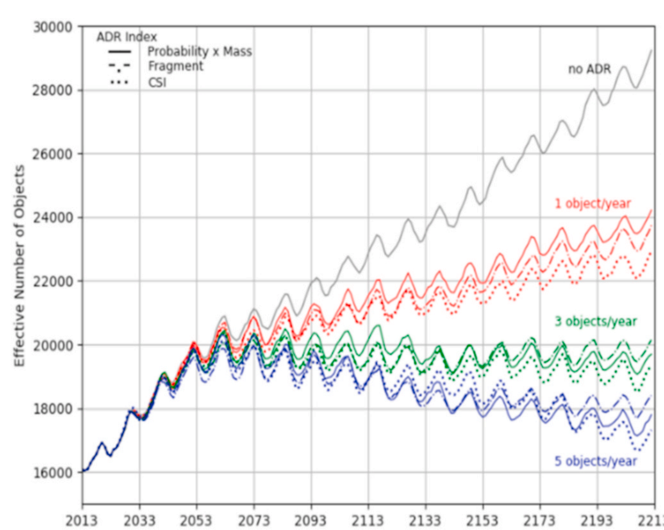

Fig. 3. Effective number of objects predicted by NEODEEM with ADR of 1/3/5 objects per year based on each index.

RCS_{tot} x Pc. The likelihood of an event occurring is encompassed in the probability of collision (Pc). RCS_{tot} is the combined average radar cross-section (RCS) of the two objects and is a proxy for the amount of debris that is expected if a collision were to occur. For a catastrophic collision, the amount of debris objects expected above a fixed object size follows a power law distribution proportional to $M_{tot}^{0.75}$ where M_{tot} is the combined mass of the objects [28]. RCS is generally proportional to the physical cross-section of the object, especially for large objects, and it is reasonable that the power law distribution would scale as the cross-sectional area to roughly the unity power for a uniform density object.

Having defined the amount of debris created, a follow-up consideration is the impact of that debris on the environment, such as how long it persists in orbit, the likelihood of it interacting with other objects, and the likelihood of it interacting with active satellites. These are difficult effects to quantify – barring additional information and complete modeling, we believe that an equal weight should be given to collisions through LEO from 400 km to 1500 km altitude when considering the impact from an individual event. In determining the most-risky defunct objects in LEO, the total impact of any given object is determined by the cumulative summation of the collision impact score across all events, over a statistically reasonable time period. When rating the most-risky objects in LEO, it is also important to consider their lifetime on orbit; thus we multiply by a persistence factor. We select a relatively sharp persistence factor, with values of approximately 0.1 at 400 km, 0.5 at 500 km, and 1 above 700 km. The argument here is that an object that exists at altitudes above 700 km will persist for decades or centuries. The total duration does not matter at that point, as the impacts will continue for the foreseeable future, until there is either a collision or the object is removed.

Dolado Perez & Ruch, France, CNES: The definition of the risk posed by an object to the orbital environment is complex, and subject to variations depending on the concerns of each stakeholder. In order to assess the risk posed by intact objects to the orbital environment, both short- and long-term, CNES is developing INDIGENE, a tool that calculates an environmental index for a given object [32,33]. Given the multi-dimensionality of the problem, and in order to capture globally the impact that an object or a space mission may have on the orbital environment, INDIGENE is built from methods computing the interaction between an intact object or a space mission and a given orbital population, such as CSI [18] and ECOB [16], combined with numerous additional data related to how the satellites are built and operated. Each term contributing to the environmental index is normalized in order to be able to sum up comparable terms. They are then weighted by the user (e.g., certification authority) according to the importance attributed to the different terms. In the frame of this study, we will not consider all the operator data, most of which is unavailable for the objects under consideration. As the calculation of the ECOB can be relatively long, we start by establishing a preliminary ranking with the CSI.

On the basis of the latter, we obtain the final ranking by analyzing the indices of the first 400 objects in the preliminary ranking. The final index is obtained according to the following calculation:

$$I = \omega_{ECOB} I_{ECOB} + \omega_{CSI} I_{CSI} + \sum_k \omega_k I_k \tag{6}$$

where:

$$I_{ECOB} = p_{coll} e_{coll} + p_{exp} e_{exp}$$

p_{coll} and p_{exp} : probability that a fragmentation (collision and explosion, respectively) occurs, as described in [16].

e_{coll} and e_{exp} : effects of considered fragmentation (collision and explosion, respectively) as described in [20].

I_{CSI} : index described in Ref. [18], but with a slight modification of the lifetime calculation to correspond as closely as possible to the lifetimes calculated by the STELA semi-analytical propagator [31].

