Criteria for a Time-effective Selection of Active Debris Removal Targets

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Criteria for a Time-effective Selection of Active Debris Removal Targets

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Nomenclature & Abbreviations

ADR	**Active debris removal**
DEB	**Debris (either from on-orbit collisions or explosions)**
ESA	**European Space Agency**
Expl.	**Explosion**
GEO	**Geostationary orbit**
IADC	**Inter-agency Space Debris Coordination Committee**
ID	**International Designator (number attributed to an object after launch in order to identify it all over its period of presence in space)**
Incl.	**Inclination of the orbit (in degrees)**
JAXA	**Japan Aerospace Exploration Agency**
LEO	**Low-Earth orbit**
MC	**Monte-Carlo**
MRO	**Mission related object (complementary object within the launch, that is excluding payload and rocket' upper stage)**
NASA	**National Aeronautics and Space Administration**
Nb.	**Number**
NEODEEM	**Near-Earth Orbit Environment Evolutionary Model**
ODQN	**Orbital Debris Quarterly News (magazine that records all events occurring in space within three months, at each publication - provided by NASA)**
PMD	**Post-mission disposal**
RAAN	**Right ascension of the ascending node (one of the 6 orbital elements, expressed in degrees)**
R/B	**Rocket body**
S/C	**Spacecraft (either payloads, or space shuttles)**
TLE	**Two Line Elements (characteristics of a catalogued object's orbit)**

1. Introduction

a. Background & Motivations

Since the launch of Soviet Sputnik satellite in 1957, the number of objects in orbit around the Earth has kept increasing. With time, many objects have become non operational anymore, but have remained on their orbit. Now, the proliferation of these debris appears as a real problem for human missions in space, due to higher collision risks with operational spacecrafts and threats for astronauts' life. In this context, it has become necessary to proceed to remediation activities in order to keep a control on the future population of objects around the Earth before the situation reaches a non-return state. Mainly, this whole research, dealing with the understanding of removal conditions, has been triggered and oriented both by previous own observations and by space agencies' previous studies and requirements, as detailed from now.

First, the progressive growth of the population has led to a congestion of mostly used orbits, mainly the LEO-altitude orbits and GEO-altitude orbits. Together with this phenomenon linked to the formation of high-density zones, the risk of on-orbit collisions is rising more and more everyday in these highly populated areas. This fact has been recently observed through the record of collisions that occurred between catalogued objects. The first recorded collision happened in 1991 (see Table 1 for the references). This is the first time such an event could be identified, which proves that the space environment has recently become critical, with the increase of the objects present in near-Earth orbits. From this date, the number of on-orbit accidents due to collision events has kept increasing, reaching the number of nine events until 2013. Table 1 gathers information about the collision events that could be recorded from 1991 until now. Data have been updated as of August 2016, mainly concerning the number of remaining debris on orbit. Furthermore, the number of catalogued debris includes the colliding objects' parts and the fragments on their original orbit.

NAME	ID	EVENT DATE	CATALOGUED DEBRIS	REMAINING DEBRIS	APOGEE (KM)	PERIGEE (KM)	INCL. (DEG)	COMMENT	REFERENCE
COSMOS 1934	1988-023A (18985)	1991/12/23	3	3	1010	950	83.0	HIT BY DEBRIS (13475)	TM-2008-214779
CERISE	1995-033B (23606)	1996/07/24	2	2	675	665	98.1	HIT BY DEBRIS (18208)	TM-2008-214779
JASON	2001-055A (26997)	2002/03/16	3	3	1336	1336	66.0	HIT BY UNCATALOGED DEBRIS	ODQNv15i3
COSMOS 539	1972-102A (6319)	2002/04/21	2	2	1380	1340		HIT BY UNCATALOGED DEBRIS	ODQNv7i3
THOR BURNER 2A R/B	1974-015B (7219)	2005/01/17	5	5	885	775	99.1	HIT BY DEBRIS (26207)	TM-2008-214779
COSMOS 2251	1993-036A (22675)	2009/02/10	1668	1117			74.0	HIT BY IRIDIUM 33 (24946)	ODQNv13i2
IRIDIUM 33	1997-051C (24946)	2009/02/10	628	352			86.4	HIT BY COSMOS 2251 (22675)	ODQNv13i2
GOES 10	1997-019A (24786)	2011/09/05			GEO+355	GEO+335		HIT BY UNCATALOGED DEBRIS	ODQNv16i1
BLITS	2009-049G (35871)	2013/01/22	2	2					ODQNv17i2
NEE 01 PEGASUS	2013-018B (39151)	2013/05/23	1	1				HIT BY UNCATALOGED DEBRIS FROM SL-14 R/B (15890)	ODQNv17i3

Table 1. Information on recorded collisions

Two main concerns can be raised from the information provided in Table 1.

First, from the first collision in 1991, the frequency of the catalogued events has become higher until 2013, occurring at closer dates along the period since an event occurred at a rate of one per 6 years, whereas this rate is nowadays at one per 2 years: 1991, 1996, 2002, 2005, 2009, 2011 and 2013. In addition, the number of collisions per year has also increased, from "only" one event at the first dates (1991, 1996, 2005) to two events nowadays (2002, 2009, 2013). This is a dramatic observation since the more the collision rate increases, the more the number of fragments increase, leading to higher risks of new collisions through the phenomenon of chain collisions.

Then, it should be noticed that the most impactful collision occurred in February 2009 between COSMOS 2251 and IRIDIUM 33 satellites, generating more than a thousand fragments in space; as specified in Table 1, most of them are still present in orbit today, increasing the risk of new possible collisions in the future. Moreover, this collision contributed to rank COSMOS 2251 and IRIDIUM 33 respectively at the second and the fourth positions in the Top 20 list of objects generating debris during a breakup event.

The consideration of this new phenomenon, well known now as the Kessler syndrome, represents thus a first trigger to this study, by underlying the necessity to build and start immediately a precise process that will enable to provide a safer space environment.

Secondly, and taking as basis, inter alia, the previous observations, all space entities are aware of the threat due to the growth of debris population. Until now, major work has been done to encourage the development of passivation methods such as PMD on payloads or rocket upper stages [1, 2]. However, in view of the rapid degradation of the space environment, performing remediation processes, like active debris removal, appears necessary [3] to complement the efforts of passivation processes; mainly Liou et al. [4] compared three different scenarios for the evolution of LEO environment: PMD only; combination of PMD and ADR of 2 objects per year; combination of PMD and ADR of 5 objects per year. Their results are represented through the well-known graph of Fig. 1 [4].

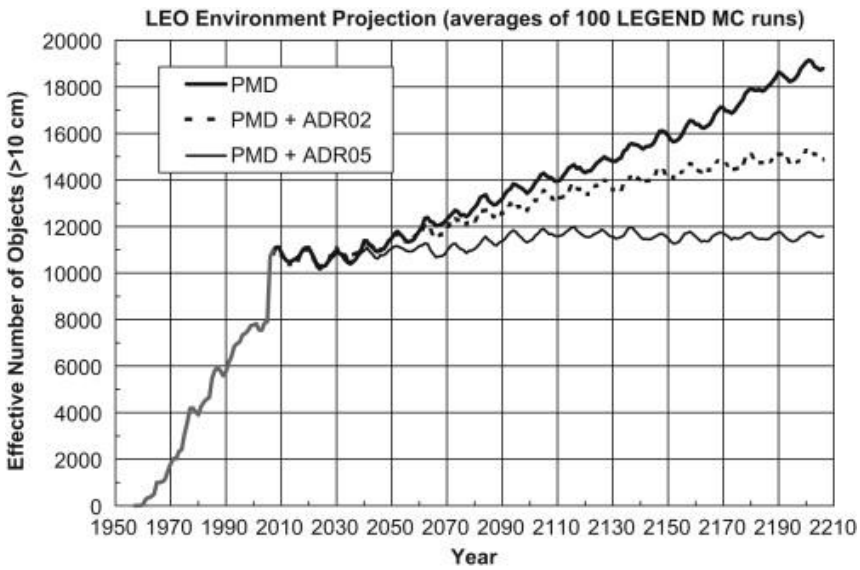


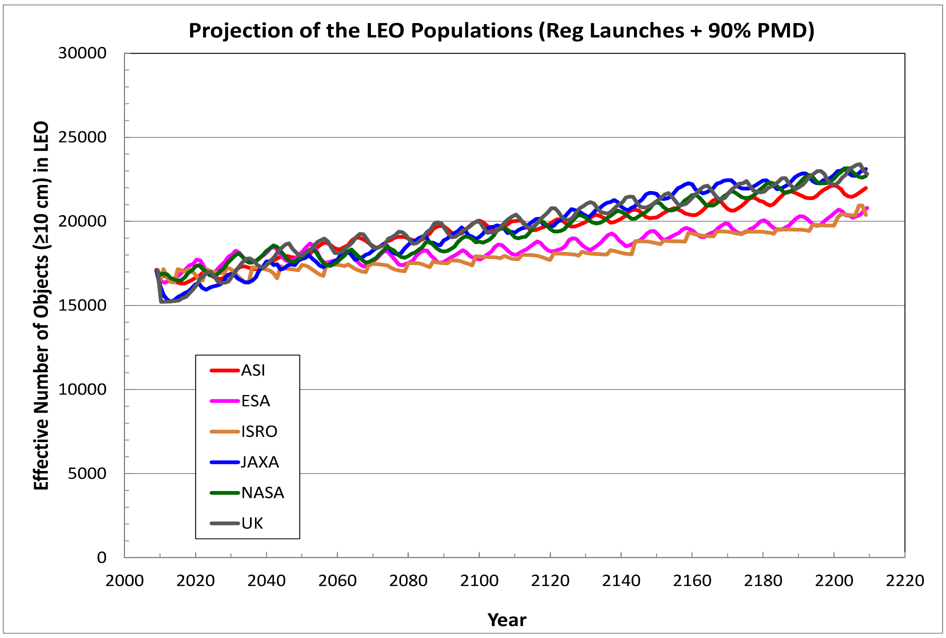
Figure 1. Comparison of three different scenarios for the evolution of LEO environment (PMD 90% assumed): PMD only; combination of PMD and ADR of 2 objects per year; combination of PMD and ADR of 5 objects per year

This graph shows that performing only a post mission disposal (PMD), even in the best case at a 90% success rate, is not enough to control the growth of the future population [3, 5]. Performing a complementary active debris removal appears therefore as a requirement, and the number of objects to be removed also enters into consideration since it is noticeable that the future population is expected to remain stable from a rate of at least five removed objects per year, under the consideration of a very high PMD rate (90 %), which is an optimistic scenario, but not necessarily the most realistic one [6, 7, 8].

Now the emergency to proceed to ADR has been underlined, and since the technology to do so is under development and nearly at disposal as explained by Wormnes et al. [9], or as it can be seen through technology demonstration by entities such as D-Orbit Srl., Astroscale PTE. LTD., Surrey University (see ESA website about e.Deorbit [10]), the importance is then to identify and select the targets that would enable the most efficient removal process in terms of time and objects' number. Therefore, using as a base support the results from these previous researches, the aim of this study is to take consideration of the number of removed objects, the importance of their on-orbit location, and various parameters presented later in order to point out which objects should be chosen so as to perform an efficient removal in terms of impact on the future LEO population.

To choose the appropriate targets, it was first necessary to better understand the lying phenomenon under the predicted change in the evolution of the future space environment. To do so, a preliminary study was conducted over 200 years, considering the best PMD case scenario of 90% success rate in order to focus on the impacts of a combined ADR process. Precisely, the IADC Working Group 2 - Action Item AI27.2 – conducted this study in 2012, using an initial population recorded on May 1st 2009 (see [3, 14] for more details). The projections were performed by all the agencies under the same assumptions: a PMD rate set as 90%, a continuation of launch traffic (based on a 2001-2009 traffic cycle) and no explosions in the future. Figure 2 shows the results gathered by the six participating agencies, known as ASI (Italian space Agency), ESA (European Space Agency), ISRO (Indian Space Research Organization), JAXA (Japan aerospace Exploration Agency), NASA (National Aeronautics and Space Administration) and UK (United Kingdom Space Agency) [3].

Through Figure 2 [3], Liou et al. provided results coming from all the 6 agencies' models concerning the projection of LEO population and the number of catastrophic collisions in LEO.



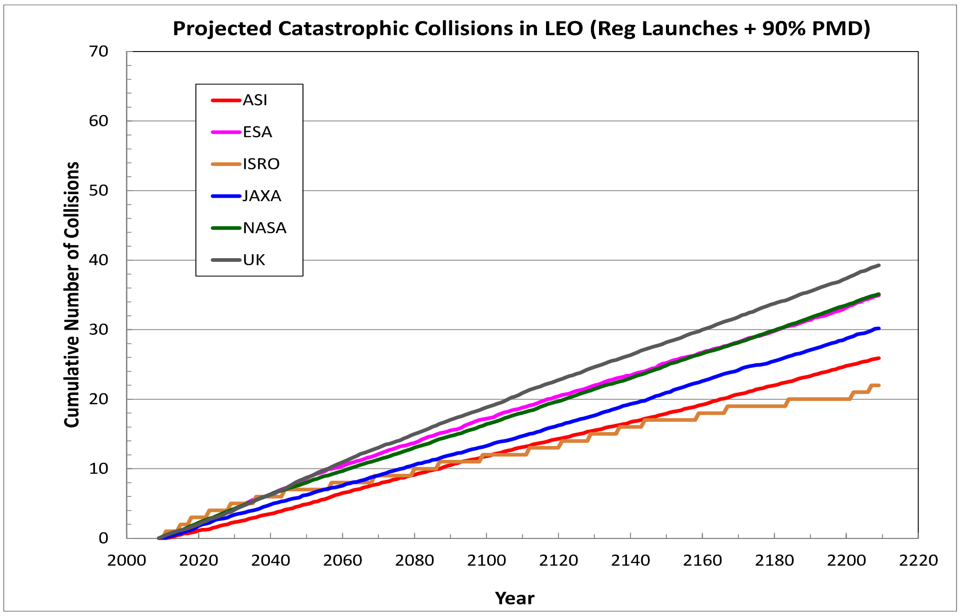


Figure 2. Evolution of future LEO population (up) and cumulative number of collisions (down) according to 6 agencies' models under no ADR assumption and PMD 90% success rate

By looking at Fig. 2, it is obvious that all the 6 agencies' models predict the same behaviour for the LEO population in the future, showing an increase of the number of objects, and clearly linked this trend to the continued increase of catastrophic collisions between on-orbit objects, leading to more and more fragments in the future. The fact that each agency was free to use its own evolutionary model proves that these conclusions are independent from the model. In other words, the problem of collision events lying under the increase of the future population is a reality that has been put in evidence, which fully justifies the orientation and the motivation of this research.

