Most-concerning derelict objects in LEO Insights from social choice

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Most-concerning derelict objects in LEO
Insights from social choice[*]

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Abstract

Eleven teams of experts were solicitated to provide a ranked list of the 50 statistically-most-concerning objects in LEO. The approaches used by the experts and resulting lists are described in McKnight et al.(2021). An aggregation rule that leads to a collective list is also proposed. This paper offers a view from social choice theory on the aggregation process. We show that different aggregation rules may yield different conclusions concerning the most concerning object. We also discuss alternative aggregation rules, and provide some recommandations concerning the question that could be addressed to experts.

Keywords: Space debris, Active debris removal, LEO, Social choice

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1 Introduction

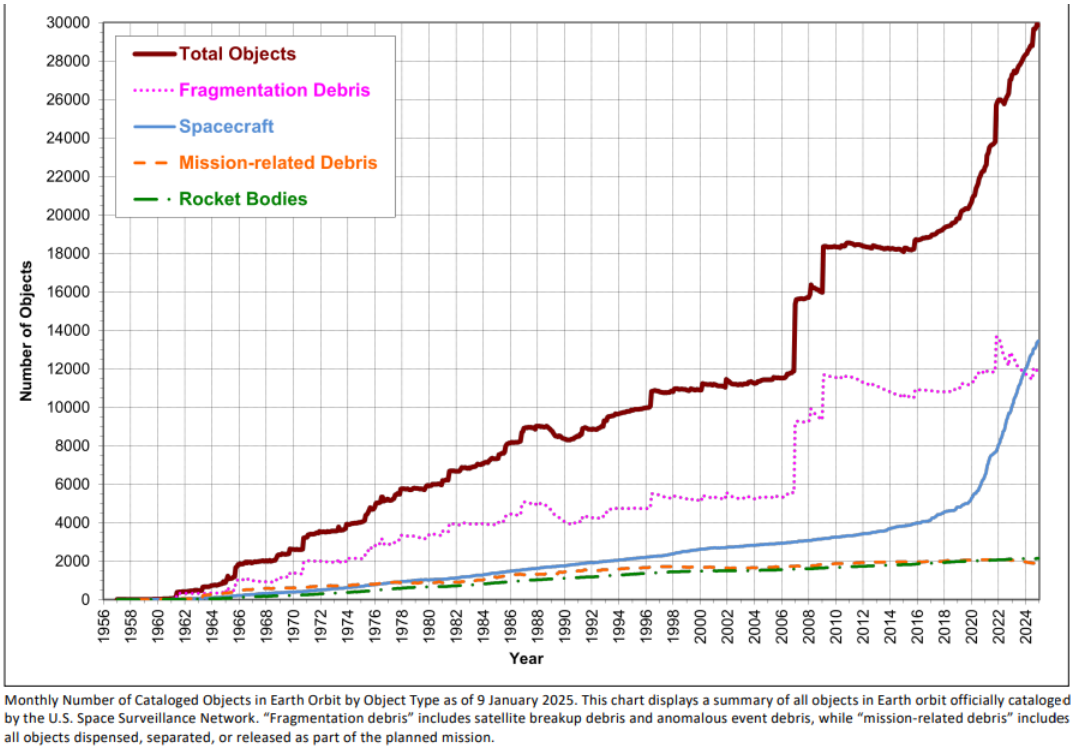
For several decades now, there has been a broad international consensus that space debris (despite the absence of a international legally binding definition) poses two distinct threats: 1/ the risk of damaging or destroying satellites in orbit, and 2/ the risk of causing damage, or even casualties, on Earth through uncontrolled atmospheric reentry.

To counter these threats and prevent them from increasing, various attempts have been made to stop the creation of new debris. The European Space Agency (ESA) created the ESA-PSS-01-40 standard by in 1988. Although very clear and detailed, this standard very quickly appeared unrealistic as it would have made any space mission virtually impossible. In 1995, NASA brought together measures needed to reduce the production of debris and proposed the NSS-1740-14 standard. The spirit of this text was subsequently adopted by several national agencies, such as Japan's JAXA and France's CNES. Real reflection, followed by initiatives, began at the international level with the creation of the Inter-Agency Space Debris Coordination Committee (IADC) in 1993. Indeed the dimension of the risks requires an international treatment.

IADC is currently the largest and most representative international specialized organization of actors capable of generating space debris. Broadly speaking, IADC has three missions. Firstly, to identify, assess and protect against risks. The second is to study possible joint actions. Finally, on the basis of the previous two missions, the IADC is to draw up international proposals for eliminating or, at the very least, mitigating space debris. Thus, after years of debate, the IADC unanimously adopted guidelines in 2002, which have since been revised several times, the latest version being for 2025. The study of the risks posed by space debris, and the initiatives to remedy them, are not the sole work of the IADC at international level. In fact, for several decades now, the United Nations (notably through COPUOS), the International Organization for Standardization (ISO) (in particular with the ISO 24113 standard), the World Economic Forum, as well as industry groups (e.g. Space Safety Coalition, CONFERS, GSOA), have been very active on these issues.