Thus, the lifetime is calculated as follows:

$$lifetime\left(h, \frac{S}{M}, \overline{F_{10.7}}\right) = f\left(\frac{S}{M}\right) \times g\left(\overline{F_{10.7}}\right) \times e^{ah^b + c} \tag{7}$$

where. $f(x) = \frac{1}{\left[\left(\frac{x}{S_0/M_0} + 5\right)^{0.35} - 5^{0.35}\right] e^{\frac{x}{50\left(\frac{S_0}{M_0}\right)}}}$

$S_0/M_0 = 0.012\ m^2/kg$ and. $g(x) = \frac{116 \times 10^6}{x^{4.4}}$

I_k: other contributors to the index. In this study, it includes the post-mission disposal success rate [32].

Jing, Dan & Wang, China, CAS: Three factors are taken into account for determining the criteria of ADR target selection (I_{ADR}): object mass, collision probability, and spatial density. The scoring uses the following equation:

$$I_{ADR} = M^{0.75} \cdot P \cdot \rho \tag{8}$$

Where.

M = normalized mass factor, mass divided by 1 kg
P = collision probability from other cataloged objects
ρ = normalized spatial density of cataloged objects as a function of apogee/perigee and inclination, spatial density divided by $1/km^3$

Objects with perigee larger than 2000 km or eccentricity larger than 0.5 are not considered to be ADR targets.

3. Individual and composite results

Fig. 4 summarizes common features and differences of the algorithms. It highlights that all methods focused primarily on mass (as a surrogate for consequence), then some measure of probability of collision and, finally, the approaches diverged by looking at proximity to operational satellites, persistence of the debris, and ease of collective retrieval. The top 50 SMC objects for the 11 different methods are tallied by CSpOC Satellite Number in Table 3.

A special thanks is extended to the ESA Space Debris Office for assisting in the correlation of the ESA catalog with the CSpOC SATNOs to identify some of the objects in the top 50 list, as well as for the provisioning of and permission to use population data used in the DAMAGE study by Dr Lewis. This extra effort highlights the need for more discussion on items as basic as names of objects in reputable space catalogs.

While it is difficult to see exactly which objects are overall the statistically-most-concerning, it is clear that there is commonality between the Top 50 lists from the 11 approaches; the bolded items are objects that appear in six or more of the lists. Only one object, 22,566,

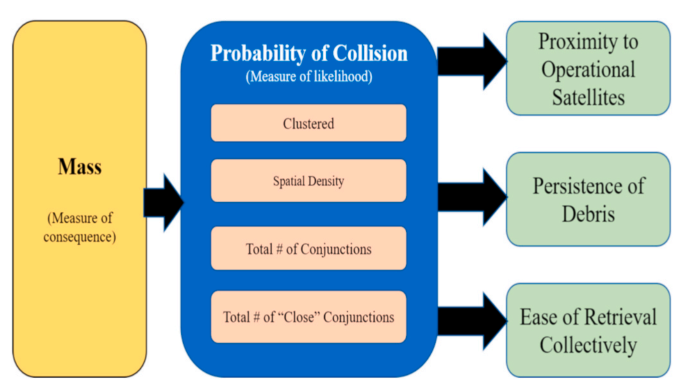

Fig. 4. All methods focused primarily on mass, then some measure of probability of collision and, finally, the approaches diverged by looking at some combination of proximity to operational satellites, persistence of the debris, and ease of collective retrieval.

Table 3
The top 50 SMC objects (identified by CSpOC Satellite Number) for each algorithm are summarized below.