Now the motivation and the process of this study are underlined, a more detailed presentation of the tools used to conduct it, together with the methodology adopted, is done in the next sections, after a brief explanation concerning the structure of this paper in the following sub-section.

b. Structure of the study

This thesis is structured within nine parts, including the present introduction and the conclusion. The structure is summarized in Figure 3.

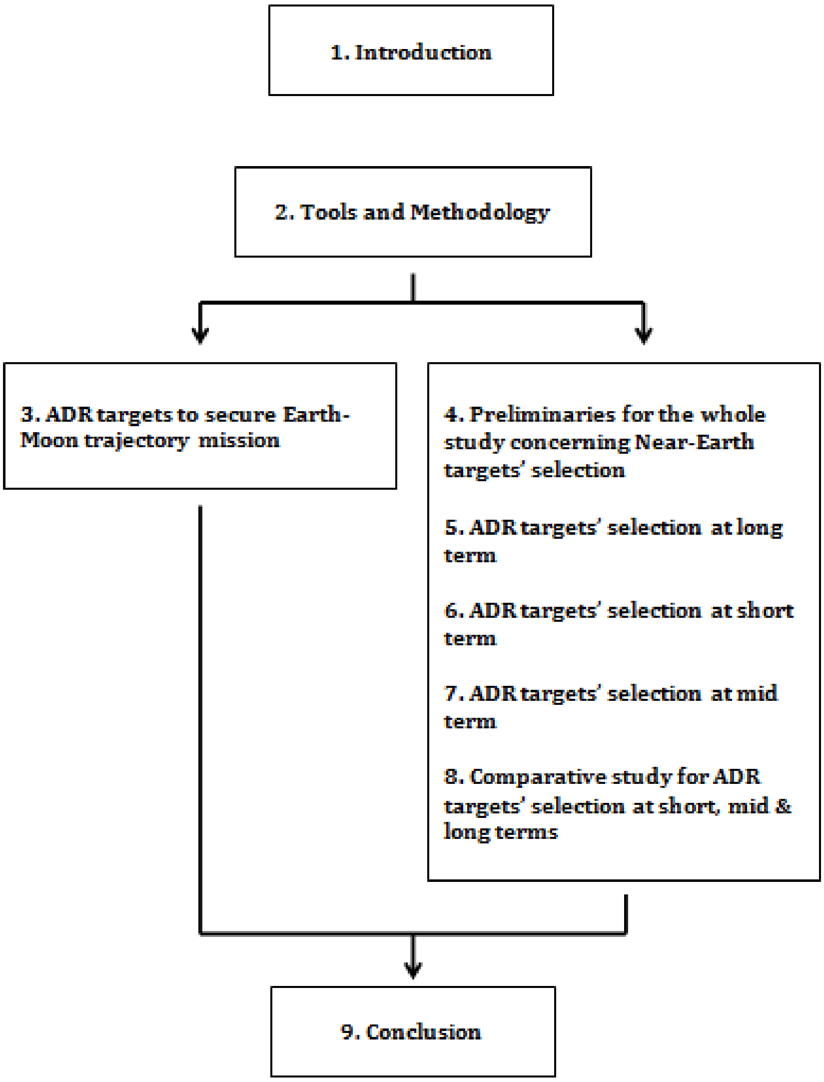


Figure 3. Structure of the thesis paper

The contents of each chapter, including this introduction, are now independently presented.

The introductive Chapter 1 presents the background that motivated the whole study detailed in this thesis. The aim in this part is both to underline the necessity to conduct such a research focusing on removal conditions and taking great care to improve the future space environment; and to define the structure of the present paper in order to make the difference between the two studies that were conducted as clear as possible.

Chapter 2 presents the tools necessary to conduct the whole study. It is divided in two sub-sections, each dedicated to one tool. The first tool is the space environment evolutionary model called NEODEEM; it is described together with the settings adapted to the different conditions, the inputs and the outputs required for its use. The second tool is the debris' origin tracking program, and a particular care is given to its description since this tool was developed entirely during this Doctoral research for the purpose of the different studies conducted inside. Examples of use are also provided.

Concerning the following parts, this Doctoral research is divided in two main general studies, as it is represented in Figure 3. The two studies can be considered independently, however they are gathered in this thesis because they follow the same motivation by looking for an adequate remediation way to secure a targeted future. Therefore, in the structure of this paper, Chapter 3 should be considered independently from the block of Chapters 4 to 8.

Chapter 3 presents the study jointly conducted with Astroscale PTE. LTD. It deals with the evaluation of collision risks for a lunar spacecraft on its trajectory to the Moon. After calculating the probability of collision with any space objects around the Earth, a ranking of the most probable collision-inducing objects was set up in order to determine the current targets prior to be removed in the context of the mission.

Chapters 4 to 8 present another study, jointly conducted with JAXA. These chapters are linked together and show the evolution of the whole research through the results obtained at each step (and presented in each corresponding chapter) until the final comparison analysis.

Chapter 4 can be considered as the introductive part of the whole study dealing with the determination of adequate criteria for a removal targets' selection to match a given period of observation. It mainly presents the motivations that triggered this study, conducted through a very particular orientation. The whole study tries to evaluate the role of criteria such as altitude of objects, number of removed targets, and the implication in chain-collision phenomena, according to different periods of observation. Indeed, it will be demonstrated that one given future requires an adequate and particular criterion to select the best removal scenario in terms of efficiency on its population.

Chapter 5 focuses on the long-term period of the whole study, by looking at criteria that induce major impacts over 100 years in the future (until year 2109). To do so, the evolutionary model NEODEEM is used to simulate the future environment, then the tracking program is applied to find out the origins of the fragments detected in this 100-year future. A ranking list concerning the objects generating the more fragments is set up, and simulation scenarios concerning the removal of selected targets among the list are run once again to verify the effectiveness of the process.

Chapter 6 presents exactly the same approach as in Chapter 5, but focuses on the short-term period of the whole study. NEODEEM and the tracking program are used in the same way, and the remediation effects are evaluated over 20 years in the future (until year 2029) to look for the best matching selection criteria corresponding to this short-term future.

Chapter 7 presents again the same approach as in Chapter 5 and 6, but focuses on the mid-term period of the whole study. NEODEEM and the tracking program are used in the same way, and the remediation effects are evaluated over 50 years in the future (until year 2059) to look for the best matching selection criteria corresponding to this mid-term future.

Chapter 8 gathers the results obtained through the studies of Chapters 5, 6 and 7 to propose a comparative analysis between the three different time scales. The aim is to understand the differences in the nature of the selection criteria and to find out a possible removal scenario suitable for all periods of observation. This Chapter also helps to summarize and clarify the criterion that must be adopted in order to choose the best matching removal scenario according to the future that is considered.

Finally, Chapter 9 concludes the entire Doctoral research by summarizing both the lunar-mission study and the study concerning the targets' selection criteria. It gathers all the results and tries to propose new perspectives to continue this study, mainly by underlying the possible adequacy of the "double-check" process (using the tracking program) to other researches dealing with the problem of space debris.

2. Tools used to conduct the study

In this study, the near-Earth environment has been simulated to evaluate the possible future evolution of the debris population under different conditions. Simulations have been performed using the analytical evolutionary model NEODEEM, and have been checked with the help of a back-in-time process available through a complementary event-track tool.

a. Environment evolutionary model

In order to simulate the space environment as it may be in a defined epoch, a debris environment evolutionary model from low-Earth orbits to geostationary orbit is used. The model used for this study is called NEODEEM (Near-Earth Orbit Debris Environment Evolutionary Model), and is jointly developed at Kyushu University and JAXA. NEODEEM is provided with five projection modes, defined as *Historical* mode, *Future* mode, *Target* mode, *Removal* mode and *Propagation* mode. The user can choose the simulation mode according to the results he/she wants to get. The *Historical* mode is dedicated to predict the current state in space through the modelling of historical trends. To do so, this mode does not implement events like explosions or collisions, but focuses only on orbital insertions and the propagation of each object's orbit; the orbital insertions (new launches) are made here every day. The *Future* mode is used for the prediction of the future environment by taking into consideration various selected events (according to the user's goal) like collisions, explosions, orbital insertions, and by propagating each object's orbit from an initial year to a final year. In this mode, orbital insertions are made every year. The *Target* mode focuses on one designated object (target). By concentrating on this particular object's orbit, this mode enables to evaluate the probability of collision with all other objects present in the model at the same year, as well as the cumulative collision probability, and calculates the expected value of the number of fragments generated by each collision event. It should be noted that this mode performs neither collision decision nor new debris generation. The *Removal* mode performs calculation to decide on the target object to be removed according to selection criteria for removal. Lastly, the *Propagation* mode is used only for orbital calculation.

In the two main studies included in this Doctoral research, the various simulations aim to evaluate the environment of all space objects in the future, for each year from the initial year until the final year (in case of the study concerning removal's impacts on the evolution of LEO population) or until the insertion of the target vehicle (in case of the Earth-Moon trajectory study). Therefore, the mode defined as *future mode* in NEODEEM is the best matching mode for this research, and has been selected to perform the different projections. In the particular case of the lunar-mission study, the *target mode* has also been used in complement to focus on the lunar spacecraft.

i. Initial population in year 2009 and Assumption on launch traffic

To start a simulation, the knowledge of the initial population is required as a baseline for the environment to be propagated then in the model. This baseline file lists all the objects that are present in orbit around the Earth as of May 1st, 2009. It has to be noted that only objects bigger than 10 cm in size are recorded; and all over the years, in any scenario, the evolutionary model enables the user to propagate and simulate the environment only for objects superior to 10 cm in size. Smaller objects are not taken into account, in any occurring event, due to a lack of knowledge and data for this category of object. This is one of the limits in this modelling (it is currently the black point of many models over the world), and should be considered as a point to be improved in order to raise the accuracy of the results in the future. This task was not done in this research both because of a lack of time (gathering all data concerning small objects could consist in one full research study) and because the purpose of this research is to underline the events at the origin of risk generation for space mission and at the origin of the increase of future space population. The focus was therefore made on the development of useful tools and processes in order to enable such works.

In this Doctoral research, two separated studies have been conducted for different purposes according to the requirements of the collaborating entities. Therefore, it has to be underlined that, in the followings, **the initial population is different between** the study concerning the Earth-Moon trajectory presented in **Section 3**, **and** the study linked to the effects of ADR on the evolution of future population presented in **Sections 4, 5, 6, 7, 8**. The reason is that the research aiming to evaluate the impacts of removal process is made in collaboration with JAXA, thus the credits to use the initial population file created by ESA for IADC Working Group 2 - Action Item AI27.2 - have been received. In this provided file, 20 788 objects are listed, gathering all space-crafts, rocket bodies, mission related objects, previous explosion fragments and collision fragments catalogued in May 2009 for IADC members. It must be underlined that neither the name of the objects nor their International identification number are provided, therefore in the related studies, some objects could not be identified with current existing objects. The reader is therefore expected to understand that the targets selected for some removal cases are only presented through their mass and orbital characteristics, rather than their name, when the identification could not be done manually. The author apologizes for this inconvenient. To represent the population in its initial state, and as a comparison for the results on the choice of removal scenarios that will be presented in next sections, the following graph illustrates the orbital regions of the baseline population:

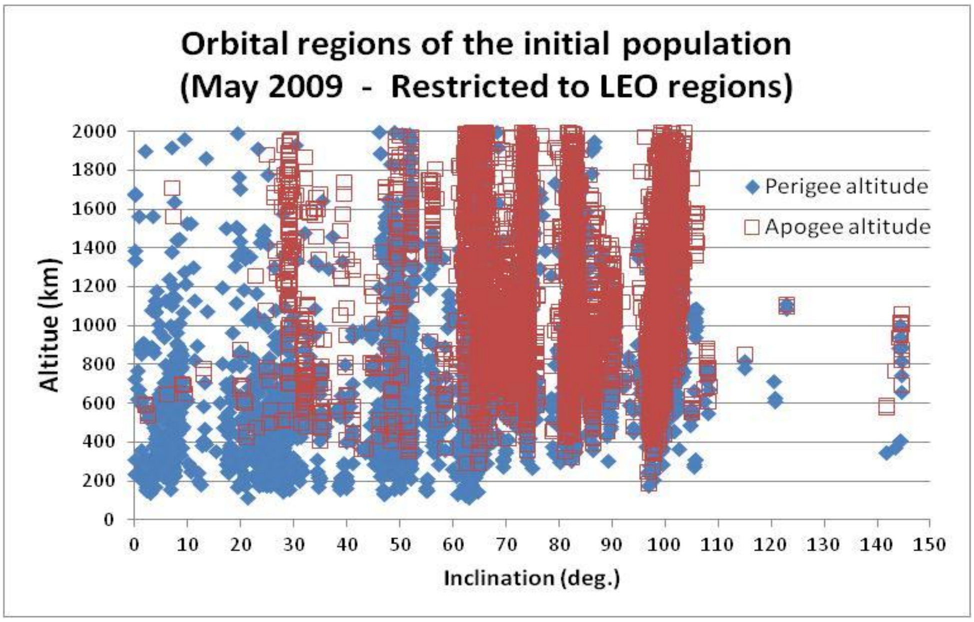


Illustration. Introducing illustration of orbital areas for the initial population

However, this file of initial objects is not accessible to any other entities (out of IADC members), therefore, it has been necessary to create our own baseline file for the study concerning the Earth-Moon trajectory, conducted for Astroscale PTE. LTD. In this case, the name of the objects is therefore known, and the previously underlined problem of identification does not exist here. For this Earth-Moon-trajectory study, the initial file was created by tracking all catalogued objects for this year, including launched space-crafts, rocket bodies, mission related objects and fragments. Fragments are issued from either explosions or collisions in space. Therefore, the resulting environment of year 2009 after all events and launches has been retraced as precisely as possible. This thorough task was done thanks to the use of Agencies' databases, reference books [11, 12, 13], as well as results from simulation. In the case of this 2009 baseline file, 20 788 objects have been listed. The nature of the data concerning the objects is the only difference between the two initial files; **their format remains the same in input of the model**.

