A QUANTITATIVE EVALUATION OF THE ENVIRONMENTAL IMPACT OF THE MEGA CONSTELLATIONS

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ABSTRACT

The main focus of this work is to highlight the main parameters driving the future evolution of the debris environment, in presence of the planned LEO mega constellation of satellites. First, in order to identify the most important parameters that are actually driving the evolution of the environment and in an effort to discriminate between possibly equivalent scenarios, we applied tools from the statistical sciences, namely the *Wilcoxon signed rank test*, a non-parametric test which allows us, given two samples, to assess whether their population mean ranks differ. Then, by means of a simplified model of the constellation building and managing, we define an index able to quantify the environmental impact of the mega constellations. The index takes into account the physical and orbital characteristics of the constellation satellites, along with the mitigation practices adopted for each constellation. Based on the expected collision risk and the capability of avoiding impacts, the operational and non-operational satellites and the related upper stages, present in each constellation, enter the index computation with different relative weights to properly account for the global constellation effects on the environment. The model and the associated index, along with other metrics described in [6] and [4], allows us not only to highlight the prominence of some of the parameters entering in the definition of a satellite constellation but also to "predict" the influence that a change in that particular parameter is going to produce on the long term evolution of the environment. In the simulated scenarios, the parameters playing a major role in the effect that a mega-constellation cause on the environment are: the mass and the area of the satellites, the failure rate in the operational orbit and the collision avoidance success rate.

Keywords: Mega constellations; long-term simulations; evaluation index.

1. INTRODUCTION

In the next decades a number of large satellites constellations are expected to be launched in Low Earth Orbit. The huge number of satellites involved in these constellations poses new challenges to the space debris community at large. As currently envisaged, these large ensembles of satellites will mainly fly in the already crowded LEO region and the proper management of the launch and disposal traffic will be essential to limit the impact of these space structures on the future evolution of the space environment.

A preliminary study of the possible impact of the mega constellations on the LEO environment can be found in [1]. Following the study in [1], thanks to a contract with the European Space Agency, an extensive simulation campaign was performed considering many different scenarios, in an effort to identify the influence of different constellation design parameters on the long term evolution of the LEO debris environment. The preliminary results of this study were presented in [2]. A more detailed analysis can be found in [4] and in the paper by Lewis *et al.* in this volume.

Here, in Sec. 2, we concentrate on possible evaluation criteria allowing us to properly discriminate in a quantitative physically based way between similar simulation scenarios. Later on, in Sec. 3, based on the understanding reached with the long term simulations, a simplified analytical model able to reproduce the main characteristics of the planned constellations and to compute an evaluation index is presented.

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2. EVALUATION CRITERIA

As mentioned above, a very large number of simulations was performed in the framework of this study, changing, often slightly, different parameters of the considered scenarios.

Given the large number of simulation performed and the intrinsic stochasticity of the results of the Monte Carlo runs, it is often difficult to establish, simply looking at the plots showing ,e.g., the number of objects as a function of time, whether two scenarios can be considered statistically equivalent or, conversely, the considered parameter has a significant influence in the long term evolution.

Indeed, in the statistical sciences there are a number of known methods to determine whether two sets of data are significantly different from each other.

In [6] we proposed the so-called *criticality norm*, based on the average quantities (i.e., number of objects, number of collisions, ...) and standard deviation of the Monte Carlo runs. This norm is quite effective in visually representing the typical outcomes long term simulations (see, e.g., [7]).

Nonetheless, considering the results of the N Monte Carlo runs (e.g., the number of objects at the end of the simulation time span), we a priori ignore the statistical properties of their distribution (e.g., we might be in presence of a not normal distribution). Hence we looked also for other comparison methods and, in particular, we focused on the *Wilcoxon signed rank test*. The Wilcoxon test, is a non-parametric test which does not assume normality in the data and allows us, given two samples, to assess whether their population mean ranks differ. The mathematics of the Wilcoxon test can be found in textbooks of statistics (e.g., [8]). In our analysis we consider two scenarios A and B, with some difference in one or more parameters of the simulation setup, and we want to determine if this parameter has a statistically relevant effect on the long term evolution of the environment. For our analysis here it suffices to mention these characteristics of the Wilcoxon method:

1. The test verifies the null hypothesis which tells us that, given two scenarios A and B, the difference between two distributions of data $(n(A) - n(B))$ comes from a distribution with zero median. And it does it assuming a *significance level* (α, whose default value is 5 %), i.e., the test rejects, or confirms, the null hypothesis of zero median at the level α, established in input.

2. The output of the test gives the *p-value*, defined as the probability of obtaining a result equal to or “more extreme” than what was actually observed, when the null hypothesis is true. If the p-value is less than or equal to α, the test suggests that the data are inconsistent with the null hypothesis, so the null hypothesis must be rejected. In our case where $\alpha =$ 0.05, the null hypothesis is rejected when $p < .05$ and not rejected when $p > .05$. We interpret the results of the test where $p < .05$ saying that the scenarios A and B give statistically significantly different outcomes, hence the level of variation of the analyzed parameter can play a role in the long term evolution of the debris environment.

Note that whereas the p-value is not the probability that the null hypothesis is acceptable or not acceptable, given two scenarios, the lower the p-value the more significant is the conclusion that the null hypothesis has to be rejected. As a consequence we cannot use the p-value to actually rank all the simulation scenarios, but we can use it, as stated above, to determine if a change of a given parameter is influential with respect to a reference value (or vice versa: when a change of a given parameter is not influential).