	McKnight	Witner	Anselmo/ Pardini	Letizia/ Lemmens	Rossi	Baranov/ Grishko	Lewis	Kawamoto	Nicolls	Dolado Perez/ Ruch	Jing/Dan/ Wang
1	**27,006**	12,504	**27,006**	**27,386**	**27,006**	**28,353**	**27,006**	**27,386**	**23,705**	17,240	27,601
2	27,001	14,625	**25,400**	**26,070**	**24,298**	**24,298**	**28,353**	**23,088**	**19,120**	**27,006**	24,277
3	14,625	12,835	27,470	**23,088**	**28,353**	**22,220**	27,001	**22,285**	19,119	13,719	**27,386**
4	**25,407**	**27,006**	**17,974**	**23,705**	**31,793**	**22,566**	24,279	**23,405**	27,601	37,932	27,387
5	**31,793**	10,776	**22,803**	**20,625**	**20,625**	**25,407**	**23,405**	**17,590**	24,277	10,537	27,597
6	**22,220**	12,786	**24,298**	**19,650**	**23,088**	15,334	**16,182**	**26,070**	**16,182**	23,533	25,261
7	**22,285**	13,272	**22,285**	**28,353**	**22,566**	**31,793**	21,090	**20,625**	**22,285**	21,667	33,772
8	10,732	12,092	**28,353**	**24,298**	**22,285**	**23,705**	14,966	**22,803**	23,087	22,208	23,561
9	17,290	15,890	**31,793**	**23,405**	**23,705**	**19,650**	20,491	**27,006**	28,352	**22,566**	15,334
10	**17,974**	25,861	**23,405**	**22,566**	**23,405**	**16,182**	21,232	**28,353**	**26,070**	24,279	21,610
11	13,113	7594	**23,705**	**25,407**	**26,070**	2825	22,488	**22,566**	**22,220**	10,732	17,973
12	12,092	23,180	**17,590**	**16,182**	**19,650**	15,772	**22,803**	**17,974**	24,297	**27,386**	23,704
13	25,861	18,959	**20,625**	**31,793**	**25,407**	**19,120**	**20,625**	**25,407**	**22,803**	27,061	**22,220**
14	**22,566**	10,731	**22,220**	**25,400**	**16,182**	1245	12,298	**31,793**	**31,793**	39,060	41,341
15	10,138	**22,220**	**26,070**	**17,974**	**22,220**	**26,070**	22,969	**19,650**	23,704	40,358	15,772
16	13,917	10,693	**19,650**	**17,590**	**22,803**	**17,974**	15,598	**23,705**	**19,650**	17,525	23,087
17	22,308	21,090	**16,182**	**22,803**	**17,590**	**23,088**	36,095	**16,182**	15,334	16,727	37,932
18	21,153	9044	**23,088**	**22,220**	**17,974**	**22,803**	**23,088**	**22,220**	15,333	21,153	**20,625**
19	24,277	22,308	**22,566**	**19,120**	10,539	**23,405**	**26,070**	**24,298**	12,646	**26,070**	19,649
20	10,693	10,732	**25,407**	27,597	28,367	727	24,306	**19,120**	28,059	8597	15,755
21	21,090	**17,974**	**19,120**	24,277	**19,120**	**22,285**	20,305	15,596	33,272	20,305	**25,407**
22	9613	**22,285**	28,910	15,596	36,095	**17,590**	**31,793**	**25,400**	13,552	**25,400**	42,925
23	**16,182**	**31,793**	23,447	31,114	3081	**20,625**	**22,566**	41,858	15,755	15,077	25,860
24	7594	7009	23,793	40,069	40,541	21,015	18,130	27,601	**17,590**	27,001	**19,650**
25	**23,705**	23,342	21,034	27,601	27,001	16,012	16,728	31,114	25,261	**20,625**	**16,182**
26	9848	16,510	16,144	37,932	15,597	22,081	**22,220**	23,087	**20,625**	**23,705**	39,771
27	7009	27,001	20,741	28,480	**25,400**	12,792	15,056	33,272	**25,400**	**25,407**	**22,566**
28	12,504	**22,566**	27,001	44,387	10,531	20,433	13,111	20,624	17,973	**24,298**	19,119
29	23,180	10,138	19,791	**27,006**	13,113	19,039	19,336	37,932	**27,386**	13,617	**23,088**
30	**26,070**	11,239	21,305	35,865	33,319	16,953	13,917	28,480	20,624	**17,590**	21,574
31	20,670	11,803	21,785	15,334	35,688	23,432	20,578	26,069	**25,407**	11,238	22,565
32	16,494	14,084	22,693	20,322	37,795	6966	16,511	19,119	21,610	17,159	**25,400**
33	8874	21,902	18,794	22,823	36,600	11,574	13,128	29,499	**17,974**	21,087	28,352
34	16,292	16,292	24,731	25,634	40,341	18,096	11,309	23,704	13,649	24,678	20,624
35	10,600	9848	20,238	13,719	40,112	13,771	11,321	19,649	**23,405**	11,667	38,341
36	6149	9613	23,005	11,166	39,242	7493	19,325	22,802	33,500	43,689	**26,070**
37	11,736	8874	22,188	7210	22,782	5732	16,292	27,387	27,387	16,494	20,443
38	9044	13,757	12,879	17,973	28,352	5918	25,569	36,089	16,495	12,298	22,830
39	13,128	13,917	13,589	11,289	17,589	7275	22,007	17,589	**24,298**	23,561	**22,803**
40	**23,405**	17,290	17,588	41,858	**27,386**	7210	20,805	15,338	12,785	13,114	**19,120**
41	9638	21,089	22,652	4420	36,520	8846	10,138	27,597	**22,566**	10,693	**23,705**
42	16,511	16,511	22,040	37,214	20,528	6393	17,240	28,931	24,279	32,382	33,500
43	15,598	16,494	15,475	12,646	22,802	9904	23,180	43,610	28,050	23,774	28,932
44	8597	10,991	27,061	10,515	24,279	5118	28,060	25,994	14,551	20,238	28,499
45	**20,625**	6708	27,870	8294	20,826	11,963	13,302	28,352	22,565	26,819	2142
46	14,966	12,682	12,115	7575	22,565	12,457	15,360	23,404	15,772	9044	**22,285**
47	10,776	7593	28,421	8800	23,704	13,403	21,667	24,277	24,793	**16,182**	**17,974**
48	13,066	9638	18,340	6257	26,069	11,166	10,732	24,297	**23,088**	**23,405**	15,595
49	6708	14,974	15,171	9904	22,284	7364	7594	22,219	13,719	8874	**31,793**
50	8646	13,066	27,466	12,457	24,297	8800	6149	5105	25,861	**23,088**	**23,405**