Yet, despite the existence of these numerous initiatives and recommendations, and the progress made by some players, the amount of space debris continues to grow, as demonstrated by the graph below from NASA (2025, p. 8).

Figure 1: Monthly number of objects in Earth orbit by object type (NASA [2025])



More the outlook presented by the IADC (2025, p. 23) for low-Earth orbits in the two graphs below is alarming:

Figure 2: Number of objects larger than 10cm in LEO in the simulated scenarios of long-term evolution of the environment(IADC [2025])

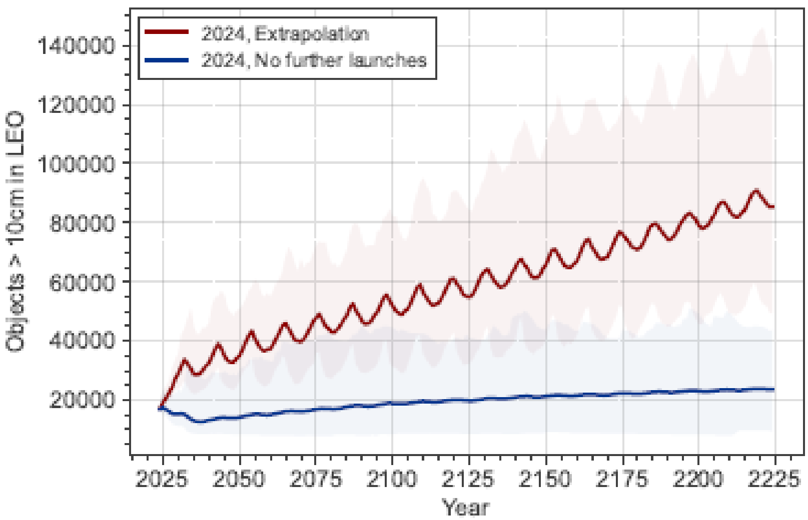
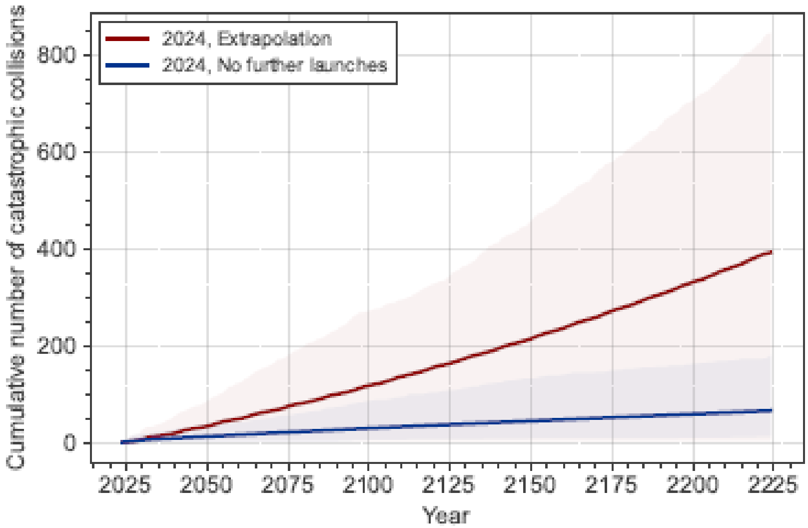


Figure 3: Cumulative number of catastrophic collisions in LEO in the simulated scenarios of long-term evolution of the environment (IADC [2025])



Solving the problem of space debris will most certainly involve a number of avenues, and in particular an increase in the surveillance and tracking capabilities in space, the development of in-orbit services (SeO), and the implementation of binding and respected international rules. However, even in the long term, particularly in view of possible bankruptcies and/or non-compliant States, these avenues, while indispensable, will not be sufficient: "[...] even with widespread adoption of these guidelines and recommendations, or even stricter behaviours, the consensus is that the environmental impacts cannot be removed completly and additional steps nedd to be taken, such as enabling the technology for active debris removal" (IADC, 2025, p. 5).

To just stabilize the space environment at its current level (i.e. the population of debris in low-Earth orbit), a scientific consensus seems to be gradually emerging around the fact that, on the one hand, international recommendations should be scrupulously respected and, on the other, around five to ten pieces of debris of more than 10cm should be removed each year before they fragment. Fortunately, thanks to a great deal of research over the last few years, several technical solutions have been proposed for actively removing this debris (for a recent overview of techniques, see Mark and Kamath, 2019). The first operational tests are scheduled for 2025 or 2026.