We applied the Wilcoxon test to the large set of simulations performed with DAMAGE (see the paper by Lewis *et al.* in this volume for further details). For sake of conciseness we are not reporting here the very long list of whole the scenarios simulated, which can be found in [4].

First we considered as reference the baseline scenario, described in [4], where a single mega-constellation, comprising 1080 operational satellites, with mass M=200 kg and cross sectional area A=1 m^2, at 1100 km altitude, arranged in 20 orbital planes, inclined at $85°$ following a Walker-delta geometry, is considered. On top of this reference case many other scenarios, where some of the parameters of the constellations are changed, were simulated. A non-exhaustive list include: mass and/or area of the constellation satellites, launch rate and policies (e.g., altitude of the release orbit), de-orbiting strategies (impulsive vs. low thrust maneuvers, kind of disposal orbit), collision avoidance level, failure rates (both during the operational life and in the de-orbiting phase), lifetime of the whole constellations and of the single satellites, compliance to mitigation measures, upper stages management, etc.

According to the Wilcoxon test, none of the test scenarios, compared to the Reference one, satisfy the null hypothesis. I.e., as expected, the long term evolution obtained in the varied cases cannot be considered statistically fully equivalent to the reference one. Nonetheless, the real interest of the methodology was to check, within the modified scenarios, to what level the variation of the analysed parameter is effective. Therefore, for some of the analysed parameters, we compared the subset of simulations where the investigated parameter is slightly changed. Here we report the results about some specific subsets of simulations:

- Two sets of 6 simulations were performed assuming different constellation altitudes: 700 and 900 km respectively. The five simulation scenarios assume:
  1. disposal of constellation satellites as in the reference case (with M = 100 kg and A= 1 m^2) on

a pre-defined orbit living less than 25 years;

2. disposal of constellation satellites according to the 25-year rule;
3. constellation satellites having mass, M = 100 kg and area A= 1 m^2
4. constellation satellites having mass, M = 100 kg and area A= 6 m^2
5. constellation satellites having mass, M = 400 kg and area A= 1 m^2
6. constellation satellites having mass, M = 400 kg and area A= 6 m^2

All the scenarios from 2 to 5, at 700 km, verify the null hypothesis when compared against the scenario 1) at 700 km. I.e., they are statistically equivalent. We may argue that, at such a low altitude, the higher background population and the natural cleaning of the environment are dominating over the possible effects of the changed parameters. On the other hand, at 900 km, the same is not true and only the case 3) is equivalent to the reference case 1; i.e., halving the mass, leaving everything else unchanged, at this altitude, does not change the simulation outcome.

- Three sets of five simulations were performed assuming different number of constellation satellites: 180, 300 and 600 active satellites respectively. The five simulation scenarios assume:

  1. constellation satellites having a mass, M = 200 kg and an area A= 1 m^2 (same as the Reference constellation)
  2. constellation satellites having a mass, M = 100 kg and an area A= 1 m^2
  3. constellation satellites having a mass, M = 100 kg and an area A= 6 m^2
  4. constellation satellites having a mass, M = 400 kg and an area A= 1 m^2
  5. constellation satellites having a mass, M = 400 kg and an area A= 6 m^2

  In the scenarios with 180 satellites, due to the low numbers involved, only the case 5) (very large satellites) is statistically different, whereas all the others verify the null hypothesis w.r.t. case 1. Going to higher numbers, in the 300 and 600-satellite constellations both cases with large areas (3 and 5) are not verifying the null hypothesis, while for small areas the relatively small number of satellites keeps the evolution unchanged. We can conclude, first, that the area is a more sensitive parameter with respect to the mass. Moreover, clearly, small constellations are less affected by the change of only one of the physical parameters.

- A set of 6 simulations assuming different constellation geometry: 4 Walker-delta constellations with inclinations at 45, 55, 65, 70 deg and 2 Walker-star constellations. These cases were all compared against the reference constellation ($i = 85°$ following a Walker-delta geometry). None of the modified case satisfies the null hypothesis. This seems to point us to the known relevance of the inclination on the collision probability.

- A set of 3 simulations assuming different collision avoidance success rate of operational constellation satellites against the background population (in the default case it was assumed 100 %): 50 %, 70 % and 90 %. The three cases result statistically equivalent (with a much larger p-value when comparing 50 % and 70 %). I.e., collision avoidance is important (none of these 3 cases is actually equivalent to the reference one) but the interaction of the active satellites in the operational orbit with the background is not the driving factor. Note that a 100 % efficiency of collision avoidance between constellation satellites is also assumed in all these cases.