The baseline file is a 13-column by X-line file (where X represents the number of objects in the file), presenting the following data for each object: the item number (from 1 to X); the type of the object (1 for a spacecraft, 2 for a rocket body, 3 for a mission related object, 4 for a fragment due to an explosion, 5 for a fragment due to a collision); the mass in kilograms; the size (diameter) in meters; the cross-sectional area in square meters; the six orbital elements, i.e. the semi-major axis in kilometres, the eccentricity of the orbit, its inclination, the right ascension of the ascending node, the argument of perigee, the mean anomaly; the status of the object (under control or not); and the lifetime of the object in space. In the case the object exists well before 2009, a long lifetime is attributed in order to differentiate it from objects created during 2009 or that will be generated later during the simulation.

In addition to the initial population, the knowledge of launch frequency is also necessary in order to bring more precision to the propagation mode of the model. Indeed, from a given population of objects, the model predicts the evolution of each object's orbit, the interactions that may happen between different objects, the possible events that occur, as well as the insertion of new objects. This last point is difficult to predict since there is no precise idea of the nature and frequency of future launches. This depends on various needs and resources of Space agencies and companies, as well as possible space regulations that might be imposed according to the evolution of the environment around the Earth. Therefore, to overcome this difficulty, it has been decided to use past launch traffic data that were recorded from year 2003 to year 2010. For each of these years, all the launches announced by governments and agencies have been gathered, including rocket bodies (last stages that remain in orbit), the payload satellites and shuttles, and all objects related to the launches (known as mission related objects). This launch file forms an 8 year-cycle database that can then be repeated every eight years, starting from January 1st, 2010. An explanation for the use of this launch cycle in the propagation mode is provided in Figure 4. It is quite obvious that this proposal to simulate future launches is not accurate, in the sense that future launch traffic has a great chance to differ from the past one due to the above explanations. However, new launches will have a strong impact on the space environment, therefore it is necessary to simulate them and consider them in the model for more accuracy of the results. In this way, a constant traffic launch over eight years has been assumed, which allows predicting the evolution of the environment in the case that human activities remain the same. This launch file lists 699 launched objects between 2003 and 2010, presenting data for each launched object during this period, as follows: the item number (from 1 to 699), the insertion year, the type of the object, its mass, its size, its average cross sectional area, and the six orbital elements.

Figure 4. Launch-cycle propagation

For the study dealing with the safety of Earth-Moon trajectory mission (Section 3), all events must be taken into consideration in order to evaluate all collision risks as precisely as possible. Therefore, the assumption of new launches in the future has been made, and the launch cycle has been used in input. However, in the studies linked to the evaluation of impacts from removal process (Sections 4, 5, 6, 7), the focus has been set on the current existing objects only, thus the simulations have been performed under the conditions of no new launch, and the launch cycle is not used in these cases.

ii. Collision probability and Settings for occurring events in the simulations

During the projections, spacecrafts are assumed to have an 8-year mission lifetime. After this time, if the spacecraft is still present in the NEO environment, its status is moved to drifting object. As for the rocket upper stages, they are left in their target original orbit after payload liberation. Concerning the LEO environment, a PMD can be performed in order to limit the long-term presence of spacecraft and launch vehicle upper stages after the end of their mission, keeping in mind the completion of the 25-year rule required by the IADC Space Debris Mitigation Guidelines [1, 14]. Moreover, in order to simulate the evolution of space environment by assuming current configuration as a baseline scenario, no removal is performed, except in the removal-case studies of course.

In addition to defining the future launch traffic, the propagation mode also aims to update the parameters of the existing objects in orbit for each year of the simulation. To predict the orbit, the evolutionary model calculates the perturbations of the orbital elements through Lagrange and Gauss Planetary equations. The main perturbation physical forces considered in the equations are the effects of Sun gravitation, Moon gravitation, Solar radiation pressure (for LEO), atmospheric drag (for low altitudes), and the non-spherical parts of the Earth gravitational attraction with J_2, J_3 and J_4 terms.
Furthermore, explosions in the future have been set to zero since previous study has shown that their impact on object population was negligible [14, 15, 16] (IADC Working Group 2, 2013; Ariyoshi, 2012; Hanada and Yasaka, 2004). Therefore, the future environment is evaluated without taking into account the potential fragments generated by explosions of existing objects after year 2009. However, at the opposite of explosions, collisions between objects are evaluated since their resulting fragments are supposed to have the more important impact on the growth of the population. Collisions between two objects are evaluated through the calculation of collision probability. The calculation method proceeds in two steps, and is fully detailed by Hanada and Yasaka [16], and Ariyoshi [15]. The following description simply gives a general image of the process.
The first step of the algorithm consists in evaluating whether the existence spheres defined around each of the two objects are overlapping each other. If they do not overlap, the objects will never collide, so the corresponding probability is set to zero. If they overlap, a second step consists in calculating the probability of collision between the two objects. The calculation uses the volume of the overlapping region of the spheres, the sum of the cross-sectional areas of the objects, their relative velocity, together with their probability of existence in the overlapping portion and density. In NEODEEM, all spacecraft larger than 10 cm in size and all rockets are tracked individually, which enables this model to calculate a one-by-one collision probability. Two filters are adopted to reduce calculation time. Any pair of objects that pass the filters are only judged for the further collision analysis.
The first filter compares the apogee and perigee radius. This filter provides a rough cut to determine if close approaches are possible. If the difference between the larger perigee and the smaller apogee is positive and greater than the desired distance tolerance (set at 20km in NEODEEM), the two satellites will never approach one another.
The second filter compares the minimum distance between the orbits and the desired distance tolerance. This filter provides a precise cut to determine if collisions are possible. If the minimum distance is greater than the desired distance tolerance, the two satellites will never collide with one another. Assuming that the orbits are in different planes, the minimum distance between the orbits should be on the nodal line of the two orbit planes; and the nodal vector between the orbit planes is along the crossing line of the two orbital planes. Orbits that satisfy this second filter need no further processing. It is assumed that the object can exist inside the sphere uniformly. If two spheres overlap each other, then the two objects can collide with one another inside the overlapping portion. The time that the object spends in the sphere can be approximated, which enables the calculation for the probability that the object will be in the sphere during one revolution. The knowledge of the probability that the primary object will be inside the overlapping, together with the density of the secondary object finally lead to the collision probability between the two objects inside the overlapping portion. At the end, if the collision is estimated to happen, it is determined to be catastrophic or not according to the definition of the NASA standard breakup model, 2001 revision [21].

The main assumptions and conditions for the simulations conducted for the Earth-Moon-trajectory study and the research concerning the impacts of removal are presented respectively in Table 2 and Table 3.

Event	Status in the simulation
New launches	Yes
Objects' removal	No
Future explosions	No
Collisions	Yes
Performed PMD	30% success rate

Table 2. Settings in NEODEEM (Earth-Moon-trajectory study)

Event	Status in the simulation
New launches	No
Objects' removal	No
Future explosions	No
Collisions	Yes
Performed PMD	Not applicable

Table 3. Settings in NEODEEM (Removal-impacts study)

In the study concerning the safety of Earth-Moon trajectory mission, a realistic case (closer to reality) has been selected through the value of the PMD (30%) in order to fit as possible the current status of space-crafts. In parallel, the study underlying the impacts of ADR aims to warn about the necessity to perform efficient removal strategies and does not take into account new launches so as to show the emergency to perform removal even in an ideal scenario; since PMD is a process applied for new launched objects, it is not used in this second study. With the above settings that are summarized in Tables 2 and 3, the model performs a projection of the environment from year 2009 until the selected target year, depending on the study.

As explained above in this part, events linked to explosions have been neglected in the rest of the study due to conclusions made by previous work [14, 16]. To complement this conclusion and better understand the lying phenomenon under the predicted change in the evolution of future space environment, a study was conducted within the IADC Working Group - Action Item AI31.5 - in 2014, by propagating the initial population of all objects catalogued as of January 1st 2013 and provided by ESA. This population was propagated over a 200-year simulation time. It was divided in three sub-studies, each considering one of the three different PMD rates (30%, 60%, and 90%), in order to focus on the impacts of a combined ADR process. The results were obtained through the mean of one hundred Monte-Carlo simulations, with the assumptions of no explosions, but a continuation of launch traffic (based on a 2005-2013 traffic cycle), and four ADR scenarios: no ADR performed, 2 objects removed per year, 5 objects removed per year, and 8 objects removed per year. If ADR is performed, the removal process starts from year 2025 until the final year 2213. During the projections, space-crafts are assumed to have an 8-year mission lifetime. After this time, if the spacecraft is still present in the near-Earth-orbit environment, its status is moved to drifting object. As for the rocket upper stages, they are left in their target original orbit after payload liberation. Concerning the execution of the PMD inside the model, it is performed only regarding the 25-year rule for all the objects that require it. No other options, such as transfer to graveyard orbits or other processes, are considered. This remark is applicable to all the studies presented in this article when the simulations are performed with the evolutionary model NEODEEM.

The following figures 5 and 6 present results only in the case of a 90% PMD success rate, so the best PMD case scenario, in order to fully concentrate on ADR effects. The two other studies, where 30% PMD and 60% PMD rates were respectively implemented, led to a degradation of the future environment as the rate is higher. However, the cases of 30% PMD rate and 60% PMD rate are not presented in this article since the related observations and conclusions raised about the evolution of the future debris population were similar in terms of relative impacts between ADR rates and determination of main causes for the population growth. This one-case presentation has therefore been decided to avoid redundancy in the explanations of the phenomena.

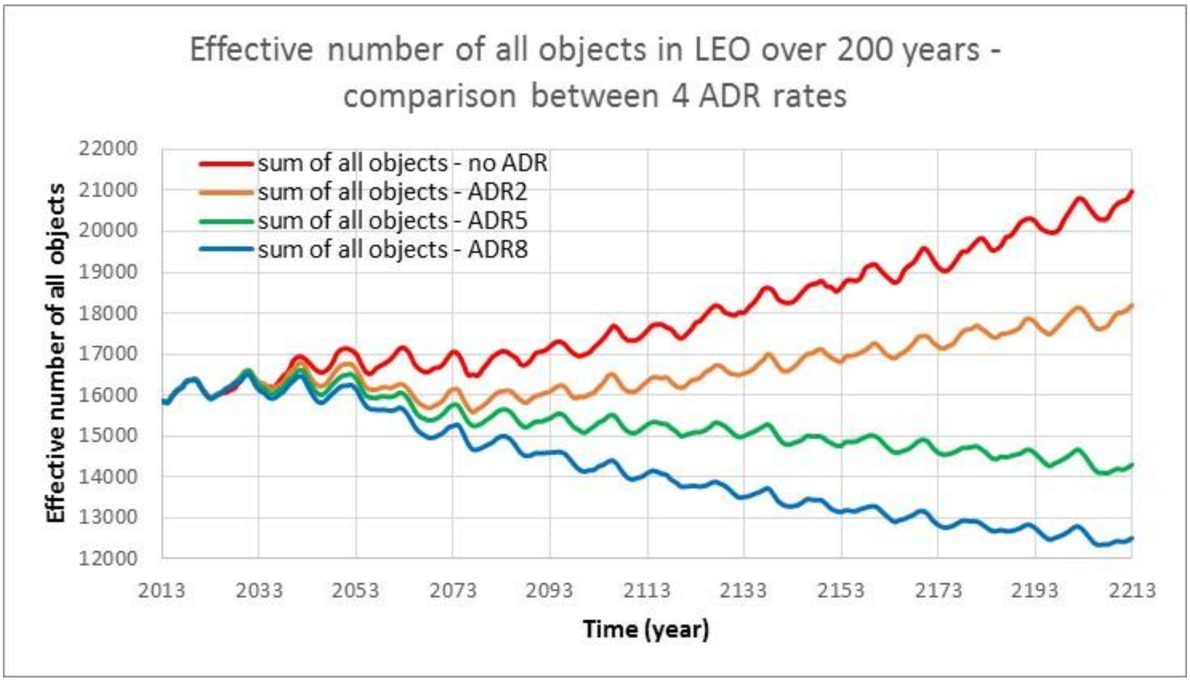
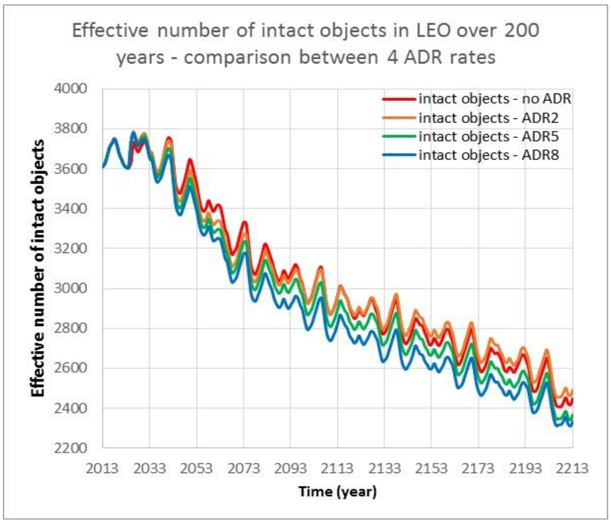