appeared on all 11 lists; it is underlined in the table. Six of the objects appeared on 10 of the 11 lists. Table 4 identifies the number of lists in which each of the top 50 objects appeared.

The scoring of the composite Top 50 list was executed in three steps. First, each object was given a score consistent with its place on each list; object 1 received 50 points, object 2 received 49 points, and so on until object 50 received one point. Second, points for each object from each list were summed. Third, this score was then adjusted by multiplying it by the number of lists that each object appeared on.

For example, if an object appeared as object 41 on five of the 11 lists, it would have received 10 points five times for a total of 50 points, which is then multiplied by the number of lists on which it appeared – in this case, five – to get its final score of 250 pts. Other methods of scoring were also considered, based on medians and rank aggregation [34,35] but the top 25 did not change regardless of which scoring methodology was used, so these alternative scorings were not used. Table 4 presents the composite top 50 SMC objects including on how many individual lists each object appeared.

While the majority of the objects in the Top 50 are of Russian (1992 onward) or Soviet (through 1991) origin, 16% of the objects collectively come from (2%) China, (6%) the European Space Agency, and (8%) Japan. While only one list (Baranov/Grishov) specifically excluded payloads as possible objects to be selected, 39 of the top 50 SMC objects are rocket bodies (RBs), and only 11 are payloads.

It is interesting to note that 40 of the top 50 SMC objects were placed in orbit December 31, 2000. Only 10 objects in the Top 50 list were abandoned from January 1, 2001 onward, meaning that 80% of all objects in the Top 50 were abandoned before 2001.

Fig. 5 depicts the distribution by country, object type, and date abandoned.

Fig. 6 plots the average altitude and inclination of the top 50 and provides insights into efficient removal of the objects. Most importantly, the three numbered ellipses represent the grouped priority of removal, driven by both the ranking the top 50 and by their orbital positioning. The obvious trend toward both inclination and altitude binning was only explicitly discussed by Baranov/Grishko, however, all methods were sensitive to collisions amongst massive derelicts so this distribution is not completely surprising.

Table 4
The composite top 50 SMC are summarized below.