- A set of 8 simulations assuming different management of the Upper Stages (U/S):

  1. constellation U/S are de-orbited according to the 25-yr rule with 90 % compliance
  2. constellation U/S are de-orbited according to the 25-yr rule with 60 % compliance
  3. constellation U/S are de-orbited according to the 10-yr rule with 90 % compliance
  4. constellation U/S are de-orbited according to the 10-yr rule with 60 % compliance
  5. double launch rate and constellation U/S are de-orbited according to the 25-yr rule with 90 % compliance
  6. double launch rate and constellation U/S are de-orbited according to the 25-yr rule with 60 % compliance
  7. double launch rate and constellation U/S are de-orbited according to the 10-yr rule with 90 % compliance
  8. double launch rate and constellation U/S are de-orbited according to the 10-yr rule with 60 % compliance

  Comparing cases 2-8 against case 1, we see that only the cases 1 and 3 are equivalent. The proper U/S management is clearly a must in this case and only at the 90 % compliance level the different residual lifetime is not significant

- A set of 13 simulations assuming different disposal orbits for the constellation satellites at the End-of-Life:

  1. disposal into a 300 × 300 km orbit
  2. disposal into a 300 × 500 km orbit
  3. disposal into a 300 × 700 km orbit
  4. disposal into a 300 × 900 km orbit
  5. disposal into a 300 × 1000 km orbit

6. disposal into a 300×1100 km orbit
7. disposal into a 400×400 km orbit
8. disposal into a 400×500 km orbit
9. disposal into a 400×700 km orbit
10. disposal into a 400×900 km orbit
11. disposal into a 400×1000 km orbit
12. disposal into a 500×500 km orbit
13. disposal into a 500×700 km orbit

Here we compared the 13 cases above, all against the case number 3. All the cases 1-11 are equivalent to case 3 and only the cases 12 and 13 differ. This is dictated by the low altitude of the perigee of cases 1-11 which assures a fast disposal, along with an almost instantaneous freeing of the constellation altitude. The importance of a proper disposal is, once again, highlighted.

- A set of 11 simulation scenarios assuming the launch of two different mega constellations: the reference one plus a Boeing-like constellation (see e.g., http://spacenews.com/boeing-proposes-big-satellite-constellations-in-v-and-c-bands/) at different altitudes and with the following characteristics:

  1. 2 constellations, Reference plus a Boeing-like at 1100 km
  2. the same as 1. but with both constellations de-orbited according to the 25-year rule
  3. 2 constellations, 25-yr rule, with the Boeing-like at 1150 km
  4. 2 constellations, 25-yr rule, with the Boeing-like at 1200 km
  5. 2 constellations, 25-yr rule, with the Boeing-like at 1250 km
  6. 2 constellations, 25-yr rule, with the Boeing-like at 1300 km
  7. 2 constellations, 25-yr rule, with the Boeing-like at 1100 km, and with satellites having M=400 kg, A=2 m^2
  8. 2 constellations, 25-yr rule, with the Boeing-like at 1150 km, M=400 kg, A=2 m^2
  9. 2 constellations, 25-yr rule, with the Boeing-like at 1200 km, M=400 kg, A=2 m^2
  10. 2 constellations, 25-yr rule, with the Boeing-like at 1250 km, M=400 kg, A= 2 m^2
  11. 2 constellations, 25-yr rule, with the Boeing-like at 1300 km, M=400 kg, A=2 m^2

  Here we compare all the cases against case 1. All the cases 2-6 satisfy the null hypothesis, i.e., are equivalent to case 1. I.e., adding a second constellations makes a difference w.r.t the case where only one is present in space, but a moderate change in the altitude of the second one does not cause significant changes to the evolution. This can also be interpreted as an indication of a low level of interaction between the two satellite systems, as long as the collision avoidance and disposal practices are working well. On the other hand, the cases 7-10 do not satisfy the null hypothesis. Increasing the size of the satellites in the second constellation is increasing the production of collisional fragments from that altitude and there is, therefore, an increased interaction between the two constellations. Finally, case 11 turns out to be equivalent to case 1: here perhaps the larger separation in altitude between the two constellations minimizes the interaction of the first constellation with the collisional fragments from the second one.

As mentioned above, many other scenarios were simulated in the ESA Study. For reasons of space and time limitation we are not mentioning them all here. Nonetheless with this short section we have highlighted the usefulness of the Wilcoxon test in helping us to discriminate in a non-subjective way the complex output of apparently similar scenarios, allowing, in some case, to identify key parameters driving the evolution of the mega-constellation scenarios.

3. THE CCI

Building on the lessons learned from the simulations described in [4] (and in the paper by Lewis *et al.* in this volume), we propose here an analytical formulation to evaluate the impact of a given mega constellation on the LEO environment. This is the Criticality of Constellation Index (CCI), and it is based on the idea described in [3]. The whole LEO region is divided in N shells of 50 km of altitude in the range $[150 : 2000]$ km, and to each shell is associated a criticality index, as a function of the year, of the objects orbiting through the given shell and the time they spend in it. The criticality of the LEO region is the sum of the indexes over all the shells. In [3], the criticality index adopted is the CSI (Criticality of Spacecraft Index), following [6]. For a given object, the CSI can be written as

$$\Xi = \frac{M}{M_0} \frac{\rho}{\rho_0} \frac{\mathcal{L}}{\mathcal{L}_0} f(i), \tag{1}$$

where M is the mass of the object, ρ the spatial density associated with the given shell in the given year, $\mathcal{L}$ the lifetime of the object at the altitude corresponding to the shell, and $f(i)$ a function of the orbital inclination i. The terms M_0, ρ_0, and $\mathcal{L}_0$ are normalizing factors. The CSI of the LEO region for a given year is thus

$$\Xi_{LEO} = \sum_{i=1}^{N} \sum_{j=1}^{p(i)} \Phi_{i,j} \Xi_j, \tag{2}$$

where $p(i)$ are 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.