However, once the principle of removing five to ten pieces of debris per year has been accepted, and the technology(ies) chosen, there remains an important question: where to start? In other words, which debris should be removed first?

In 2021, for the first time, eleven international teams of experts proposed an answer to this question by drawing up an ordered list of the fifty most concerning pieces of space debris in low-Earth orbit (McKnight et al, 2021), based on the American public catalog (space-track.org). The aim was to identify intact debris as either posing the greatest risk to operational satellites, or reducing the risk of collisions between them. The approaches used by the experts take into account four main factors: mass, encounter rates, orbital lifetime, and proximity to operational satellites. The eleven ranked lists are given in McKnight et al. (2021), and an aggregation rule is proposed to obtain a collective ranked list.

One line for further research pointed out in McKnight et al. (2021) concerns the process of aggregation of the list. This is the objective of this paper. We study the aggregation of these eleven lists from a social choice perspective. We demonstrate that the method used has an impact on the result obtained and, more generally, that social choice theory emphasizes that drawing up an ordered list of debris to be removed requires a set of questions to be answered beforehand (Who votes? What question are voters being asked? What answer can the voters give?).

The rest of the article is structured as follows. Section 2 reviews the aggregation method used by McKnight et al. (2021). Section 3 demonstrates that by using the same eleven lists but changing the aggregation method, the conclusions obtained change. Section 4 examines the sensitivity of the results to the number of voters and their homogeneity. Section 5 discusses the possible forms of ballots. Section 6 highlights the fact that drawing up an aggregated, ordered list of the fifty most dangerous pieces of debris from different lists does not require each voter to draw up a list of fifty pieces of debris. Finally, section 7 concludes our article by reiterating our three main conclusions, highlighting two difficulties, and making a suggestion for the next time a set of experts, agencies, or States wishes to propose a list of the most concerning debris.

2 Spatial debris vote

The collective process to evaluate space debris can be modelled as follows. A set of n experts vote on a catalog of space debris, $\mathcal{C}$. Let $\mathcal{N} = \{1, ..., n\}$ be the set of the experts' labels. Generic debris are denoted by x, and y, while e_j denotes a generic expert (with $j \in \mathcal{N}$).

Given the large number of debris in the catalog experts cannot vote on all of them: k-truncated ballots are used. That is, experts are required to choose the k most concerning debris from the catalog. With k-truncated ordered ballots, experts rank debris from the most concerning to the k-most concerning one. Let $\mathcal{M}_j \subset \mathcal{C}$ be the subset of the k most concerning debris that expert e_j ranks (for any $j \in \mathcal{N}$). We denote by $p_j(x)$ the position that expert e_j gives to debris $x \in \mathcal{M}_j$. No tie is allowed for objects on the list: $p_j(x) \neq p_j(y)$ whenever $x \neq y$. We have $1 \leq p_j(x) \leq k$ with the following interpretation: the smaller $p_j(x)$ is, the more concerning x is according to expert e_j.

We denote by $\mathcal{M} \subset \mathcal{C}$ the set of the m debris that appears in at least one list:

$$\mathcal{M} = \bigcup_{j \in \mathcal{N}} \mathcal{M}_j.$$

The presence of a debris on an expert's list can be represented by an indicator that takes the value 1 if the debris appears on the expert's list, and 0 otherwise. For an object $x \in \mathcal{M}$, let $a_j(x)$ keep track of whether debris x appears (or does not) on expert e_j's list. That is,

$$a_j(x) = \begin{cases} 1 & \text{if } x \in \mathcal{M}_j \\ 0 & \text{otherwise.} \end{cases}$$

For each object $x \in \mathcal{M}$, the number of experts who include it on their lists is given by $A(x) = \sum_{j \in \mathcal{N}} a_j(x)$.

In McKnight et al. (2021), the ranking of the top 50 most concerning debris is established with the help of $n = 11$ teams of experts or organizations.[1] Those chose and ranked $k = 50$ debris from the catalog Space-track.org. Table 3 in McKnight et al. (2021) gives the ranked top 50 lists of the 11 experts (this table is reproduced in the Appendix). Objects are identified by their CSpOC Satellite Number.

The total number of debris that appears in at least one list is $m = 273$. These 273 objects can be distributed according to the number of lists in which they appears. Our Table 1 below gives the number of debris with $A(x) = 1, 2, ..., 11$.

Table 1: Number of debris with $A(x) = a$.

a	11	10	9	8	7	6	5	4	3	2	1
$\#\{x \text{ such that } A(x) = a\}$	1	6	4	3	5	3	1	7	22	46	175

One single object (debris $22,566$) appears in all lists. There are 6 objects which appear in 10 lists (4 out of 6 appear in all lists but expert e_2's one and 2 out of 6 appear in all lists but expert e_{10}'s one). In total, 22 debris appear in a majority of lists (at least six lists).