Figure 5. Evolution of the future LEO population (mean effective number on 100 MC runs) after simulating 4 different ADR scenarios under assumptions of 90% PMD and no explosion: no ADR; ADR at 2 objects/year; ADR at 5 objects/year; ADR at 8 objects/year



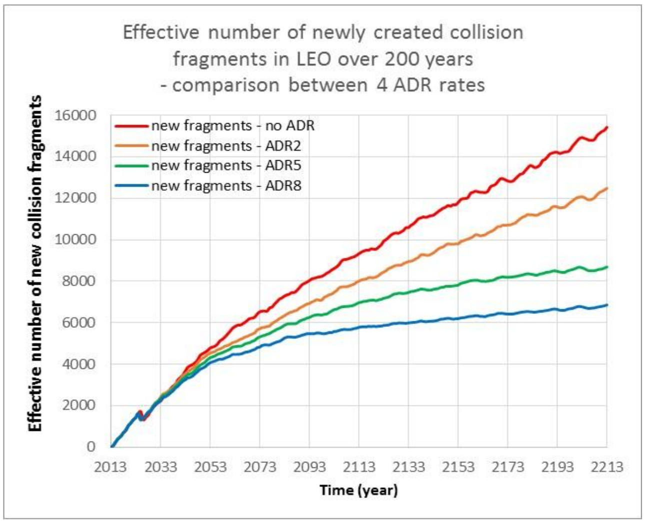


Figure 6. Evolution of LEO intact objects (left) and fragments generated by collisions (right) (mean effective numbers on 100 MC runs) for each of the 4 ADR scenarios under assumptions of 90% PMD and no explosion: no ADR; ADR at 2 objects/year; ADR at 5 objects/year; ADR at 8 objects/year

Leaving aside the obvious observation that high ADR rates lead to a more positive impact on the evolution of the population, this section tries to analyse the evolution of space objects relatively to the general population inside each ADR scenario. The above Figures 5 and 6 clearly show the same behaviour in the evolution of the different kinds of objects in the LEO population independently of the considered rate for ADR. Indeed, in low ADR rate scenario (ADR0, ADR2), the predicted increase of the LEO population all over the simulation period (200 years) appears to be totally linked to the huge increase of the collision events that are expected to occur during the same period, as shown on the right part of Fig. 6. At the opposite, even under new launch assumption, the population of intact objects (space-crafts, rocket bodies) follows a decreasing trend, due to ADR, PMD, and natural re-entry phenomena. As for high ADR rates (ADR5, ADR8), the predicted decrease of LEO population seems to be supported by a stabilisation in the creation of collision fragments, combined with the decrease of intact objects. Looking at the scales, newly generated fragments are presented in dozens of thousands, whereas intact objects are expected to remain below 4000. Therefore, both the behaviour of the respective populations and the difference in the number of each kind of objects invite to raise the same conclusion: the strongest phenomenon lying under the evolution of future LEO population consists in the generation of new fragments by collisions, which strengthens previous study concerning the analysis of explosion fragments [14, 16]. Furthermore, by looking more particularly at the differences issued from the selection of ADR rates, these graphs contribute to reinforce the discussion concerning the necessity of ADR to improve the stability of future space environment. Keeping in mind the conditions of this study, once again it should be noted that this behaviour and these conclusions come from projections without explosion events. According to the explosion rates, the results may vary, but the trend given by collision phenomena may be still observable.

The above results, obtained for IADC Working Group - Action Item AI31.5 - in 2014, also strengthens conclusions from previous studies of IADC Working Group 2 - Action Item AI27.2 - made in 2012 using an initial population recorded on May 1st 2009 (see [14] for more details) and presented in Introduction as the background that triggered this Doctoral research.

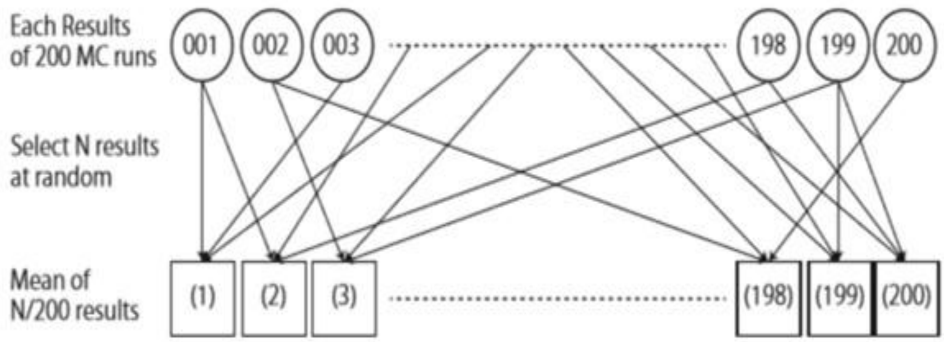
Together with IADC studies that gather results from various and independent evolutionary models of space agencies, these observations underline the main effect of collisions as an explanation for the evolution of LEO environment, and fully justify the orientation and the motivation of this Doctoral research. In this way, the creation and the implementation of a program able to detect collision events and track their origin back in time until the generation year appears as necessary to support this research and is then fully justified. This program is presented later in sub-section c.

b. Statistical analysis concerning the number of MC runs for the study

The evolutionary model has been used through 100 Monte-Carlo simulations to conduct the whole study and the preliminary study. This choice has been done to give the highest accuracy and robustness in the results (mainly based on the arithmetic mean of the parameters returned by the simulations) as possible, regarding the computational power at disposal. The analysis of the minimum required number of Monte-Carlo runs is based on a previous study now detailed in this section ([15], pp. 60-62), as well as the method proposed for the evolutionary model LEGEND of NASA.

For the present study, the evolutionary model uses random numbers to evaluate the future environment, mainly through the prediction of collision events, interactions between space objects, and so on. Therefore it is necessary to perform multiple trials by simulation. To determine the necessary number of runs to be performed, the analysis is based on the Bootstrap method [22] used in LEGEND [6]. The procedure is simply developed here, through four steps:

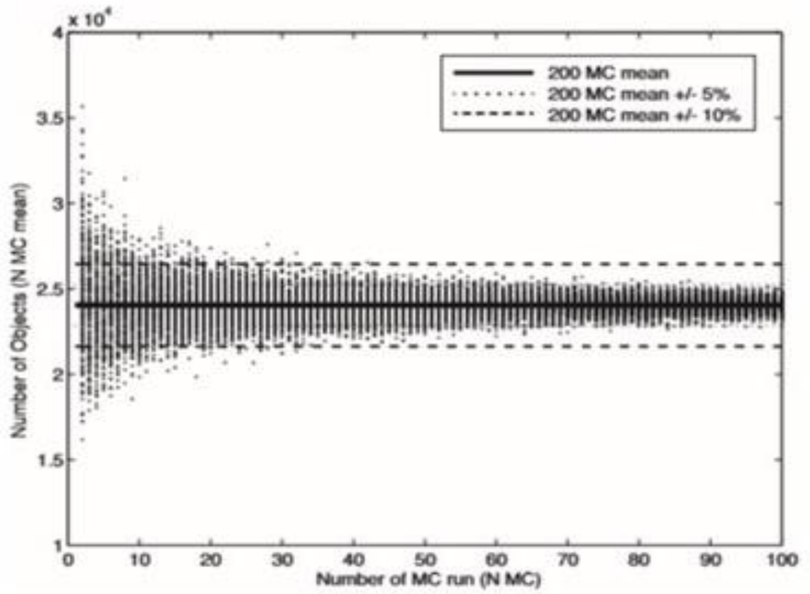
- **Step 1**: 200 MC runs are performed. Among the 200 trial results, a number N of results are randomly extracted (with N < 100). The Bootstrap method is illustrated as:



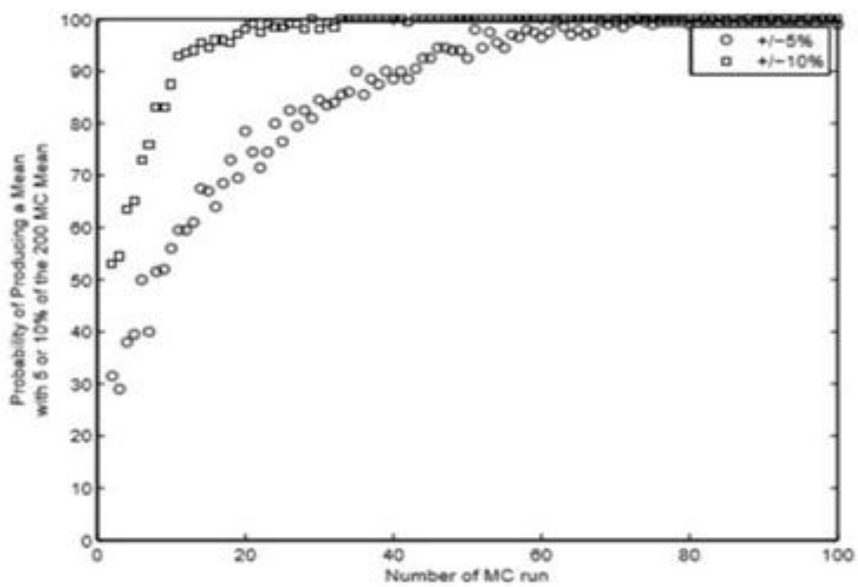
- **Step 2**: The mean of the trial results from the N-sample is calculated.
- **Step 3**: Step 1 and Step 2 are performed 200 times.
- **Step 4**: For N varying from 2 to 100, Steps 1 to 3 are iteratively calculated.

Ariyoshi [22] performed the analysis by using an initial population as of January 1st, 2010, and propagated it over 200 years until January 1st, 2210. Moreover, he didn't consider PMD, debris removal, new launches, neither the generation of fragments from explosions; only collisions were believed to generate new fragments. These settings were chosen to focus on collisions since they are supposed to be the events the most dependent on the generation of a random number.

The convergence of the results was analysed and presented through the graphs G1 and G2 ([22], p.61). Precisely, taking as criterion the mean of the trial results among the 200 runs, these graphs illustrate respectively the number of objects (on the mean of N simulations) and the probability to produce a convergent mean according to the number N of simulations performed. The ranges of +/-5% and +/-10% around the criterion mean are illustrated too.



Graph G1: Comparison between the criterion average among 200 MC simulations and the means calculated in the case of each simulation (from the N performed)



Graph G2: Number of mean values from each simulation number (among the N performed) included within the ranges of +/-5% and +/-10% around the criterion mean of the 200 simulations

As illustrated on the graphs, in NEODEEM, 90% of the samples gather within +/-10% range around the mean in the case of 14 runs, and within +/-5% range around the mean if 42 runs are performed. Therefore, NEODEEM can produce statically meaningful results with 14 to 42 runs performed. However, looking at the graphs, more robust results can be produced from a value of at least 60 simulations, from which the convergence of the mean number of predicted objects is obtained.

Considering the above analysis and the computational power at disposal, it has been decided to perform 100 MC simulations for the completion of the present study. This choice also enables to include statistical statements during the explanation of the results presented inside the different studies. These statistical statements includes a comparison between different removal scenarios MC run by MC run to strengthen the mean analysis with a case-by-case analysis (the scenarios have been compared each against another for each of the MC simulations that were performed).

c. Tracking program for the identification of debris' origins

The demonstration study presented in Section 2.a. has clearly underlined a strong correlation between the evolution in the number of future collisions and the increase of the predicted NEO population all along the simulations obtained through various evolutionary models. The fact that gathering main agencies' results leads to these same conclusions invites to give a key role to collision events, and consequently to collision fragments, in the expected increase of near-Earth orbit population. This is also strengthened by the Kessler syndrome theory presented previously in Introduction. It is therefore necessary to better clarify these events that may have a strong impact on the future evolution of near-Earth object population, which justifies the implementation of a program dedicated to find out the origins of collisions back to the past until the identification of "parent" objects in initial year, i.e. at the beginning of a given simulation. This is the tool presented here, specially developed to support the study conducted in the context of this Doctoral research. This tool gave the possibility to think about potential targets for removal processes in a different way than the current one adopted by Space agencies. Agencies mainly establish their priority list according to the product of the mass of the object and its collision probability at the time of collision (see [17]); thus they don't take into account the possible evolution and the repercussions in the future. However, in the context of this Doctoral research, the future period is given a major importance in order to determine the objects that may impact it. In other words, the tool that will be presented here enables to anticipate the consequences on the future, according to the time spent from the possible collisions and the scenarios that should be engaged in order to compensate these effects. This is a strong point of this study since it may be considered as a new approach for target selection and thus as a proposal for new considerations in the purpose of securing the near-Earth environment, purpose shared by space agencies and companies.

This program uses as inputs the list of all collisions at each year of the simulation, from initial year to a selected final year, as well as the list of the object population at each year. It is then able to give in output the list of debris-inducing objects that are present in the initial year. The methodology adopted to build the program is detailed in Fig. 7.