For a mega constellation, we modify the definition in (1) in order to account also for the cross-sectional area, say A, of the satellites. In particular, we consider

$$\tilde{\Xi} = \frac{A}{A_0}\frac{M}{M_0}\frac{\rho}{\rho_0}\frac{\mathcal{L}}{\mathcal{L}_0}f(i), \tag{3}$$

where the normalizing area is $A_0 = 1$ m^2. Considering the LEO environment before the launch of the constellation, its criticality is thus given by

$$\tilde{\Xi}_{LEO} = \sum_{i=1}^{N}\sum_{j=1}^{p(i)}\Phi_{i,j}\tilde{\Xi}_j, \tag{4}$$

where $p(i)$ is the number of historical objects.

Our aim is to depict the variation of this value caused by the mega constellation, according to given hypotheses on its composition, building, maintenance and disposal practices. Let us assume the following information:

- a, e, i, M, A for all the satellites of the constellation;
- collisional avoidance capability, say $\mathcal{C}$, and probability of failure, say $\mathcal{F}$, for all the satellites of the constellation during the operational phase;
- collisional avoidance capability, say $\mathcal{C}_d$, and probability of failure, say $\mathcal{F}_d$, for all the satellites of the constellation during the de-orbiting phase;
- first and last year of launch , duration of the building phase, satellite operational life;
- number of launches and number of satellites per launch during the building phase of the constellation;
- number of launches and number of satellites per launch during the replenishment phase of the constellation;
- initial pericenter and apocenter for the de-orbiting phase, and duration of the de-orbiting phase.

The algorithm proposed processes all this information to provide the variation of $\tilde{\Xi}_{LEO}$ for each year when any satellite of the constellation is present in the region. The CCI for a given year can be written as

$$CCI = CCI_{LEO}^{dir} + CCI_{LEO}^{non-dir}, \tag{5}$$

that is, the variation is due to direct and non-direct contributions associated with the launch and the de-orbiting of the spacecraft. The direct term is simply the sum of the $\tilde{\Xi}$ of the spacecraft of the mega constellation, either operational or de-orbiting, weighted for their collision avoidance capabilities and their probability of failure, namely,

$$CCI_{LEO}^{dir} = \sum_{i=1}^{N_O}\sum_{j=1}^{p_o(i)}[(1-\mathcal{C})(1-\mathcal{F})+\mathcal{F}]\Phi_{i,j}\tilde{\Xi}_j + \sum_{i=1}^{N_D}\sum_{j=1}^{p_d(i)}(1-\mathcal{F})[(1-\mathcal{C}_d)(1-\mathcal{F}_d)+\mathcal{F}_d]\Phi_{i,j}\tilde{\Xi}_j + \sum_{i=1}^{N_O}\sum_{j=1}^{p_d(i)}\mathcal{F}\Phi_{i,j}\tilde{\Xi}_j, \tag{6}$$

where N_O and N_D are the shells interested by the operational and by the de-orbiting phase, respectively, and p_o and p_d the number of operational and de-orbiting objects, respectively, for the given year. Note that the second term is first weighted by $(1-\mathcal{F})$, in the sense that only the "fraction" of satellites which did not fail are able then to de-orbit. The third term indeed represents the failed satellites which remain on the operational shells forever. The non-direct contribution is instead due to the variation of the density of each shell caused by the presence of new spacecraft, namely,

$$CCI_{LEO}^{non-dir} = \sum_{i=1}^{N}\sum_{j=1}^{p(i)}\Phi_{i,j}\frac{A}{A_0}\frac{M}{M_0}\frac{\Delta\rho}{\rho_0}\frac{\mathcal{L}}{\mathcal{L}_0}f(i), \tag{7}$$

where p here includes the historical existing objects, plus the operational and the de-orbiting objects of the mega constellation, and the density variation is weighted as a function of $\mathcal{C}, \mathcal{C}_d, \mathcal{F}, \mathcal{F}_d$, similarly to what is done in (6).

The cumulative CCI is the sum of the CCI over all the years, until all the satellites have cleared the whole LEO region.

3.1. Examples of the CCI application

Let us take as reference the following scenario:

- $\tilde{\Xi}_{LEO}$ computed considering all the objects such that $M > 100$ kg from the MASTER database;
- $a = 7478.14$ km, $e = 10^{-4}$, $i = 85°$, $M = 200$ kg, $A = 1.$ m^2;
- first year of launch: 2018; last year of launch: 2070;
- duration of the building phase: 3 years; 20 launches per year, 18 satellite per launch;
- 12 launches per year, 18 satellites per launch during the replenishment phase;
- operational lifetime: 5 years;
- disposal orbit: 6678.14×7478.14 km, duration[1]: 4 years;
- $\mathcal{C} = 0.9, \mathcal{C}_d = 0.8, \mathcal{F} = 0, \mathcal{F} = 0.2$.

[1]The duration is computed offline with FOP [5], considering the proper A/m.