In order to obtain a collective ranking of the debris, McKnight et al. (2021) assigns to each debris $x \in \mathcal{M}$ a score, denoted $D(x)$. Debris are then ranked accordingly. The D-score of an object is obtained as the product of its Borda (1781) score and the number of lists in which the object appears. The Borda score assigns k points to a debris each time an expert ranks it in first position, $k - 1$ points each time an expert ranks it in second position,... and 1 point each time an expert ranks it in position k. The number of points given by expert e_j to debris x, denoted $b_j(x)$, is thus given by:

$$b_j(x) = \begin{cases} k + 1 - p_j(x) & \text{if } x \in \mathcal{M}_j \\ 0 & \text{otherwise.} \end{cases}$$

[1] As we are exclusively interested in the aggregation process, we will refer to each team or organization as an "expert" and anonymously refer to them as e_1,...,e_{11}.

If a debris does not appear on an expert's list, it receives no point from the expert.[2] The points received from the different experts are then added to obtain the Borda score of the object. If $B(x)$ denotes the Borda score of $x \in \mathcal{M}$, we have

$$B(x) = \sum_{j \in \mathcal{N}} b_j(x).$$

Multiplying the Borda score of an object by the number of lists in which it appears, the D-score is then obtained. That is, for each $x \in \mathcal{M}$, we have $D(x) = A(x)B(x)$. The 50 debris with the largest D-scores are given in Table 4 in McKnight et al. (2021). We can compare this list (denoted here $\mathcal{D}_{50}$) and the lists of the experts (that is, $\mathcal{M}_1$,..., $\mathcal{M}_{11}$). Our Table 2 below gives the number of objects from the Top 50 list that appears in each expert's list.

Table 2: Concordance of the Top 50 list with the experts' lists

	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9	e_{10}	e_{11}
$\#\left(\mathcal{D}_{50} \cap \mathcal{M}_j\right)$	27	20	21	27	25	20	20	31	33	20	30

We can observe that each expert has at least 40% of the objects that appear on the Top 50 list, with three of them who have 60% or more.

3 Different methods, different outcomes

According to the method proposed in McKnight et al. (2021) the most concerning debris is object $22,566$. This result relies on the choice of the method used to compute the scores of the objects. The two long-established methods in social choice, those respectively promoted by Jean-Charles Borda (1784) and the marquis of Condorcet (1785) would yield different conclusions. The most concerning debris is object $22,220$ according to the Borda count, or object $27,006$ according to the Condorcet winner principle.

Here we briefly review these two classical methods of social choice and compare the most concerning debris according to the different methods. With ordered ballots, there are two main classes of methods: the scoring rules and the Condorcet consistent rules.

With scoring rules and truncated ballots, experts assign points as a function of the position on the list (and 0 otherwise). Points given by the different experts are then added. Let $s_j(x)$ denote the number of points given by expert e_j and let $S(x)$ be the score of debris x. They are given by:

$$\begin{aligned} s_j(x) &= \begin{cases} f(p_j(x)) & \text{if } x \in \mathcal{M}_j \\ 0 & \text{otherwise.} \end{cases} \\ S(x) &= \sum_{j \in \mathcal{N}} s_j(x). \end{aligned}$$

[2]Strictly speaking this is the Borda score for truncated ballots (see Emerson, 2013).

The scoring rule selects the alternative with the largest score. The most well-known scoring rule is the Borda count[3] ($S(x) = B(x)$ for $f(p_j(x)) = k + 1 - p_j(x)$). Counting the number of list in which an alternative appears is another example of a scoring rule ($S(x) = A(x)$ for $f(p_j(x)) = 1$).

The second class of rules are based on pairwise comparisons of alternatives and on majorities. First let us start with the comparison of a pair of debris (say x and y) by expert e_j. We can say that expert e_j considers that debris x is strictly more concerning than y in two cases. The first case is whenever both x and y are in e_j's list, and x's position is smaller than y's position. The second case is whenever x appears in e_j's list while y does not. Let $\delta_j(x, y)$ be the indicator function that represents this comparison.

$$\delta_j(x, y) = \begin{cases} 1 & \text{if } a_j(x) = a_j(y) = 1 \text{ and } p_j(x) < p_j(y) \\ 1 & \text{if } a_j(x) = 1 \text{ and } a_j(y) = 0 \\ 0 & \text{otherwise.} \end{cases}$$

It takes the value 1 if expert e_j considers that debris x is strictly more concerning than y; and 0 otherwise. The number of experts who consider that debris x is strictly more concerning than y is given by $\sum_{j \in \mathcal{N}} \delta_j(x, y)$.