Ranking	Score	SATNO	Number of Lists	SATNAME	APOGEE, km	PERIGEE, km	INCL., deg	MASS, kg	COUNTRY	LAUNCH
1	4048	22,566	11	SL-16 R/B	848	837	71.0	9000	CIS	3/26/1993
2	3710	22,220	10	SL-16 R/B	848	827	71.0	9000	CIS	11/17/1992
3	3500	31,793	10	SL-16 R/B	846	843	71.0	9000	CIS	6/29/2007
4	3470	26,070	9	SL-16 R/B	854	827	71.0	9000	CIS	March 2, 2000
5	3330	16,182	10	SL-16 R/B	844	833	71.0	9000	CIS	10/22/1985
6	3300	20,625	10	SL-16 R/B	853	834	71.0	9000	CIS	5/22/1990
7	2880	27,006	8	SL-16 R/B	1006	986	99.5	9000	CIS	October 12, 2001
8	2862	23,705	9	SL-16 R/B	852	831	71.0	9000	CIS	10/31/1995
9	2826	25,407	9	SL-16 R/B	844	835	71.0	9000	CIS	7/28/1998
10	2800	23,405	10	SL-16 R/B	845	838	71.0	9000	CIS	11/24/1994
11	2547	17,974	9	SL-16 R/B	846	823	71.0	9000	CIS	5/13/1987
12	2412	23,088	8	SL-16 R/B	845	841	71.0	9000	CIS	4/23/1994
13	2296	22285	8	SL-16 R/B	844	840	71.0	9000	CIS	12/25/1992
14	2240	22,803	8	SL-16 R/B	850	823	71.0	9000	CIS	9/16/1993
15	1813	19,650	7	SL-16 R/B	848	831	71	9000	CIS	11/23/1988
16	1771	24,298	8	SL-16 R/B	863	839	70.8	9000	CIS	April 9, 1996
17	1650	28,353	7	SL-16 R/B	848	842	71.0	9000	CIS	October 6, 2004
18	1617	17,590	8	SL-16 R/B	841	831	71.0	9000	CIS	3/18/1987
19	1547	19,120	7	SL-16 R/B	842	814	71.0	9000	CIS	5/15/1988
20	1477	25,400	7	SL-16 R/B	813	801	98.6	9000	CIS	October 7, 1998
21	1320	27,386	5	ENVISAT	766	764	98.1	7800	ESA	January 3, 2002
22	1182	27,001	6	METEOR 3 M	1013	994	99.6	2500	CIS	October 12, 2001
23	805	24,277	4	ADEOS	794	793	98.9	3560	JPN	8/17/1996
24	600	27,601	4	H-2A R/B	836	734	98.2	3000	JPN	12/14/2002
25	564	15,334	4	SL-12 R/B(2)	847	838	71.0	2440	CIS	9/28/1984
26	512	37,932	4	CZ-2D R/B	846	791	98.7	4000	PRC	11/20/2011
27	468	10,732	4	SL-8 R/B	995	966	82.9	1435	CIS	3/15/1978
28	416	24,279	5	H-2 R/B	1306	860	98.7	2700	JPN	8/17/1996
29	384	23,704	3	COSMOS 2322	854	842	71.0	3250	CIS	10/31/1995
30	324	21,090	3	SL-8 R/B	992	961	82.9	1435	CIS	May 2, 1991
31	316	28,352	3	COSMOS 2406	863	844	71.0	3250	CIS	October 6, 2004
32	309	23,087	2	COSMOS 2278	852	841	71.1	3250	CIS	4/23/1994
33	270	19,119	2	COSMOS 1943	851	833	71.0	3250	CIS	5/15/1988
34	261	27,597	2	ADEOS 2	801	800	98.5	3680	JPN	12/14/2002
35	240	25,861	4	SL-16 R/B	645	622	98.2	9000	CIS	7/17/1999
36	240	15,772	3	SL-12 R/B(2)	848	794	71.1	2440	CIS	5/30/1985
37	228	10,693	3	SL-8 R/B	989	957	83.0	1435	CIS	2/28/1978
38	228	17,973	2	COSMOS 1844	866	824	71.0	3250	CIS	5/13/1987
39	225	27,387	3	ARIANE 5 R/B	796	748	98.6	2575	FR	January 3, 2002
40	207	7594	3	SL-8 R/B	981	955	82.9	1435	CIS	12/26/1974
41	207	23,180	3	SL-8 R/B	992	950	82.9	1435	CIS	7/14/1994
42	204	10,138	3	SL-8 R/B	1001	970	82.9	1435	CIS	August 7, 1977
43	204	13,917	3	SL-8 R/B	996	954	82.9	1435	CIS	3/24/1983
44	198	13,719	3	SL-3 R/B	896	791	81.3	1100	CIS	12/14/1982
45	194	14,625	2	SL-8 R/B	999	969	82.9	1435	CIS	November 1, 1984
46	183	20,624	2	COSMOS 2082	856	833	71.0	3250	CIS	5/22/1990
47	164	12,092	2	SL-8 R/B	996	953	82.9	1435	CIS	October 12, 1980
48	153	9044	3	SL-8 R/B	988	966	83.0	1435	CIS	7/21/1976
49	146	12,504	2	COSMOS 1275	1014	954	83.0	800	CIS	April 6, 1981
50	144	16,292	3	SL-8 R/B	996	953	82.9	1435	CIS	11/28/1985

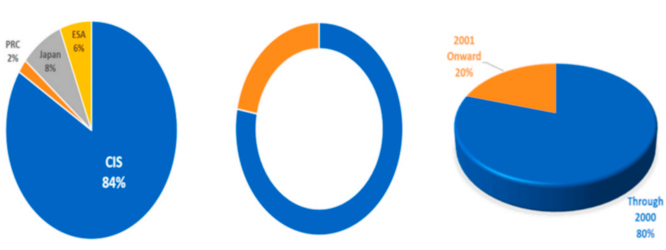

Fig. 5. The vast majority of the top 50 objects are of Soviet/Russian origin (i.e., Commonwealth of Independent States, CIS), rocket bodies, and abandoned before 2000.

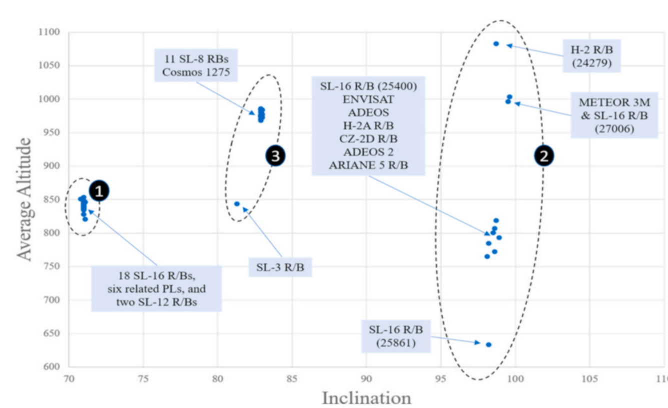

Fig. 6. Top 50 SMC objects are located in clumps that might aid in the efficient removal of them from orbit.