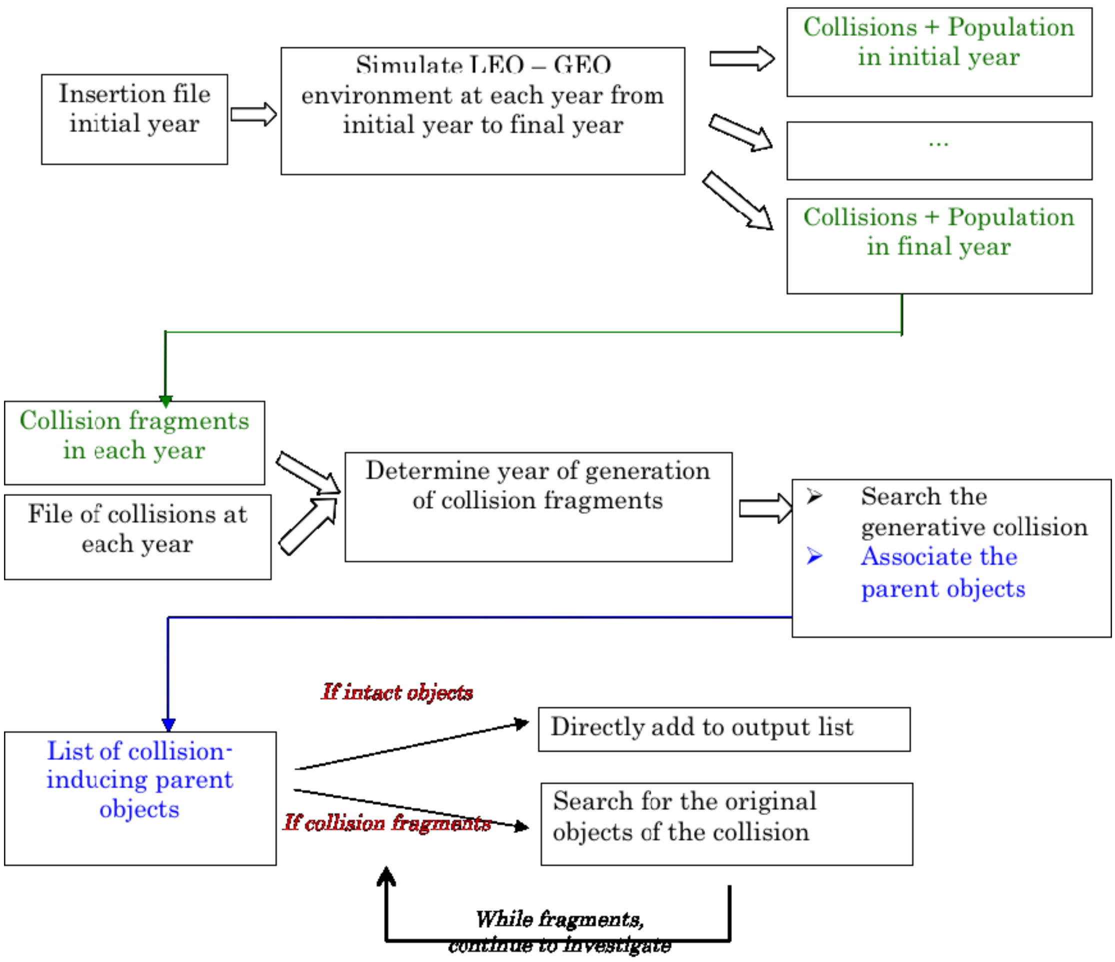


Figure 7. Origin-tracking function: implementation and methodology

It can be noted that this program is built in particular adequacy with the structure of the evolutionary model NEODEEM. However, it can be easily adapted to the outputs of other models as the lists of the estimated population and occurring events are accessible. A brief example of use is illustrated in Fig. 8.

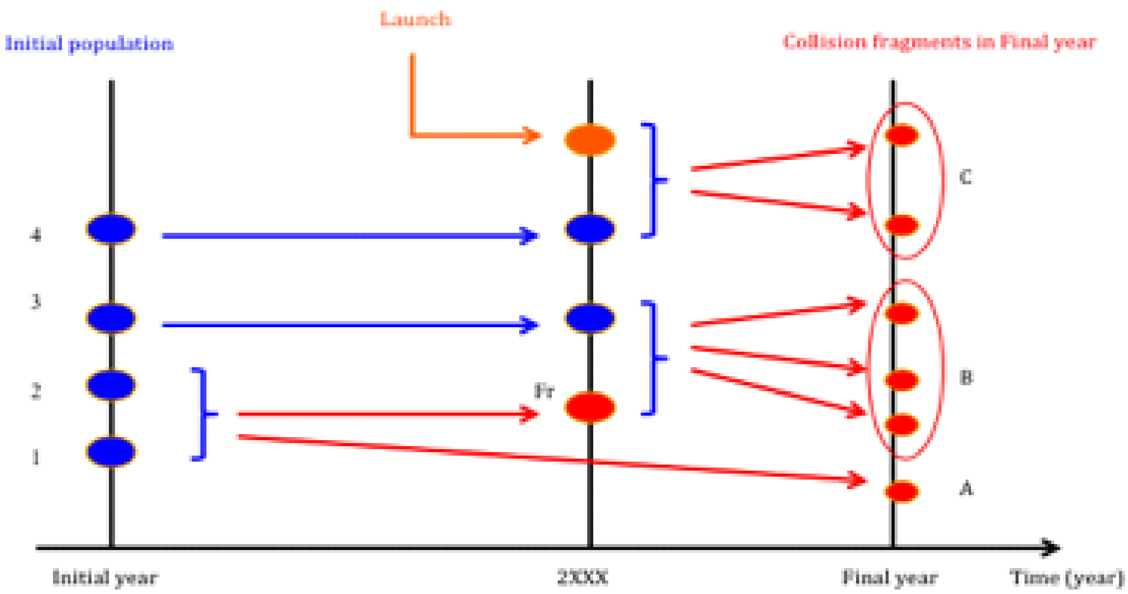


Figure 8. Process applied inside 1 MC simulation for collision fragments identified in Final year

In Fig. 8, blue dots represent the objects included in the initial population, orange dots represent objects newly launched, and red dots represent fragments generated by a collision event. The groups A, B, C defined in Final year correspond to the groups of the generated fragments, and the numbers 1, 2, 3, 4 defined in the initial year correspond to the identification numbers of the initial parent objects that generate fragments in Final year. The groups of fragments are defined with respect to the time-closest generative collision, i.e. all the fragments of a same group are generated by the same collision, as shown in Fig. 8. In each group, the information on the mass and the size of every fragment is accessible. Furthermore, at the end of the track, the list of debris-generating parent objects is given in output. In the example, they correspond to objects 1 to 4. In this list, the following data are provided for each of the parent objects: the total number of generated fragments in Final year and the corresponding fragments' groups. Therefore, thanks to the knowledge of the groups, it is possible to determine the mass and size of the fragments that may be produced in the future Final year. In the example of Fig. 8, initial objects 1 and 2 will generate the fragments of groups A and B; object 3 will generate the fragments of group B; and object 4 will generate the fragments of group C. The advantage of this program is that it tracks non-direct events, known as chain collisions, in order to associate to an original object all its resulting fragments. For example, the fragments of group B are indirectly created by objects 1 and 2 (through one fragment of their first direct collision), and directly generated by object 3. This process has been explained for a one-case simulation. Then, once all the data from each simulation are obtained, the program is applied to all the simulations, and the resulting list of parent objects is deduced from the mean of all cases, taking into account selected criteria (according to the user's objectives) such as mean on number of fragments only; mean on number of fragments overpassing a defined mass or size; as well as the recurrence (rate of appearance) in the simulations of the parent objects for example.

In order to concretely illustrate the capacity of the program and give a clear idea of the resulting outputs (nature of the data and format of the output files), the origins' track has been performed on the baseline scenario, from year 2009 to year 2109 through 100 Monte-Carlo simulations, taking the simplest assumptions of PMD 90% success rate, no new launches and no explosions in the future. Thus, focus can be made on collision events exclusively. First, the process in one particular simulation is presented. Then, the enlargement to the hundred simulations is explained.

Among all the simulations, the 2nd Monte-Carlo simulation has been selected for illustration here due to the complexity of the phenomena that occur during this case: presence of "multi-group" generating objects. The format of the resulting data (as it is given in output of the program) is shown in Figure 9, together with the graphical representation of the occurring events for this particularly interesting phenomena (multi-group generating objects).

Object's number	Type	Number of generated fragments	Groups of fragments
878	Spacecraft	1859	1 & 9
1415	Spacecraft	1859	1 & 9
1236	Rocket body	1124	2
2580	Spacecraft	1124	2
1183	Explosion fragment	4	3
11312	Explosion fragment	4	3
1354	Rocket body	856	4
4443	Explosion fragment	856	4
1476	Spacecraft	498	5
1967	Spacecraft	498	5
1629	Rocket body	565	6 & 10
6025	Explosion fragment	565	6 & 10
1352	Rocket body	1119	7 & 8 & 12
2323	Spacecraft	1119	7 & 8 & 12
1400	Spacecraft	2	8
1609	Rocket body	712	9
3466	Mission related object	24	10
825	Spacecraft	1284	11
3097	Spacecraft	1284	11
2477	Explosion fragment	3	12
2185	Spacecraft	1904	13 & 14
2383	Spacecraft	1904	13 & 14
1318	Rocket body	960	14

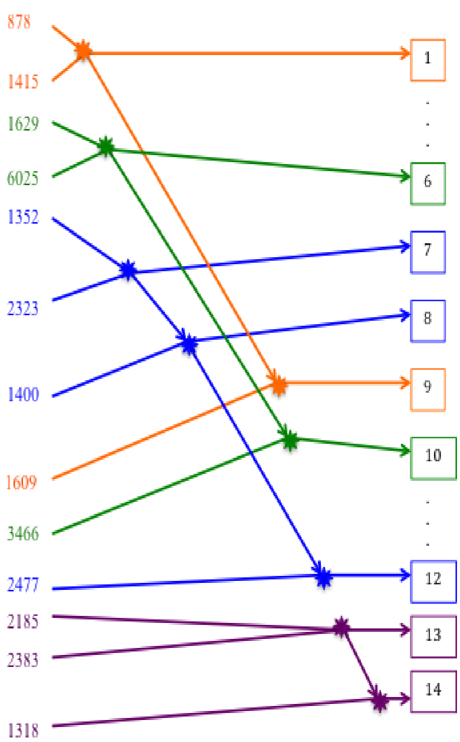


Figure 9. Results of the tracking function: output format & illustration of chain events

As presented in Fig. 9 for this particular simulation case, 23 objects of year-2009 population are estimated to be at the origin of 9213 collision fragments in total, divided in 14 groups.
The same process has been applied to all simulations, giving similar output files and analyses for each case. Therefore, to fully complete the investigation, all results have been gathered through the mean on the 100 Monte-Carlo simulations. For a simple example of possible final results, it has been decided to calculate the mean on the number of fragments generated by each parent object of all cases. The format of the final data is given in Table 4 where the beginning of the file (riskiest objects in term of generation of fragments) is detailed.

Item's number in NEODEEM	Type	Mass (kg)	Inclination (deg.)	Altitude (km)	Mean expected number of generated fragments
876	S/C	4500	64.94	950	114.19
754	R/B	8230	71	842	112.63
466	R/B	9000	71	845	100.81
700	Deb.	2990	70.94	947	98.21
841	R/B	8230	71.01	834	87.43

Table 4. Example: List of the first five objects expected to generate the more collision fragments in 2109 (mean on 100 MC cases)

As presented in Table 4, the final results concerning the list of objects at the origin of future fragments is given in decreasing order, from the riskiest (here, the object generating the higher number of fragments in the future) to the less dangerous. Information on each object is provided, mainly the internal properties of the object and its orbital characteristics at initial year or year of removal (depending on the user's objectives).

This tracking program has been applied to the different studies detailed in this Doctoral thesis. It has been a strong support to achieve the purpose of determining the objects, either among the current population or as they are expected to be in a given removal year, that may be the most efficient targets for removal according to a particular time scale. Indeed, since the future period is given a major importance in order to determine the objects that may impact it, this tool helped to anticipate the consequences on the future, according to the time spent from the possible collisions and the scenarios that should be engaged in order to compensate these effects. This is a strong point of this study since it may be considered as a new approach for target selection and therefore as a proposal for new considerations in the purpose of securing the near-Earth environment, purpose shared by space agencies and companies. This tool, together with the method it enables to use, might be apprehend as a new approach to rank objects with implication in future debris generation; it could appear as an alternative way or a complement to other studies on the same subject, such as ranking proposals from Rossi et al. [17] or Kebschull et al. [23] who added time considerations in their evaluation of environment criticality.

The application studies are now detailed in Section 3 where the problem is to secure a journey to the Moon from potential collision risks, and in Sections 4, 5, 6, 7, 8 where the goal is to better understand how to classify targets according to criteria such as number, ranking, altitude, time scale, and many others.

3. Identification of removal targets to secure future Earth-Moon trajectory mission in 2045

As detailed in general introduction, the number of objects in orbit around the Earth has kept increasing since the very first launch of Soviet Sputnik satellite in 1957. With time, many objects have become non-operational anymore, but have remained on their orbit. Now, the proliferation of these debris appears as a real problem, in particular for human space missions, due to higher collision risks with operational space-crafts and threats for astronauts' life. In this context, this first study, as a part of the full Doctoral research, aims to secure future Earth-to-Moon commercial space travels starting from year 2045. In order to achieve this objective, precise knowledge of the space environment along this transfer orbit is required. Therefore, this proposal aims to predict the debris environment of both low-Earth and geostationary orbits as it may be in the year 2045. Then, among the predicted debris population, the idea is to identify the objects potentially dangerous for the success of the mission, i.e. the objects that have a high probability to intersect the Earth-Moon transfer orbit, and to determine their origin at an earlier baseline time, set as year 2020. This identification phase is a necessary step so as to perform an effective removal process of the original objects before the generation of the identified debris, which could allow eradicating collision risks. By identifying collision risks in a relatively far future, such a proposed research could give the opportunity from now to elaborate an effective plan for debris remediation, which can be considered as an innovative aspect at a time where debris proliferation inhibition is considered as a priority by worldwide Space Agencies.