In Fig. 1 and 2, we show the CCI computed for each year, and the cumulative one, for the reference scenario (in black) and for other scenarios, characterized by different hypotheses on $i, M, A, \mathcal{C}, \mathcal{C}_d, \mathcal{F}, \mathcal{F}_d$, and de-orbiting time. In particular we consider the following variations:

- i from $45°$ to $85°$, at steps of $5°$ (Fig.1 top row: from bottom to top curve)
- Mass from 200 to 3000 kg, at steps of 100 kg up to 1000 kg, and then two cases with 2000 and 3000 kg (Fig.1 second row: from bottom to top curve)
- Area from 1 to 10 m^2, at steps of 1 ^{2} (Fig.1 third row: from bottom to top curve)
- De-orbiting time from 4 to 30 years, at steps of 1 year up to 10 years and then with steps of 5 years (Fig.1 bottom row: from bottom to top curve; note that the curves appears compressed due to the presence of the reference black curve)
- Failure probability of satellites in the constellation orbit, during operational lifetime, from 10 to 65 %, at steps of 5 % (Fig.2 top row: from bottom to top curve)
- Failure probability of satellites in the disposal trajectory, during de-orbiting, from 10 to 65 %, at steps of 5 % (Fig.2 second row: from bottom to top curve)
- Different collision avoidance success rate during operations in the constellation orbit, from 90 % to 0 % at steps of 10 % (Fig.2 third row: from bottom to top curve)
- Different collision avoidance success rate during in the disposal trajectory, during de-orbiting, from 90 % to 0 % at steps of 10 % (Fig.2 bottom row: from bottom to top curve).

First, note that only for the reference scenario, the CCI goes back to 0, once the operational life of the constellation is over. This is because in that case we assumed $\mathcal{F} = 0$, that is, the possibility of accumulating non-cooperative satellites at the end-of-life is discarded. For all the other scenarios, the general assumption is that the probability of failure is at least $\mathcal{F} = 0.1$, and this causes the increasing trend associated with the curves. Instead, the hump at the beginning is due to the traffic launch assumed and does not entail specific meanings.

Comparing the figures, it turns out that, among the investigated ones, the most critical parameters to be bounded in the design of the mega constellation are: mass, area, and failure probability during the operational phase.

It is also possible to show the criticality as a function of altitude for a given epoch. In Figure 3, we compare the criticality associated with the shells corresponding to the historical population, with the scenario corresponding to 30% probability of failure. In the shell where the mega constellation is launched (and where the satellites remain in the case of failure) the accumulation of spent satellites leads to a criticality which reaches a level of more than the 30% of the highest level of criticality of the historical population, detected at the shell at 1000 km of altitude.

From the definition of the CCI given in Sec. 3, any unlucky configuration affecting the de-orbiting time, e.g., low collision avoidance capability, or longer de-orbiting time, plays a secondary role in the overall evaluation. In Figure 4, we show a snapshot of the shells crossed during a 25-year disposal at different years, assuming different values for the failure probability and the collision avoidance capability in the de-orbiting phase. To avoid cluttering, in the Figure, the CSI corresponding to the operational shell is not shown, because its value is at least 2 order of magnitude larger than the CSI of the disposal shells. This is due to the fact that the lifetime of the objects in the single shells crossed during the de-orbiting trajectory is significantly lower than the time spent by the satellites in the operational one.

To provide a ranking of the different scenarios, we compute the ratio between the cumulative CCI at the end of the curve (operational life + disposal time) corresponding to a given scenario and the same value for the reference case. In Figure 5, for the same parameters analyzed in Figs. 1 and 2, we show the results as a function of the value of the parameter for which the curve is generated. Looking at the scale in the Y-axis the relative importance of the 8 parameters can be clearly detected. Once a given parameter has been isolated, these plots can be also useful in “predicting” the impact of the variation of that parameter on the LEO environment. This can help in reducing the number of costly long term simulations and assist in effective design of “environmental friendly” constellations.

4. CONCLUSIONS

The launch of the mega constellations in LEO is going to represent a dramatic change in the exploitation of this already crowded region of space. It has to be remarked that all the proposed constellations (as far as it can be deduced from the information openly available on these systems) come with a usually well defined debris mitigation policy. Nonetheless the possible impact of this huge number of satellites on the LEO environment can be so high that a thorough simulation work, to help defining the best mitigation practices, is in order. Following the extensive simulation campaign described in the paper by Lewis *et al.* in this same volume, first a pair-wise comparative analysis by means of the Wilcoxon signed rank test was performed, in order to highlight, in an objective, statistically sounding way, some of the relevant parameters driving the long term evolution of the LEO environment, in presence of a large constellation of satellites. E.g., the relevance of the mass and, mainly, of the cross-sectional area of the constellation satellites is underlined. Other investigated important parameters include: upper stages management, constellation operational orbit and disposal orbit altitude, collision avoidance success rate and constellation geometry. Next, based on the understanding reached with the long term simulations and on the idea described in [3] we introduced the Criticality of Constellation Index (CCI). By means of a simplified model of the constellation building and managing, the index is able to quantify the environmental impact of the mega constellations. The index takes into account the physical and orbital characteristics of the constellation satellites, along with the mitigation practices adopted for each constellation. Based on the expected collision risk and the capability of avoiding impacts, the operational and non-operational satellites and the related upper stages, present in each constellation, enter the index computation with different relative weights to properly account for the global constellation effects on the environment. An averaged, time evolving, index computed on altitude shells can give quantitative and visually effective indication of the effectiveness of the mitigation practices applied by a constellation operator. The influence of the orbital inclination, the mass and the area of the satellites, of the failure probability, of the collision avoidance success rate and of the de-orbiting time are shown, in a number of plots. These diagrams allows both to rank these effects in terms of influence on the long term evolution and to quickly "predict" the long term influence of the change of one of the above parameters.