Each ellipse contains the following SMC objects:

E. 1: #1–6, 8–19, 25, 29, 31–33, 36, 38, and 46E. 2: #7, 20–24, 26, 28, 34–35, and 39 E. 3: #27, 30, 37, 40–45, and 47-50.

Ellipse 1 contains over half of the objects on top 50 list and 18 of the first 19 objects. Ellipse 1 objects are primarily from C850 as identified in

References 4–6: 18 SL-16 rocket bodies with six of the payloads deployed by these R/Bs plus two SL-12 R/B that are not in C850. All of these objects are of Soviet/Russian origin.

Ellipse 2 contains the majority of the objects with the next highest rankings after Ellipse 1. These objects are massive derelicts with 98.0–99.6° inclinations that span altitudes from ~600 to 1300 km (i.e., sun-synchronous orbits). This grouping includes objects from four different countries/organizations.

Ellipse 3 has 11 very tightly-bunched SL-8 R/Bs plus one payload associated with the SL-8s, and one "nearby" SL-3 R/B. Most of the objects in Ellipse 3 are in the last 15 of the top 50 list.

It should be noted that in examining the "next 50" objects on the composite list, the proportion of CIS objects was ~80% with four other entities (Japan, US, PRC, and ESA/France) having objects identified.

While it is tempting to suggest that the right approach would be to start removing the top 50 SMC objects from the first object and work down the list, it is likely not the best approach for two reasons.

First, as the team of Baranov and Grishko suggested in the development of their top 50 list, there should be emphasis placed on how efficiently objects can be removed using a single system removing multiple objects. To be most efficient, the objects would have their RAANs deviations' evolution portrait determined for each Ellipse. The object with the largest RAAN deviation would be selected then collection of the other objects would proceed in the direction of the natural RAAN drift for each Ellipse.

Second, it may be true that once an object on the top 50 list is removed the objects that are remaining may indeed pose less risk. In this way, the priority of the objects may actually change as objects are removed. Examination of these mutual interactions would provide an opportunity to reduce the total number of objects that would have to be remediated to contribute to a given reduction in debris-generating potential.

These two activities will be handled in follow-on efforts: (1) detailed determination of the most efficient removal sequence based on approaches similar to those recommended by Baranov and Grishko and (2) technical analyses of interactions between members of the top 50 list that might lead to a reduction in objects to be remediated. Factors that might affect both future studies on detailing an actual remediation sequence include tumble rate, energetics on board, and owner of each object.

In addition, it would be productive to examine how both different scoring mechanisms and using a more complete database of space objects (than available through Space-track.org) might affect a composite top 50 list.

4. Closing comments

This paper describes and integrates a variety of methods to evaluate the criticality of derelict resident space objects (RSO). These 11 methods each generate different results based on diverse hypotheses and approaches. For example, several of the 11 methodologies were not geared towards ADR per se; they represent a broader view on space sustainability metrics. Other approaches, conversely, were geared more towards space safety concerns.

A state-of-the-art model consolidation approach was applied for the integration of these diverse and reputable models to create the composite top 50 list [36,37].

As a result, the final listing is globally coherent in the identification of the subset of the statistically-most-concerning derelict objects in LEO. This exercise identified 50 objects in order of priority for remediation. The consideration of these results as an absolute listing is limited by the completeness of the database provided by Space-track.org.

Today, active debris removal (ADR) is the most likely option for such remediation, but, in the future, other options may be developed. It should be noted that 37 objects of the top 50 list have a mass greater than 2000 kg; these objects might be better "remediated in orbit" by JCA, LTDM, and nano-tugs in order to eliminate the potential ground and aviation impact risk.

The significance of the process employed to create this list and the results of this effort are noteworthy – 19 experts from 13 countries/organizations had their 11 individual assessments aggregated into a list of the 50 statistically-most-concerning (SMC) objects for debris generation.

Upon examination of the original 11 top 50 lists, it is noted that all lists had between ~40 and 60% objects in common between some other top 50 list. In addition, it is also noteworthy that, even though only one of the 11 approaches specifically disregarded payloads, 39 of the top 50 SMC are derelict rocket bodies; only 11 are non-operational payloads.