The lunar mission for common people has been set during the year 2045, with a baseline for removal of identified objects in 2020. In order to determine the debris environment as it may be in 2045, the debris environment evolutionary model NEODEEM is used. This model takes as initial baseline the list of recorded space objects as of May, 1st 2009. The propagation step is based on launch traffic records from 2003 to 2010, through a repetitive 8-year cycle to simulate future launches, as explained in Section 2. The model propagates the population while evaluating the possible events that could happen in orbit, through multiple Monte-Carlo simulations. In this study, 100 Monte-Carlo simulations have been run. This prediction is made all over the years to be able to evaluate the possible environment of each year, and particularly of year 2045.

Concerning the target object, i.e. the Earth-Moon trajectory spacecraft, an example spacecraft has been inserted inside the environment model. In order to get first results, the current calculation for the translunar trajectory takes as basis Apollo 11th mission data at insertion time. Thanks to the parameters related to the vehicle and its orbit, the probabilities of collision with other objects in near-Earth orbits can be evaluated. The collision probability is calculated for each object simulated by the model and given in the output list of year 2045 objects. The objects that have been identified as dangerous for the mission (non-zero collision probability) are sorted according to the value of their collision probability. Then, the origin of these identified objects is tracked in the past, by using the catalogue of objects simulated all over the past years. The aim is to determine the event that generated the objects of 2045. This track is done until the origin appears before or in 2020, year of the scheduled removal or remediation process. Indeed, the remediation process should be made before the collision with Earth-Moon trajectory spacecraft happens, and the most effective way is to act before the original debris release the fragments that may intersect this transfer orbit. The full method can be summarized into three main steps as follows:

- Determine the objects that may collide with the lunar spacecraft in 2045 (simulation of the space environment until 2045 and calculation of collision probability in the particular year 2045)
- Identify the origin (parent object) of the colliding objects in their origin generation year
- Assimilate the original (parent) objects to their corresponding International Designator (ID) and name.

The entire process and the results are now explained more in details in the following parts. A reference is also available through [18].

In the same way, the evaluation of collision risks, together with the degree of confidence that can be attributed to such results gotten from the average of multiple simulations are also submitted as discussion points for future work, as explained in the Conclusive part of this Section.

a. Presentation of general identification procedure

In this sub-section, the process to find out the origins of objects that may induce collision risks with the lunar spacecraft is presented. From the initial population of May 1st, 2009, the evolutionary model estimates the new population at each year until year 2045. In order to increase the precision of the final results, 100 Monte-Carlo simulations have been run, as explained in previous section. The general process can be summarized as follows:

Process for 1 case simulation:

The object environment in LEO and GEO is simulated from the insertion file which sets the initial population in 2009 by taking into account the presence of intact objects[1] and fragments, launches and event data, as described in sub-section 2.a.i. The simulation is run until year 2045 (to estimate future environment).

The population simulated in 2045 is taken as a new baseline for this target year, to set the environment while inserting the lunar spacecraft. Another simulation can then be run only for year 2045, including the launch of the spacecraft. With this new simulation, potential interactions between the objects from the population in the baseline file (2045) and the target spacecraft can be evaluated through a calculation of collision probability, as described in sub-section 2.a.ii. Objects are sorted, eliminating those that are not expected to collide with the spacecraft (collision probability equal to zero), and a file of non-zero probability objects only is given in output.

From the above list, the origin of events that generate the identified listed objects in 2045 is tracked. In the case of intact objects, the generation year is found out by using all the population files created by the simulation from 2009 to 2045. In the case of collision fragments after 2020, a particular process is used to find out the parent objects of original collision fragments back in time until 2020 (while there are collision fragments, the same investigation is carried on to track the origin of the origin... of these fragments). The aim is to finally get intact objects only since they are the easiest and the most technologically feasible objects to be removed. All this process is summarized in Figure 10, that is the particular case (for this lunar trajectory study) of the general process explained in sub-section 2.b.

All Monte-Carlo cases process:

The above process, used in a one-simulation case, is entirely repeated as many times as possible in order to increase the precision and the reliability of the results. Indeed, the greater the number of simulations is, the greater the number of results is (one per simulation), and therefore, the wider the range of possibilities is. In this study, 100 Monte-Carlo simulations have been performed.

Mean of Monte-Carlo cases:

The result files issued from each Monte-Carlo case are gathered in order to determine the most reliable objects. The objects are sorted according to their recurrence number (the number of times they appear in a simulation, expressed in percentage), from the highest one to the smallest one. Indeed, the more recurrent (high ratio) an object is, the more reliable its existence is due to the frequency among the simulations. Therefore, the choice of a great number of simulations leads to gather more data, and define a mean on more results, which considerably raises the precision. But limitation by time calculation should also be taken into consideration, which explains the choice of 100 Monte-Carlo simulations.

[1] Intact objects are defined as spacecrafts, rocket upper stages, and all mission related objects.

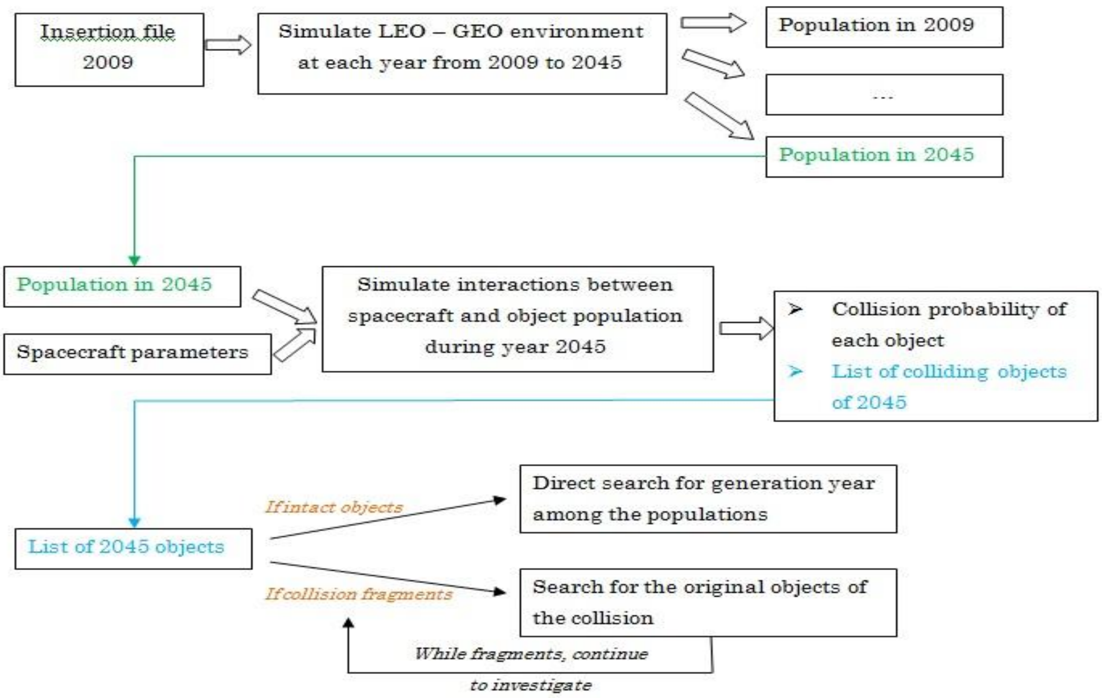


Figure 10. Process for identification of objects' origin inside one simulation case

Now the general procedure is understood, concrete results and analyses from the study are given in the following sub-sections in order to discuss the emergency to remove some particular objects, as well as the pertinence of the method.

b. Detailed scheme for origin's identification in one-case simulation

In this sub-section, the main parts of the identification process are presented more in details, through the output files, their format, the results and examples for a particular simulation case.

Simulating the space environment from 2009 to the insertion year 2045

In order to simulate the space environment as it may be in a defined epoch, here at the insertion year of the mission spacecraft in 2045, the environment evolutionary model NEODEEM has been used. To better evaluate all the possible interactions that may occur between the lunar spacecraft and the objects along its trajectory, it is necessary to understand the future population from low-Earth orbit to geostationary orbit (since the Earth-Moon trajectory crosses all this range of orbits), the *future mode* of NEODEEM is the best matching mode for this case, and has been selected to perform the projection. To do so, all the initial settings and assumptions presented in sub-section 2.a. have been taken into account. Table 5 presents these main settings as a reminder.

Event	Status in the simulation
New launches	Yes
Objects' removal	No
Future explosions	No
Collisions	Yes
Performed PMD	30% success rate

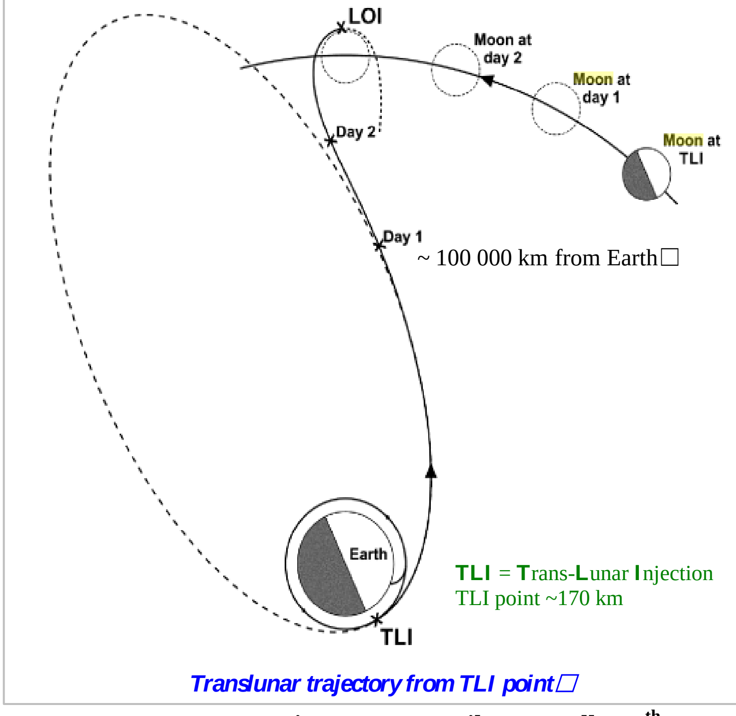
Table 5. Settings in NEODEEM for the lunar mission study

With the above settings summarized in Table 5, the model performs a projection of the environment from year 2009 until the insertion year of the lunar spacecraft, i.e. year 2045. This is the necessary preliminary step in order to better understand the future environment as it may be at the insertion year of the mission spacecraft. From this knowledge, possible interactions can then be evaluated, mainly collision risks that could endanger the lunar mission.

Evaluating collision risks between objects in 2045 and the lunar spacecraft

Once the object environment in year 2045 has been evaluated, the following step consists in determining the interactions that could happen between the existing objects of 2045 and the mission spacecraft. Therefore, the population of year 2045 gotten by the previous simulation is taken as baseline in order to perform the new simulation for year 2045 only. At the difference of the previous *future mode* projection, this simulation focuses on one particular object, i.e. the target spacecraft and its possible collisions with the other objects of the environment. To match this specific need, the projection mode called *target mode* in NEODEEM has been selected.

Concerning the Earth-Moon trajectory settings, the corresponding orbital elements have been calculated by taking as basis the 1969 Apollo 11th mission data (see [19] for details on the original Apollo 11 mission) at insertion time. This choice was made in order to be able to get first results, and check the feasibility and reliability of the method presented in this thesis. In addition to the orbital elements, the parameters proper to the spacecraft have also been used. Figure 11a provides an illustration for the Apollo11-type lunar trajectory, as well as information concerning the details of the flight.



Lunar spacecraft's elements (Apollo 11th mission type, launch from Kennedy Space Flight Center, Florida):

Launch date	2045/01/01
Launch place coordinates	28º 31' 26.61'' N 80º 39' 3.06'' W
Perigee (km)	6614.73
Apogee (km)	571 091.07
Inclination (deg)	31.383
RAAN (deg)	358.38
Arg. Perigee (deg)	4.4116
Mean anomaly (deg)	0.000646421
Mass (kg)	30 000
Size (m)	3.9
Area-mass ratio (m^2/kg)	0.00449

Figure 11a. Details on Apollo-11th-type trajectory mission

In this way, as input of the model, a target file has been created to gather all the above information. This file is a one-row (one target spacecraft) by 14-column file that includes the following parameters: the spacecraft's number in the simulation; its type (1 since spacecraft); its status (1 since controlled); the number of target objects (1: itself only); the orbit perigee (in kilometres); the apogee (in kilometres); the inclination; the right ascension of the ascending node; the argument of perigee; the mean anomaly; the size of the spacecraft (in meters); its mass (in kilograms); its area-to-mass ratio (in km^2/kg); and its lifetime. These data are useful to make collision probability calculation. This calculation uses the same method as explained in the previous sub-section concerning the simulation of the future space environment. The two-dimension configuration of the orbits is presented hereafter in Figure 11.