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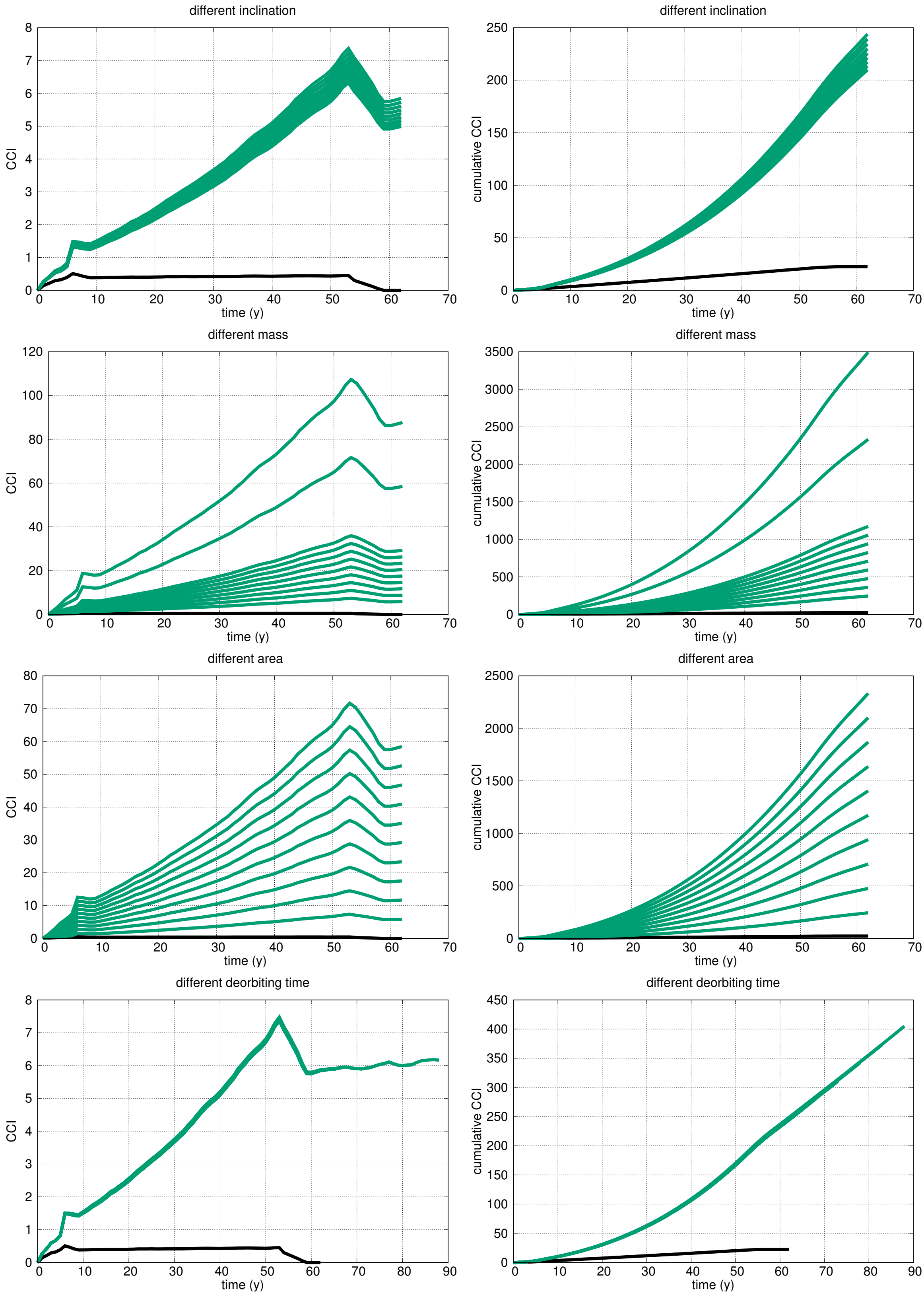

Figure 1. CCI computed for each year (left) and cumulated over time (right) for different scenarios. The black curve represents the reference case, the green curve correspond to a different value of a given parameter. From top to bottom: i, M, A, de-orbiting time (see text for details).