Second let us compare a pair of debris at the collective level. Debris x can be considered as strictly more concerning than debris y if a majority of experts judge that debris x is strictly more concerning than debris y. This can be represented by the indicator function $\Delta(x, y)$:

$$\Delta(x, y) = \begin{cases} 1 & \text{if } \sum_{j \in \mathcal{N}} \delta_j(x, y) > n/2 \\ 0 & \text{otherwise.} \end{cases}$$

It takes the value 1 if the number of experts who consider that debris x is strictly more concerning than y is strictly larger than $n/2$, and 0 otherwise. An alternative is referred to as a Condorcet winner if there is always a majority of experts who give to this alternative a smaller position than to any other alternative. That is, x is a Condorcet winner if and only if for any $y \neq x$ we have $\Delta(x, y) = 1$.

The existence of a Condorcet winner is not guaranteed. Indeed, the conditions that an alternative has to satisfy in order to be a Condorcet winner are very demanding. In many voting situations there is no Condorcet winner.[4] A Condorcet consistent rule selects the Condorcet winner when there is one, but always selects

[3] Alternative extensions of the Borda count to truncated ballots are $f(p_j(x)) = m - p_j(x)$ or $f(p_j(x)) = (m + k + 1)/2 - p_j(x)$.

[4] For example, consider three experts (e_1, e_2 and e_3) who choose and rank two debris from a global list of debris. Expert e_1 chooses x and y ; and considers that x is worse than y. Expert e_2 expert chooses x and z; and considers that z is worse than x. Expert e_2 chooses y and z; and considers that y is worse than z. We can observe that there is a "cycle" in the ranking: a majority of experts (e_1 and e_2) ranks x higher than y, a majority of experts (e_1 and e_3) ranks y higher than z, and a majority of experts (e_2 and e_3) ranks z higher than x.

one alternative. One of the simplest Condorcet consistent rule is the Copeland rule (see Nurmi, 1995). It selects the alternative with the largest Copeland score (denoted by $C(x)$), which is computed as follows. Whenever alternative x is ranked higher than another alternative by a majority, the score of alternative x is increased by one point. That is,

$$C(x) = \sum_{y \in \mathcal{M}} \Delta(x, y).$$

The maximum value of the Copeland score is $m - 1$.[5] Whenever an alternative reaches this score, it means that it is ranked higher than all other alternatives by a majority. In other words, it is a Condorcet winner. Note that if an object does not appear in a majority of lists (here 6 lists or more), its Copeland score is zero.

The three methods yield different conclusions. The most concerning object according to the Borda count is debris $22,220$, while the most concerning object according to the $D(x)$ score is debris $22,566$. Their Borda scores are quite close, with $B(22,220) = 371$ and $B(22,566) = 368$. The difference is that debris $22,220$ appears in ten lists while debris $22,566$ appears in all lists. The object with the largest Copeland score is debris $27,006$. Its Borda score is lower (with $B(27,006) = 360$) and it only appears in eight lists. This debris occupies small position in those lists: in particular it is considered as the most concerning objects by four experts (e_1, e_3, e_5, and e_7), the second most concerning by another expert (e_{10}); the fourth most concerning by another expert (e_2); and then $p_8(27,006) = 9$ and $p_4(27,006) = 29$. We obtain $C(27,006) = 272$. That is, debris $27,006$ is a Condorcet winner: it is considered as more concerning than any other debris by a majority of experts. Note that there are only 22 objects (those which appear in a majority of lists) that can have a non null Copeland score.

Our Table 3 below lists these 22 objects (in ascending order of satelite numbers). For each debris x, the score and the position in the corresponding rankings are given: $A(x)$ and $p_A(x)$ for Approval; $B(x)$ and $p_B(x)$ for Borda; $C(x)$ and $p_C(x)$ for Copeland; $D(x)$ and $p_D(x)$ for the D-rule (McKnight et al. 2021).

[5] Recall that m is the number of debris.