Further work that should be investigated include:

- Apply entire process to a more complete database of objects in orbit;
- Characterize how the composite top 50 list might change if focused solely on space safety or space sustainability but not both;
- Examine alternative scoring methods for compiling the top 50 composite list from the 11 individual contributions;
- Continue to refine approaches to sequential retrieval methodologies for ADR;
- Quantify individual object characteristics and dynamics as factors in remediation priority; and
- Study balance between ADR vs "remediate in orbit" options.

Based on the debris-generating risk posed by these abandoned objects, it is clear that executing debris remediation is a high priority to reduce the potential for large derelict-on-derelict collisions [6,7], and this list of objects and the order of their remediation provide an enhanced awareness for such efforts.

It is hoped that this effort will accelerate ongoing global efforts to start to remediate massive derelict objects in orbit [37,38] and develop other remediation options (e.g., JCA, LTDM, and nano-tugs) to enhance space safety and support long-term space sustainability.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] C. Bonnal, D. McKnight, JUST-IN-TIME collision avoidance (JCA): a realistic solution for future sustainable space activities, " 1st IAA Conference on Space Situational Awareness (ICSSA), Orlando, FL, USA, 2017.

[2] J.-C. Liou, N.L. Johnson, A sensitivity study of the effectiveness of active debris removal in LEO, Acta Astronaut. 64 (2–3) (2009) 236–243, https://doi.org/10.1016/j.actaastro.2008.07.009.

[3] A. Rossi, A. Petit, D. McKnight, Short-term space safety analysis of LEO constellation and clusters, Acta Astronaut. 175 (2020) 476–483, https://doi.org/10.1016/j.actaastro.2020.06.016.

[4] Lu Hong, Scott E. Page, Groups of diverse problem solvers can outperform groups of high-ability problem solvers, PNAS November 16 (46) (2004 101) 16385–16389, https://doi.org/10.1073/pnas.0403723101.

[5] D. McKnight, R. Arora, R. Witner, "Derelict Deposition Study," International Orbital Debris Conference, US, Houston, TX, 2019.

[6] D. McKnight, S. Speaks, J. Macdonald, Assessing Potential for Cross-Contaminating Breakup Events from LEO to GEO, " 68th International Astronautical Congress, Bremen, Germany, 2018.

[7] D. McKnight, M. Matney, K. Walbert, S. Behrend, P. Casey, S. Speaks, Preliminary Analysis of Two Years of the Massive Collision Monitoring Activity, " 68th International Astronautical Congress (IAC), Adelaide, Australia, 2017.

[8] Desmond King-Hele, Satellite Orbits in an Atmosphere - Theory and Applications, Blackie, Glasgow, 1987.

[9] De Luca, L.T. et al., Active removal of large massive objects by hybrid propulsion module, in: (Eds. O.J. Haidn, W. Zinner & M. Calabro) 5th European Conference for Aero-Space Sciences, EUCASS, DVD, Paper ID 469, June 2013 [ISBN 978-84-941531-0-5].

[10] L. Anselmo, C. Pardini, Compliance of the Italian satellites in low earth orbit with the end-of-life disposal guidelines for space debris mitigation and ranking of their long-term criticality for the environment, Acta Astronaut. 114 (2015) 93–100, https://doi.org/10.1016/j.actaastro.2015.04.024.

[11] L. Anselmo, C. Pardini, Ranking upper stages in low earth orbit for active removal, Acta Astronaut. 122 (2016) 19–27, https://doi.org/10.1016/j.actaastro.2016.01.019.

[12] C. Pardini, L. Anselmo, Characterization of abandoned rocket body families for active removal, Acta Astronaut. 126 (2016) 243–257, https://doi.org/10.1016/j.actaastro.2016.04.035.

[13] Anselmo, L. and Pardini, C., An index for ranking active debris removal targets in leo, in: (Eds. T. Flohrer & F. Schmitz) Proc. 7th European Conference on Space Debris, ESA Space Debris Office, Paper 152 (7pp), June 2017 [http://spacedebris2017.sdo.esoc.esa.int].

[14] Trushlyakov, V., Anselmo, L. and Pardini, C., Choice of a suitable target for developing proposals for an adr flight demonstration experiment, in: (Eds. T. Flohrer & F. Schmitz) Proc. 7th European Conference on Space Debris, ESA Space Debris Office, Paper 378 (15pp), June 2017 [http://spacedebris2017.sdo.esoc.esa.int].

[15] C. Pardini, L. Anselmo, Evaluating the environmental criticality of massive objects in leo for debris mitigation and remediation, Acta Astronaut. 145 (2018) 51–75, https://doi.org/10.1016/j.actaastro.2018.01.028.

[16] F. Letizia, C. Colombo, H.G. Lewis, H. Krag, Extending the ECOB space debris index with fragmentation risk estimation, in: 7th European Conference on Space Debris, 2017.