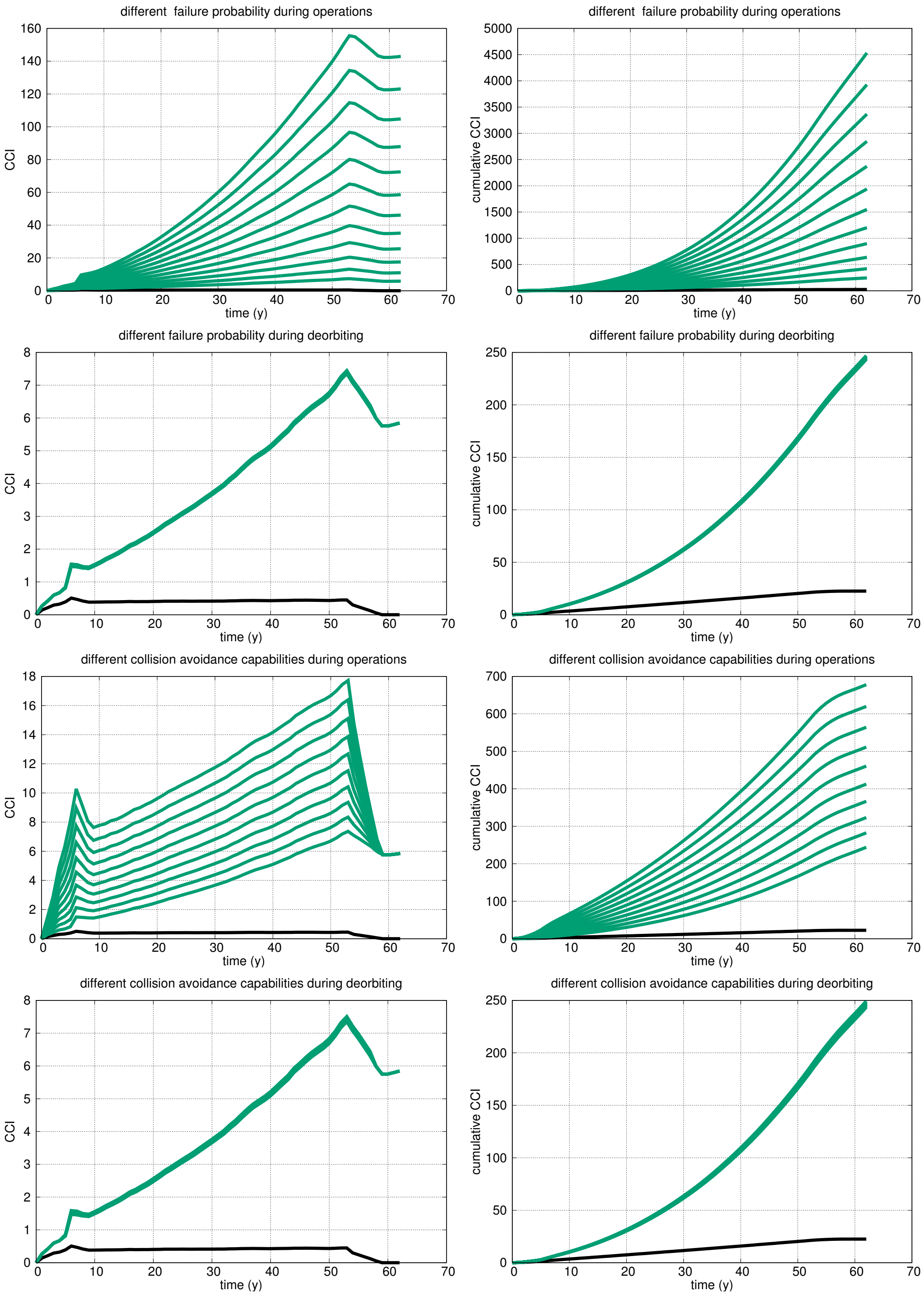

Figure 2. CCI computed for each year (left) and cumulated over time (right) for different scenarios. The black curve represents the reference case, the green curve correspond to a different value of a given parameter. From top to bottom: $\mathcal{C}, \mathcal{C}_d, \mathcal{F}, \mathcal{F}_d$ *(see text for details).*

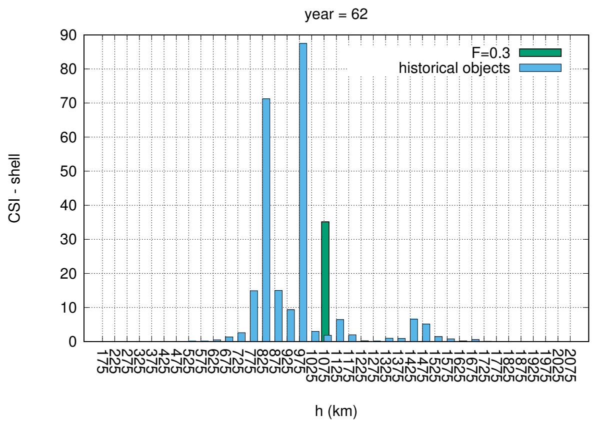

Figure 3. Criticality associated with the given altitude shells for the historical population (blue), and the scenario corresponding to a failure probability of the 30%.

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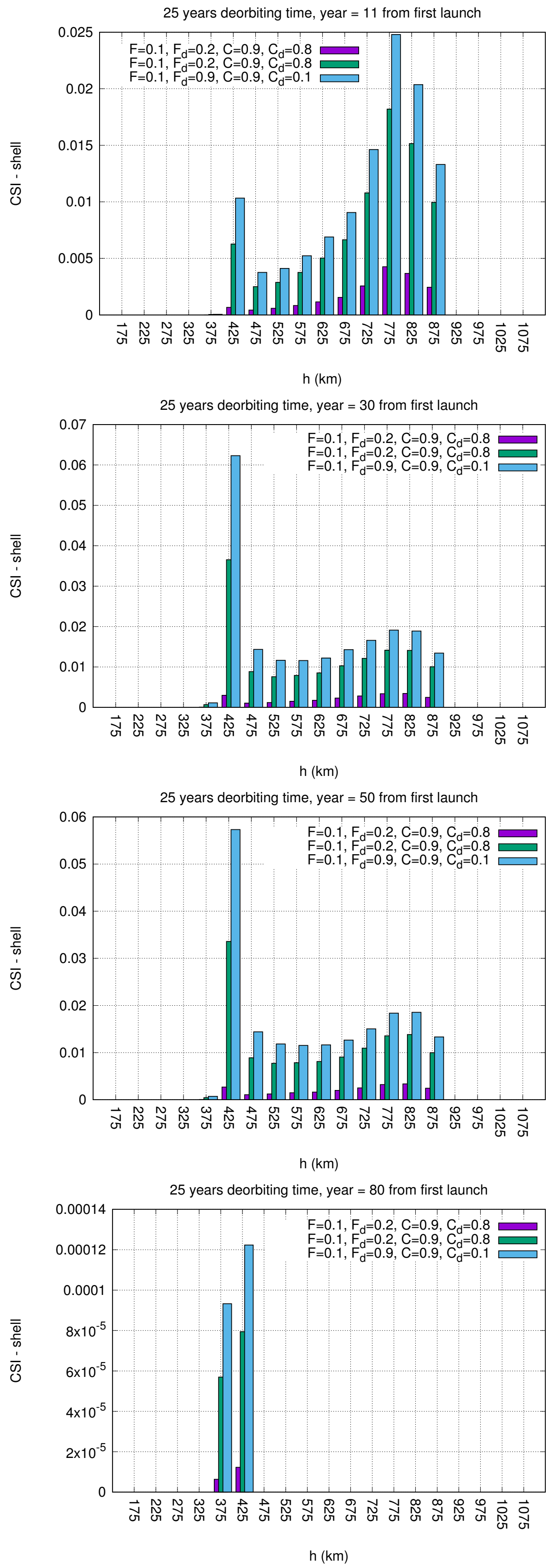