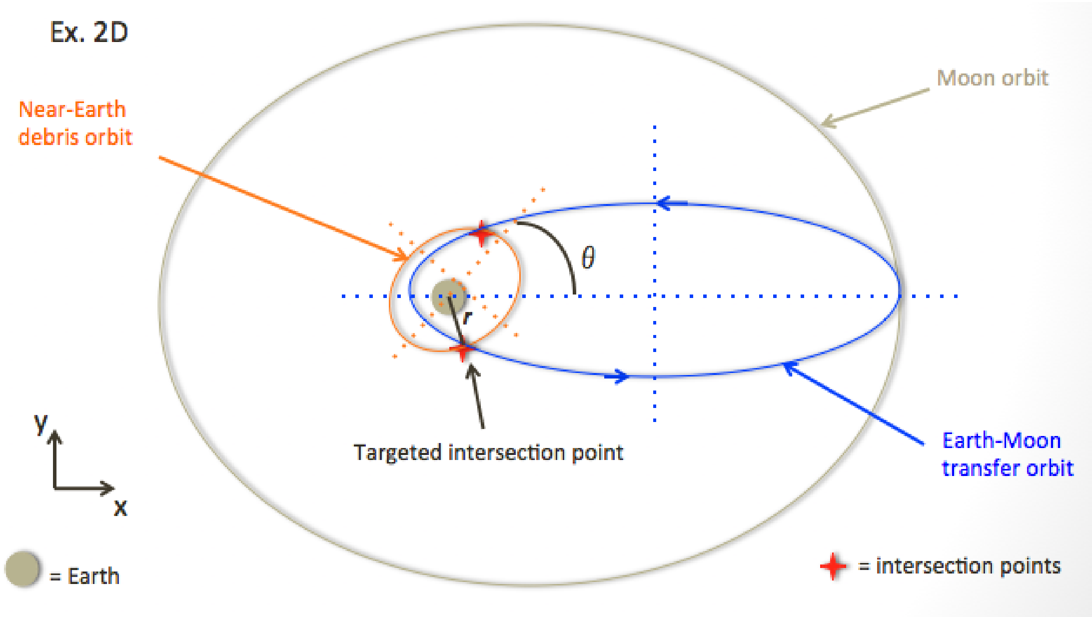


Figure 11. Identification of objects crossing Earth-Moon transfer orbit

For each object existing in the 2045 baseline file, the probability of collision with the mission spacecraft is calculated. Therefore, the objects can be divided into two categories: objects whose probability is zero, and objects whose probability is strictly positive. The objects with non-zero collision probability correspond to objects that are identified as potentially dangerous for the success of the lunar mission.

Type	Number of objects	Percentage (%)
Total	201	100
Spacecraft	27 (23 uncontrolled)	13.4
Rocket body	16	8
Mission related object	5	2.5
Explosion fragment	95	47.3
Collision fragment	58	28.8

Table 6. Nature of the identified objects colliding with the lunar spacecraft in 2045
Results from the 90th Monte-Carlo simulation case

Therefore, these identified objects are recorded in an output file of the simulation, including the data of their orbital elements, item number, mass, size, status, collision probability, and collision category. The collision category expresses if the collision is catastrophic or non-catastrophic. The nature of the collision is determined according to the level of energy it produces. A collision is said to be catastrophic when the energy produced is superior to a threshold. This case can occur for example when a massive object collides with a very small one, which may lead to the total destruction of the smallest object; or when the relative velocity at which the objects collide is very high. At the opposite, if the energy produced by the collision remains under the threshold, this collision is defined as non-catastrophic. In NEODEEM, this threshold has been set to 40 Joules/gram. Then, the objects are sorted according to their collision probability, from the highest probability to the lowest probability, in order to classify the elements of the output file. As shown as example in Table 6, the 90th simulation case has identified 201 objects potentially dangerous for the success of the mission. These objects are fragments in majority. Remembering that all explosion fragments already exist in the initial population, it has to be underlined that collisions have an important impact on the generation of high collision probability objects.

From this list of 2045 identified objects, the threats for the mission spacecraft in this simulation scenario can be deducted. And the next step of the process is then to determine the origin of these objects ahead in the past so as to be able to perform a remediation action.

Tracking the origin of identified objects until 2020 or before

In the context of the lunar mission, the above-identified objects of year 2045 represent a threat for the lunar spacecraft. Therefore, a remediation process should be thought in order to avoid the collision risks. To make this remediation more effective, it is necessary to perform it ahead in the past. In this study, a proposal is to remove non-operational or end-of-mission intact objects during the year 2020, twenty-five years before the lunar mission starts.

From the 2045 list of objects, the next step is thus to identify the origin of each object. Indeed, the removal of the origin will avoid the generation of the problematic object in 2045, and therefore will cancel the risk of collision with the spacecraft.

To determine the origin of an object, the past-year files given in output of the simulation (for each year from 2009 to 2045) are used. In NEODEEM, for the same simulation, an identification number is attributed to each object at the time of its generation, and is kept all over the years while the object exists in the environment. For example, in the 2009 initial population file, the objects receive a number from 1 to 20 788 (i.e. the number of recorded existing objects as of May 1st 2009). Then, during the simulation, projections in the future are performed for each year, which induces both the generation of new objects that receive their own number, and the destruction of old objects whose numbers are erased. In one simulation, one identification number is used only one time, only for the object it is assimilated to. Therefore, in the same simulation, objects can be tracked over the years, in the future as well as in the past, by using these identification numbers created by NEODEEM.

First of all, the first origin of each colliding object that has been identified in 2045 is searched. For each object, the files for each year from 2045 to 2009 are browsed through, and the search is stopped when the generation year file is found. Thus, the parameters of the object at that year are recorded.

Then, the type of the object is considered. If the object is intact or is an explosion fragment, the search is ended because intact objects are the objects we can act on, and all explosion fragments come from 2009 (explosions are set to zero as assumption). Therefore, collision fragments whose origin is after or in 2020 are the only objects that are considered to continue the search process.

Type	Number of objects	Percentage (%)
Total	58	100
Spacecraft	10 (6 uncontrolled)	17.3
Rocket body	1	1.7
Mission related object	1	1.7
Explosion fragment	0	0
Collision fragment	46	79.3

Table 7. Nature of the identified objects colliding with the lunar spacecraft in 2045
<u>that are generated or inserted after 2020</u>
Results from the 90th Monte-Carlo simulation case

According to the above Table 7, in the case of the 90th simulation, 58 objects among the 201 identified are generated in or after the year 2020. Among them, 46 collision fragments are present, which implies to investigate the origin of the related collisions. By using the generation year of these fragments, it is possible to determine the collision that generated them. In NEODEEM, the collision occurs one year before the fragments are generated. Therefore, among all the collisions that occur between 2009 and the year of generation of the fragments, only the collisions that generate the identified fragments are considered, and the two objects at the origin of the collision are recorded, as it is simply represented in Figure 12 where the original objects given at the end of the search are presented in green, in year 20XX. This origin-search process is repeated while there are collision fragments, and stops when all the objects at the origin of the identified collisions are intact objects or explosion fragments whose generation year has been found out.

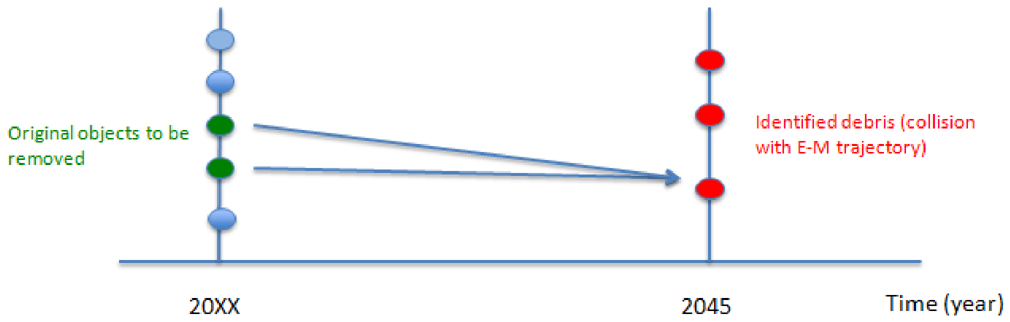


Figure 12. Determination of objects at the origin of a collision generating fragments identified in 2045

Furthermore, some of the original objects of one collision may be themselves fragments generated by a previous identified collision. In this case, these original objects are directly erased due to the avoidance of the collision they are generated by. This particular case is explained in the following Figure 13, and the effects of the first collision's avoidance on the future are presented in Figure 14.

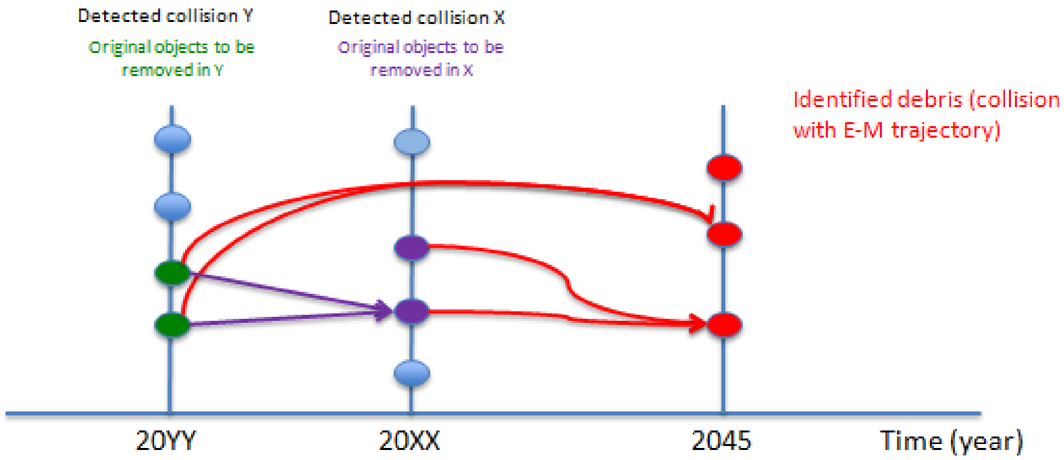


Figure 13. Determination of original objects in the case of chain collisions that lead to fragments identified in 2045

In Figure 13, the identified fragments colliding with the lunar spacecraft in 2045 are illustrated in red dots. One of them is generated by a collision that occurs in year 20XX, whose origin is due to the two objects in purple. One of the other red dots is generated by a collision that occurs in year 20YY, whose origin is due to the two objects in green dots. However, one of the purple objects that induce the 20XX collision is itself generated by the 20YY collision. Thus, by avoiding the 20YY collision, both the 2045 red object and the resulting purple object are erased, and the 20XX collision does not occur. Therefore, the final objects that will be recorded in the result file are the two green objects only. This chain avoidance effect is illustrated here, in Figure 14.

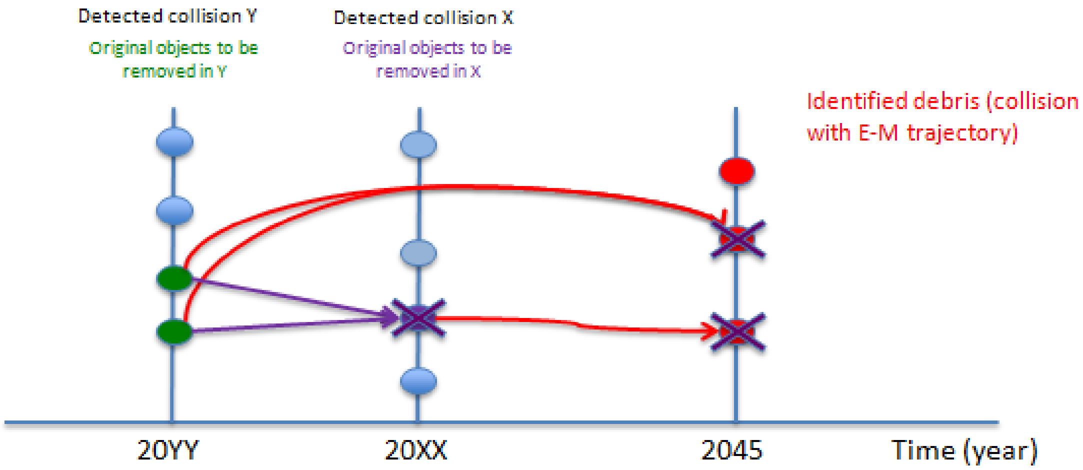


Figure 14. Determination of original objects in the case of chain collisions that lead to fragments identified in 2045 – effects of first collision's avoidance

At the end of all this process, all original objects that imply in the future a potential risk of collision with the mission spacecraft have been identified. An example of the objects' data file used in the search process is provided in Appendix A, in the case of the 90th Monte-Carlo simulation. This identification process detailed in this section is performed in the case of one Monte-Carlo simulation done with NEODEEM, and needs to be repeated as many times as possible in order to increase the reliability of the prediction as explained at the beginning of the section.

c. Average of all Monte-Carlo simulations

The identification of the original objects that generate objects colliding with the lunar spacecraft in the future is a long and complex process. It is performed inside one simulation, from the determination of colliding objects in 2045 until the identification of their origins. To raise the precision and reliability of the evaluation, this process is repeated a great number of times corresponding to the number of Monte-Carlo simulations that are run. In this study, the results are presented after running 100 Monte-Carlo simulations. Therefore, the list of original objects is given for each case, 100 times. Among these simulation results, the aim is to determine the recurrence of each object that appears in the hundred lists of objects. In other words, the number of times an object is determined as risky for the future success of the mission is evaluated in order to access the most reliable information.

In the lists of the original objects, objects are divided into two categories according to their generation year: the objects identified in 2009, and the objects that are generated strictly after 2009. This dissociation is due to the allocation of the identification number in NEODEEM. The objects that already exist in 2009, i.e. that are part of the initial population, keep the same identification number regardless of the simulation. Therefore, an object that comes from the initial population has the same identification number in all the Monte-Carlo simulations. Thus, the recurrence of 2009 identified objects can be determined by using the presence of the associated identification numbers in the various simulations. However, after 2009, the newly created objects are the products of a prediction that varies according to the simulation since the seed of each simulation is different. Therefore, the same object can be assimilated to a different number from one simulation to another, or two different objects in two different simulations can be assimilated to the same number. Thus, the recurrence of the objects that are generated after 2009 cannot be evaluated by using identification numbers. For this case, the object's parameters are directly used. These parameters are data that should remain the same regardless of the simulation. In this way, the generation year, the type of the object, its status, its mass and its size are considered to determine the presence of a same object in the different simulations.