[17] F. Letizia, S. Lemmens, B. Bastida Virgili, H. Krag, Application of a debris index for global evaluation of mitigation strategies, Acta Astronaut. 161 (2019) 348–362, https://doi.org/10.1016/j.actaastro.2019.05.003.

[18] A. Rossi, G.B. Valsecchi, E.M. Alessi, The criticality of spacecraft index, Adv. Space Res. 56 (3) (2015) 449–460.

[19] A. Rossi, L. Anselmo, C. Pardini, G.B. Valsecchi, R. Jehn, The new space debris mitigation (SDM 4.0) long-term evolution code, in: H. Lacoste (Ed.), Proceedings of the Fifth European Conference on Space Debris, ESA Communication Production Office, ESTECPUB, Darmstadt, Germany, 2009, p. 30. March - 2 April 2009, vol. ESA SP-672 (CD-ROM), article n. 1.

[20] C. Bombardelli, E.M. Alessi, A. Rossi, G.B. Valsecchi, Environmental effect of space debris repositioning, Adv. Space Res. 60 (1) (2017) 28–37.

[21] A. Rossi, E.M. Alessi, G.B. Valsecchi, H. Lewis, J. Radtke, C. Bombardelli, B. Bastida Virgili, A quantitative evaluation of the environmental impact of the mega constellations, in: Proceedings of the 7th European Conference on Space Debris, ESOC, Darmstadt (Germany), 2017, 18-21/04/2017.

[22] D.A. Grishko, PhD Thesis [in Russian], https://keldysh.ru/council/1/2018-grishko/diss.pdf.

[23] A.A. Baranov, D.A. Grishko, Y.N. Razoumny, Large-size space debris flyby in low Earth orbits//, Cosmic Res. 55 (Issue 5) (2017) 361–370.

[24] A.A. Baranov, D.A. Grishko, Y.N. Razoumny, Jun Li, Flyby of large-size space debris objects and their transition to the disposal orbits in, Leo/Adv. Space Res. 59 (2017) 3011–3022.

[25] A.A. Baranov, P. Labourdette, Strategies for on-orbit rendez-vous circling Mars, in: Proceedings of AAS/AIAA Astrodynamics Specialist Conference, Canada, Quebec, 2001. Paper AAS 01-392.

[26] A.A. Baranov, D.A. Grishko, V.V. Medvedevskikh, V.V. Lapshin, Solution of the flyby problem for large space, Debris at Sun-Synchronous Orbits //Cosmic Res. 54 (№3) (2016) 229–236.

[27] Lewis, H.G., "Understanding long-term orbital debris population dynamics", First International Orbital Debris Conference, 9-12 December 2019, Sugar Land, Texas, USA.

[28] H.G. Lewis, et al., Effect of thermospheric contraction on remediation of the near-Earth space debris environment, J. Geophys. Res. 116 (A2) (2011) A00H08.

[29] J.-C. Liou, D.J. Kessler, M. Matney, G. Stansbery, A new approach to evaluate collision probabilities among asteroids, comets and Kuiper Belt objects, Lunar and Planetary Science XXXIV (2003) paper no. 1823.

[30] N.L. Johnson, P.H. Krisko, J.C. Liou, P.D. Anz-Meador, "NASA's new breakup model of EVOLVE 4.0", Adv. Space Res. 28 (2001) 1377–1384.

[31] S. Kawamoto, N. Nagaoka, T. Hanada, S. Abe, "Evaluation of active debris removal strategy using a debris evolutionary model,", in: 70th International Astronautical Congress (IAC), 2019. Washington D.C., United States.

[32] The Semi-analytic Tool for End of Life Analysis (STELA) has been procured by CNES (The French Space Agency) to support the French Space Operations Act. https://logiciels.cnes.fr/en/content/stela.

[33] V. Ruch, Space environment index at CNES, in: 8th Satellites End of Life and Sustainable Technologies Workshop, 2020.

[34] Brian Martin, Ranking by medians, Aust. Univ. Rev. 56 (No. 2) (2014). https://www.aaai.org/ocs/index.php/FLAIRS/FLAIRS13/paper/viewFile/5893/6111.

[35] Vasyl Pihur, Susmita Datta, Somnath Datta, " RankAggreg, An R package for weighted rank aggregation", BMC Bioinf. 10 (2009) 62, https://doi.org/10.1186/1471-2105-10-62.

[36] Y. Ioannides, S. Page, The difference: how the power of diversity creates better groups, firms, schools, and societies, J. Econ. Lit. 48 (1) (2007) 108–122.

[37] Scott Page, The Hidden Factor: Why Thinking Differently Is Your Greatest Asset, The Great Courses, Chantilly, VA, 2011.

[38] C. Dickey, Three Country-Trusted Broker": an Effective Public-Private Model for Orbital Debris Remediation, 68th International Astronautical Congress, Washington, DC, US, 2019.