Figure 4. Criticality associated with the shells affected during a 25-year de-orbiting procedure, assuming different values for $\mathcal{F}_d$ and $\mathcal{C}_d$. The criticality corresponding to the operational shell is not shown. Each panel corresponds to a different year, from the epoch of the first

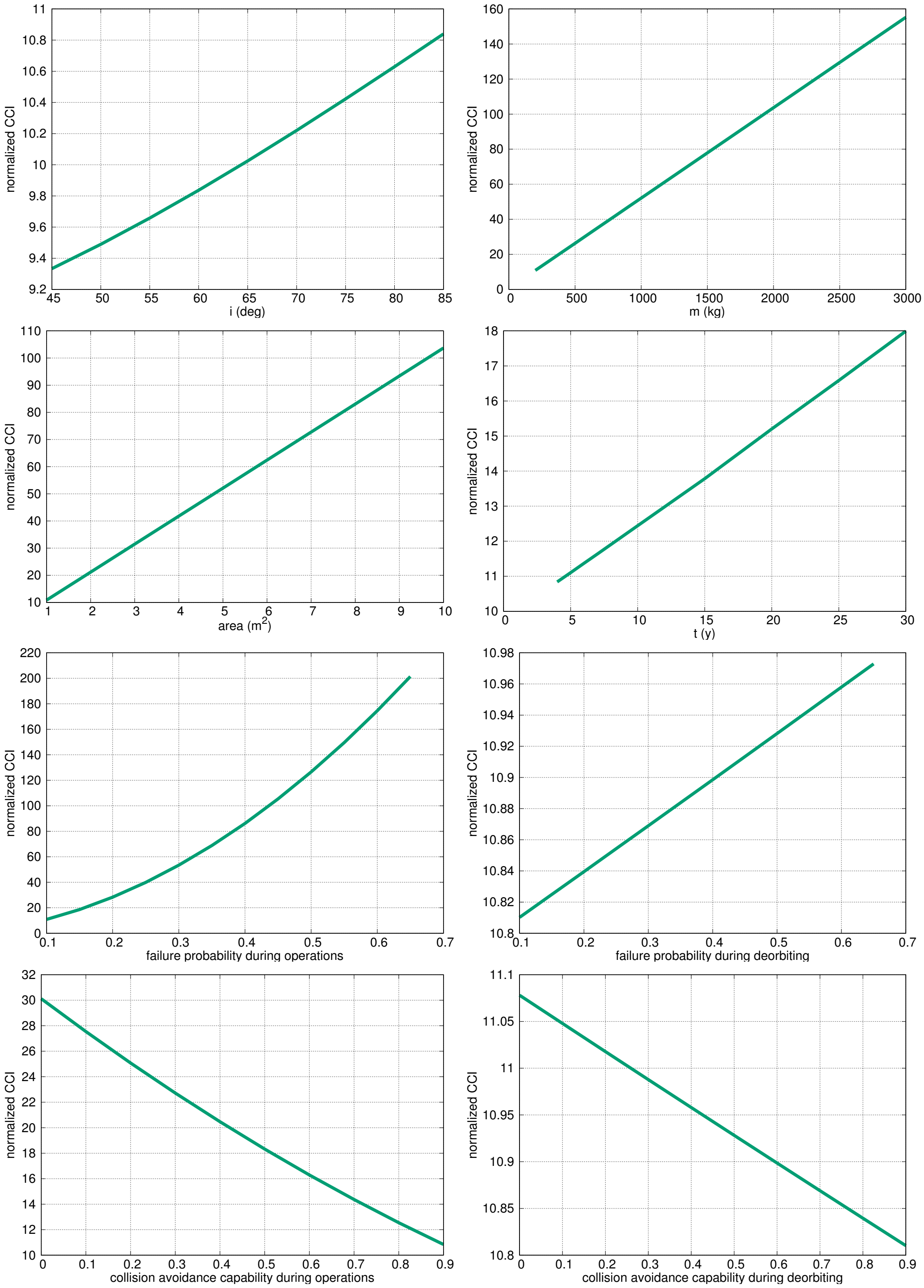

Figure 5. Ranking of the given scenarios as a function of the parameter changed.