Table 3: scores and positions of the 22 most concerning objects

x	$A(x)$	$B(x)$	$C(x)$	$D(x)$	$p_A(x)$	$p_B(x)$	$p_C(x)$	$p_D(x)$
$16,182$	10	333	261	3330	2	6	8	5
$17,590$	7	231	251	1617	15	18	17	18
$17,974$	9	283	256	2547	8	11	14	11
$19,120$	7	221	250	1547	15	19	18	19
$19,650$	7	259	250	1813	15	16	18	15
$20,625$	10	330	256	3300	2	7	4	6
$22,220$	10	371	264	3710	2	1	6	2
$22,285$	8	287	260	2296	12	10	9	13
$22,566$	11	368	267	4048	1	2	2	1
$22,803$	8	280	254	2240	12	12	15	14
$23,088$	9	268	258	2412	8	15	11	12
$23,405$	10	280	258	2800	2	12	11	10
$23,705$	9	318	262	2862	8	8	7	8
$24,298$	7	253	253	1771	15	17	16	16
$25,400$	7	211	243	1477	15	21	20	20
$25,407$	9	314	259	2826	8	9	10	9
$26,070$	10	347	267	3470	2	5	2	4
$27,001$	6	197	201	1182	20	22	22	22
$27,006$	8	360	272	2880	12	3	1	7
$27,386$	6	220	209	1320	20	20	21	21
$28,353$	6	275	257	1650	20	14	13	17
$31,793$	10	350	266	3500	2	4	5	3

Note that the top 8 objects according to the three rules (Borda, Copeland and D-rule) are identical (that is, their position in the ranking is smaller or equal than 8), although they are ranked in different positions. These objects are: $16,182$; $20,625$; $22,220$; $22,566$; $23,705$; $26,070$; $27,006$; $31,793$.

4 Who vote?

Several issues are related to this question. One concerns the right to vote: who is entitled to vote? Another concerns the importance of this right. For instance, when voters do not vote on their behalf but are representatives of groups of different sizes, some voters may have more weight than others. The presence or absence of voters is also a concern, and addresses the question of possible quorum. There is some literature about the impact of the number of voters on the outcome (see Kelly, 1974). For large elections the impact is close to zero. In small committees the influence mainly depends on how close the votes are. For instance if all experts vote in an identical manner, the impact is also zero. Here we study these issues with the data at hand.

Experts were required to give a list of 50 objects. The total number of debris that appear on the different lists is 273. This number can be compared with $11 * 50 = 550$, the maximum number of debris that could have been listed. This reflects some consensus among the experts, given the size of the catalog.

How close are experts can be seen in our Table 4 below, which gives the number of debris that appears on the respective lists of a given pair of experts. That is, let

$$a_{ij}(x) = \begin{cases} 1 & \text{if } x \in \mathcal{M}_i \cap \mathcal{M}_j \\ 0 & \text{otherwise.} \end{cases}$$

For an object $x \in \mathcal{M}$, $a_{ij}(x)$ keeps track of whether debris x appears on both lists of expert e_i and e_j. The number of objects that appear on both lists is given by $A_{ij} = \sum_{x \in \mathcal{M}} a_{ij}(x)$. Table 4 below gives the number of objects in common for each pair of experts e_i and e_j.

Table 4: Number of debris that appear in at least two lists

	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9	e_{10}	e_{11}
e_1		32	13	12	14	11	21	13	13	16	12
e_2	32		7	5	7	5	13	6	6	8	5
e_3	13	7		19	21	18	12	20	18	15	16
e_4	12	5	19		20	23	11	28	24	15	22
e_5	14	7	21	20		18	14	27	24	15	20
e_6	11	5	18	23	18		10	18	19	10	17
e_7	21	13	12	11	14	10		11	10	14	9
e_8	13	6	20	28	27	18	11		29	14	28
e_9	13	6	18	24	24	19	10	29		14	33
e_{10}	16	8	15	15	15	10	14	14	14		12
e_{11}	12	5	16	22	20	17	9	28	33	12	

All pairs of experts have debris that appear in both lists, although there are substantial differences between pairs of experts. For instance there are 32 objects that appear on the lists of experts e_1 and e_2, while only 5 objects on the lists of experts e_2 and e_4. We compute the average number of debris in common with another expert. Let:

$$\bar{A}_i = \frac{1}{n-1} \sum_{j \neq i} A_{ij}.$$

The results are presented in Table 5 below.

Table 5: Average number of debris in common with another expert

	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9	e_{10}	e_{11}
$\bar{A}_i$	15.7	9.4	15.9	17.9	18	14.9	12.5	19.4	19	13.3	17.4

Expert e_2 appears to be the one who has fewer debris in common with another expert, with an average of 9.4 objects. By contrast expert e_8 has the largest number of debris in common with another expert, with an average of 19.4 objects. Roughly speaking an expert has between 20% and 40% of the objects that coincide with the list proposed by another expert. This reflects a high degree of agreement among experts (considering that experts had to choose 50 objects out of a catalog of thousands of objects).

In order to see the impact of the presence or absence of experts, we realize a simple simulation that consists in removing an expert. Our Table 6 below gives the debris that would be selected when an expert is removed from the committee.

Table 6: Most concerning debris when an expert is removed

Removed expert	Borda	Copeland	D-score
e_1	22,566	27,006	22,566
e_2	26,070	26,070	26,070
e_3	22,566	22,566	22,566
e_4	$\begin{cases} 22,220 \\ 27,006 \end{cases}$	27,006	22,566
e_5	22,220	$\begin{cases} 26,070 \\ 27,006 \end{cases}$	22,566
e_6	27,006	27,006	22,566
e_7	22,220	$\begin{cases} 22,566 \\ 27,006 \end{cases}$	22,566
e_8	22,220	27,006	22,566
e_9	27,006	27,006	22,566
e_{10}	22,220	31,793	22,220
e_{11}	27,006	27,006	22,566

If the committee had been composed of ten experts, debris 22,566 is still the debris with the largest $D(x)$ with two exceptions. If expert e_2 had not participated then debris 26,070 would be the one with the largest $D(x)$. Debris 26,070 does appear on the list of expert e_2 and gets a slightly larger Borda score than debris 22,566. If expert e_{10} had not been present then debris 22,220 would have been the debris with the largest $D(x)$. Against debris 22,220 does not appear on the list of expert e_2 and gets a larger Borda score than debris 22,566. The Borda count is more sensitive to the non-participation of one expert.

Another simulation consists in replicating an expert: this may account for giving more weight to an expert (see our Table 7 below).

Table 7: Most concerning debris when an expert is replicated

Replicated expert	Borda	Copeland	D-score
e_1	$22,220$	$27,006$	$22,566$
e_2	$\begin{cases} 22,220 \\ 27,006 \end{cases}$	$27,006$	$22,566$
e_3	$27,006$	$27,006$	$22,566$
e_4	$22,566$	$26,070$	$22,566$
e_5	$22,566$	$27,006$	$22,566$
e_6	$22,220$	$22,566$	$22,566$
e_7	$27,006$	$\begin{cases} 22,566 \\ 22,220 \end{cases}$	$22,566$
e_8	$22,566$	$27,006$	$22,566$
e_9	$22,220$	$26,070$	$22,566$
e_{10}	$22,566$	$27,006$	$22,566$
e_{11}	$22,220$	$22,566$	$22,566$

The debris with the largest Borda score remains debris $22,220$ with the replication of one of the following experts: e_1, e_2, e_6, e_9, e_{11} (with the replication of expert e_2, debris $22,220$ and debris $27,006$ would be tied with the largest Borda score). The debris with the largest Borda score becomes debris $22,566$ with the replication of one of the following experts: e_4, e_5, e_8, e_{10}. The debris with the largest Borda score becomes debris $27,006$ with the replication of one of the following experts: e_2, e_3, e_7. By contrast when we add an expert the most concerning debris is object $22,566$ according to the D-score, which is identical to what was obtained with 11 experts. The Copeland rule would give different results, depending on the expert who is replicated.

In spite of these differences we can conclude that the committee is quite homogeneous. A homogeneous committee is less sensitive to the removal of a voter than a very heterogeneous committee.

5 Input and output of a rule

A rule takes as input the judges ballots and provides a collective outcome as an output. The input reflects the question addressed. In McKnight et al. (2021) the input were 50-truncated ordered ballots. That is, experts were required to choose exactly 50 objects from the catalog and rank them. Here we discuss two characteristics of the ballot (and thus the question that was addressed to the experts).

The first characteristic makes a distinction between ordered ballots and evaluative ballots. An ordered ballot requires experts to rank the debris from the most-concerning debris to the least concerning one. Different questions could be answered with evaluative ballots. One would be "Do you consider that the following debris should be removed?" In this case the evaluative ballot may propose three possible answers: "yes", "abstain", and "no". Another question may be "What level of risk do you associate to the object of the catalog?" In this case numerical evaluative ballots would ask experts to give a score to each object (that reach a certain threshold of risk). A third type of question would ask experts to give a categorical grade to each debris, such as "very concerning", "concerning", etc. The simplest categorical evaluative is the approval ballot. This ballot would require experts to divide debris into "concerning" or "non concerning" debris.

In our context, evaluative ballots may be more appropriate than ordered ballots. This choice is in line with the discussion in voting theory between preferences and judgments (Hillinger, 2005; Balinski and Laraki, 2007). Indeed, with ordered ballots voters (here experts) have to compare objects and determine which one is the most preferred (here concerning), and rank all objects. By contrast, with evaluative ballots experts judge objects on the basis of their own characteristics, not in comparison with the other objects. Note that this is what most experts did: they often associate a certain level of risk to each object and then derived an ordered list (see McKnight et al., 2021).

Another reason that pleads in favor of evaluative ballots is that two objects may be considered as concerning for different reasons. With an evaluative ballot experts do not have to decide which reason prevails on the others. By contrast an ordered ballot requires experts to rank objects and thus to decide which reason matters more.

Removing one object from the list may modify the ranking of other objects with ordered ballots, while the evaluation is not modified. This can be illustrated on a simple example for the Borda count. Consider 5 experts and 3 objects (x, y and z). Three experts rank first x, then y and finally z, while two experts rank first y, then z and finally x. The object with the largest Borda score would be alternative y.[6] Now imagine that alternative z (which is the one with the smallest Borda score) is removed. In this case the alternative with the largest Borda score is then object x.[7] This property is coined dependence to irrelevant alternatives. An illustration of this problem is the 2002 presidential election in France (see Laruelle, 2021a). No occurence of the dependence to irrelevant alternatives appears in the ranking of the experts in McKnight et al. (2021) for three rules tested: the most concerning object is not modified even if we remove one object from the list of the experts.

The second distinction between ballots is whether experts have to cast a vote on the entire list, whether they can choose to cast a vote on part of the list or whether they have to vote on a given number of objects. An k-truncated ballot asks voters to select k debris and rank them from the most-concerning debris to the k-most concerning debris (in the case of an ordered ballot) or give each of them a grade (in the case of an evaluative ballot). It implicitely assumes that the remaining debris are the least concerning debris (in the case of an ordered ballot) or would receive

[6]We have $B(x) = 3 * 3 + 2 * 1 = 11$; $B(y) = 3 * 2 + 2 * 3 = 12$ and $B(z) = 3 * 1 + 2 * 2 = 7$.

[7]We have $B(x) = 3 * 2 + 2 * 1 = 8$ and $B(y) = 3 * 1 + 2 * 1 = 7$.

the lowest grade (in the case of an evaluative ballot).

In our context, it may be arbitrary to ask experts to rank exactly k objects. Experts should choose the number of objects that they consider as concerning. In particular, if experts associate to each object a level of risk, objects above a certain threshold may be considered as concerning, no matter their number.

Often in practice the input and the output of a rule take the same form, as is done in McKnight et al. (2021). Experts were asked to provide the list of the 50 most concerning objects and the outcome was the top 50 list of the most concerning objects. The question addressed in the ballot may however differ from the collective answer. For instance experts may be given evaluative ballots, and the collective outcome may the most concerning debris.

In our context, the outcome may be a classification of debris rather than a ranking of objects. There may be two or more categories. Objects may be collectively divided into concerning, and non concerning objects. Other division can be considered, as extremely hazardous, hazardous, etc. Indeed the vote of the experts may be seen as a first screening in the choice of the objects that should be removed. Indeed other considerations, such as the costs of removal and the available budget may play an important role. For instance if the costs of removal differ according to the objects, it may be better to remove two objects with low costs of removal rather than one that is much more costly to remove.[8]

Moreover, as commented in McKnight et al. (2021), once an object is removed, the risk of the remaining objects may be modified. That pleads in favor of choosing a bundle of objects to remove under the constraint of a given budget.

6 Concluding remarks

Our paper leads to three main conclusions. First, the eleven top 50 lists present similarities, although experts used different hypotheses and approaches to obtain them. In particular, it is worth noting that one debris appears in all top 50 lists and 22 debris appear in a majority of them. On average, at least of dozen of debris appear in any pair of top 50 lists. Second, the aggregation rule is important in the sense that it impacts the results. The most concerning debris is not the same depending on whether the Borda count or the Condorcet principle is used. This results is especially worth noticing, as experts are fairly highly homogeneous. The composition of the committee of experts is also important. Removing or replicating an expert would also have an impact on the selection of the most concerning object. Thirdly and finally, there is no reason to impose a given number of debris: it would have been preferable to let each teams of expert determine the number of dangerous debris.

[8]The problem may then be similar to a problem of participatory budgeting (see Laruelle, 2021b).

Our article, like that of McKnight et al. (2021), has a first blind spot. At no point did we discuss the costs associated with debris removal and the overall budget required. As far as we know, the cost of removing one of the actual biggest debris is currently evaluated, to the best of our knowledge, on the order of $10 to $20 millions, depending on the technology involved. In many respects, the problem is comparable to the one of by participatory budgeting. If the study by McKnight et al (2021) is carried out again, it could take into account costs as follows. In a first stage experts would be asked to vote with evaluative ballots on as much debris as they wished. These could be include categorical grades such as "Extremely hazardous debris", "Hazardous debris", etc. The output may result in several categories, one being "Extremely hazardous debris". The debris in this category would be associated with a removal cost. Based on this information and the available budget a second vote could be taken in order to determine which pieces of debris could be removed.

The second blind spot, partly related to the first, is linked to the dynamic aspect of the list and externalities. As commented in McKnight et al (2021) the removal of one piece of debris has impact on the ranking of the others.

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Declaration of interest

The authors declare no conflict of interest.

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8 Appendix

Table 3 in McKnight et al. (2021)

	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9	e_{10}	e_{11}
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	224,277	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