Then, the number of times an object appears among the hundred simulations is evaluated through Monte-Carlo average, and the objects are sorted according to their recurrence ratio, from the highest recurrence number to the smallest one. The objects whose recurrence ratio is high are the objects that are the most probable objects to induce risks of collision and damage to the lunar spacecraft. Therefore, their existence and risk prediction is the most reliable. If a removal has to be performed, the targets should be these high recurrence ratio objects in priority. For the moment, the threshold above which the recurrence ratio is considered as high has been set to 10%.

d. Results from the average of the 100 Monte-Carlo simulations

As results of this study, by considering a threshold of 10%, the objects whose recurrence ratio is above the threshold are all originated from the 2009 initial population, and represent a total of 24 objects. The corresponding list of their parameters and information is presented in Figure 15, where the NEODEEM identification number is written in second column, and the recurrence ratio is in the first column. The file also provides information on the six associated orbital elements, mass, size, but some columns have been suppressed here for readability question.

Rec. ratio	Item number	Generation year	Type	Status	Mass (kg)	Size (m)	Area (m^2)	a (km)
1.60E-01	413	2009	2	2	1.43000E+03	3.44000E+00	9.29710E+00	7.31100E+03
1.50E-01	164	2009	1	2	4.50000E+02	3.86000E+00	1.17282E+01	7.30000E+03
1.30E-01	2707	2009	1	2	8.03000E+02	1.55000E+00	1.88600E+00	7.36410E+03
1.30E-01	207	2009	1	2	2.70000E+03	3.59000E+00	1.01402E+01	7.02100E+03
1.20E-01	968	2009	1	2	6.61000E+02	5.32000E+00	2.22506E+01	7.15850E+03
1.20E-01	108	2009	2	2	2.37000E+03	2.48000E+00	4.83770E+00	7.72800E+03
1.20E-01	960	2009	1	2	6.61000E+02	5.32000E+00	2.22506E+01	7.15280E+03
1.10E-01	3009	2009	4	2	1.93000E+01	1.19000E+00	1.97700E-01	7.15950E+03
1.10E-01	3089	2009	1	2	1.44000E+02	1.10000E+00	9.53800E-01	7.82790E+03
1.10E-01	511	2009	1	2	1.00000E+02	6.59000E-01	3.41500E-01	7.10000E+03
1.10E-01	1236	2009	2	2	1.42000E+03	4.06000E+00	1.29163E+01	7.36210E+03
1.10E-01	1831	2009	1	2	7.28000E+02	2.96000E+00	6.88480E+00	7.18180E+03
1.10E-01	2691	2009	1	2	8.03000E+02	1.58000E+00	1.95890E+00	7.35960E+03
1.10E-01	439	2009	1	2	2.25000E+02	1.12000E+00	9.81300E-01	7.86100E+03
1.10E-01	2397	2009	1	2	5.70000E+02	2.06000E+00	3.31720E+00	7.47590E+03
1.10E-01	3098	2009	1	2	1.02000E+02	1.09000E+00	9.35300E-01	8.66990E+03
1.10E-01	3096	2009	4	2	5.69000E+01	1.09000E+00	9.34000E-01	7.43370E+03
1.10E-01	4644	2009	4	2	1.56000E+01	6.15000E-01	2.97200E-01	7.30490E+03
1.10E-01	172	2009	1	2	1.45000E+03	3.71000E+00	1.08063E+01	7.11600E+03
1.00E-01	625	2009	3	2	5.00000E+01	2.36000E+00	4.35730E+00	7.23900E+03
1.00E-01	10037	2009	4	2	1.82000E+00	2.38000E-01	4.43000E-02	7.18200E+03
1.00E-01	2297	2009	1	2	1.67000E+03	2.26000E+00	4.00510E+00	7.48650E+03
1.00E-01	1759	2009	1	2	6.94000E+02	3.11000E+00	7.59570E+00	7.36700E+03
1.00E-01	12630	2009	4	2	1.67000E-01	1.77000E-01	1.74000E-02	7.27440E+03

Figure 15. List of the 24 most reliable objects that may induce collision risks with the lunar spacecraft in 2045

If an effective removal performed with current technology devices is in question, the target objects should be enough large and solid to catch them easily and without fragmentation risks. Therefore, among the final identified objects (high recurrence ratio), the objects that could be proposed as a target for removal are only uncontrolled and end-of-mission objects. Since five of the final objects are explosion fragments (the type in fourth column is 4), the number of objects that may become targets for future removal decreases to 19. However, among the five explosion fragments, three have a mass above 15 kg and a size bigger than 60 cm, thus the possibility of a removal for these particular fragments might also be considered if the necessity was established.

Furthermore, in order to better characterize the final identified objects, their orbital regions have been traced, which gives a first idea of their repartition in space. Figures 16 and 17 compare the altitudes of perigee and apogee of the objects as a function respectively of the inclination and of the right ascension of the ascending node (RAAN). The figures show the repartition of the objects in different groups according to the three specified parameters that are altitude, inclination and RAAN. In the graphs, the data of two objects have been underlined in yellow. These data are the altitudes of the two explosion fragments that are too small and lightweight to be removed as explained in the previous paragraph. Therefore, these two data may be ignored in the case of a removal target search.

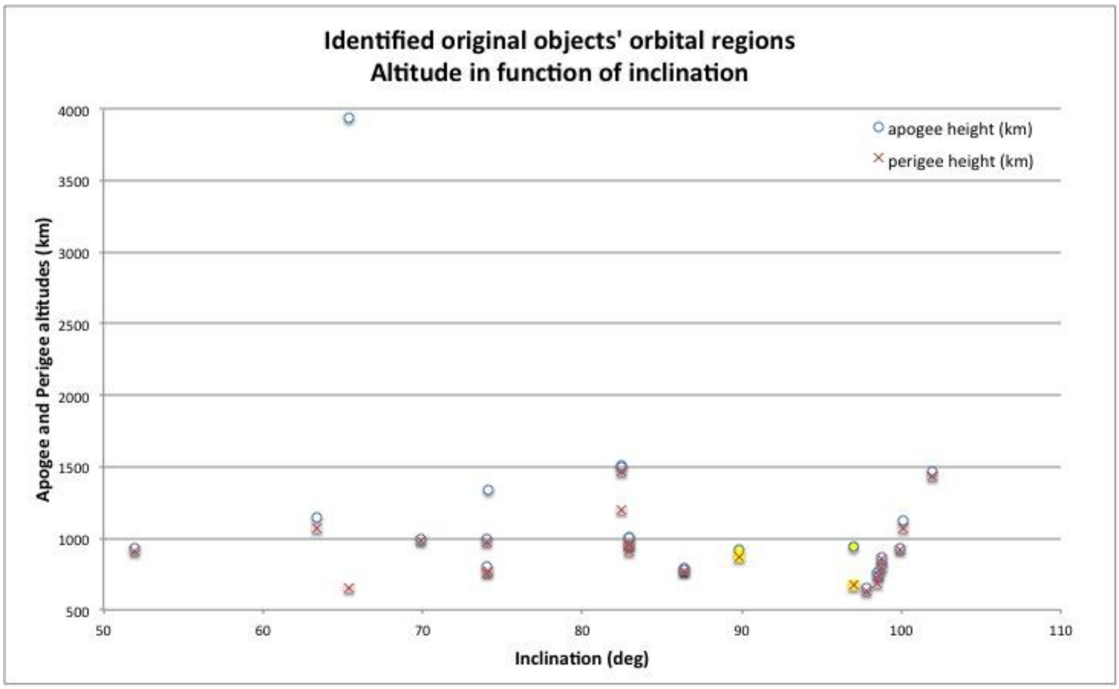


Figure 16. Population of the 24 most reliable objects that may induce collision risks with the lunar spacecraft in 2045 – Region as a function of altitude and inclination

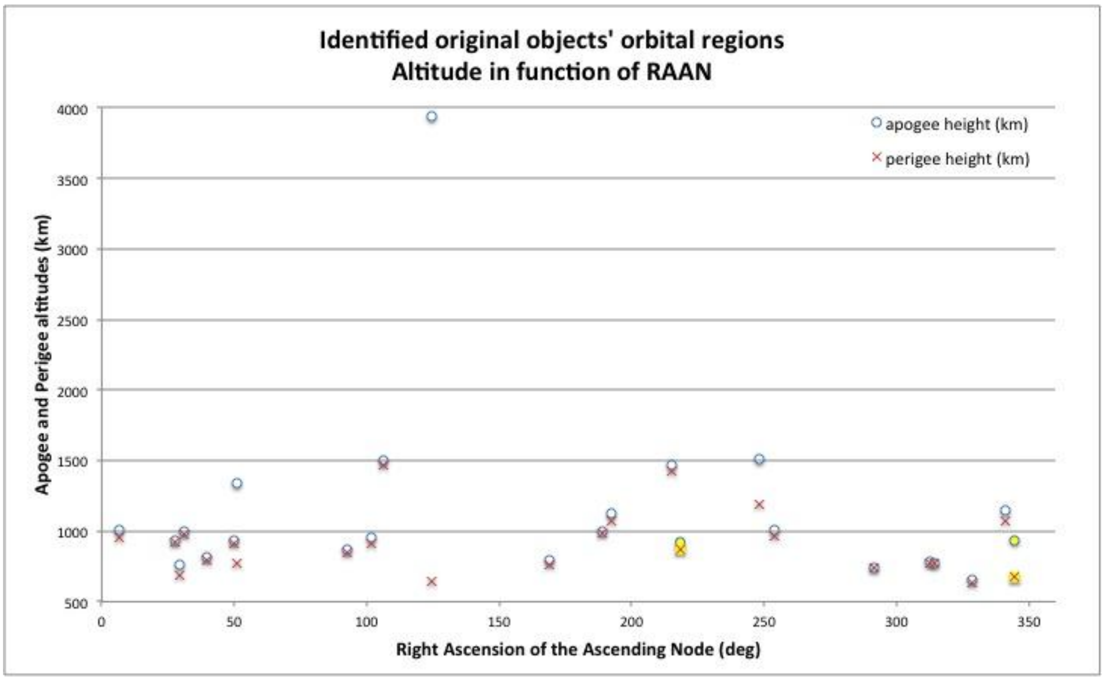


Figure 17. Population of the 24 most reliable objects that may induce collision risks with the lunar spacecraft in 2045 – Region as a function of altitude and RAAN

As a first remark, the graphs show that all the identified objects are present in Low-Earth orbits. The highest apogee is located at about 3930 km high. This is probably due to the fact that the great majority of the debris is located in LEO, since this is the most used orbit for human activities. The results are thus consistent with presupposed idea. Then, almost all the objects remain in the 500km – 1500km altitude region, and can be divided into groups. According to the inclination, three main groups can be identified. The most populated region corresponds to objects with altitudes from 500 km to 1500 km and inclinations around 100 degrees; another region corresponds to objects with altitudes from 900 km to 1500 km and an inclination of 82 degrees; and the last region gathers objects with altitudes from 700 km to 1400 km and an inclination of 74 degrees.

According to the RAAN, one region is particularly populated comparing to other ranges of values. This region gathers objects with altitudes between 700 km and 1000 km, and a RAAN around 30 degrees. In Figure 18, the graph representing RAAN in function of inclination shows that 3 objects in particular are located in the restricted region that corresponds to an altitude in the 700km – 1000km interval, an inclination of 100 degrees, and a RAAN between 30 degrees and 39 degrees. These objects are circled in red on Figure 18. If a removal is considered in the future, these three objects should be tracked as group objects in the case their evolution let them in the same configuration until 2020.

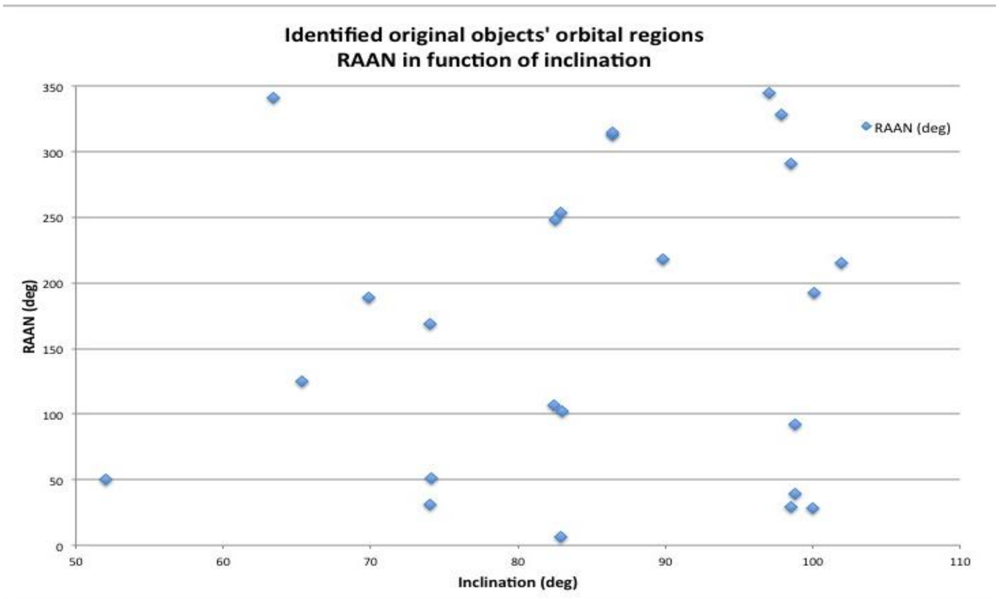


Figure 18. Population of the 24 most reliable objects that may induce collision risks with the lunar spacecraft in 2045 – Region as a function of RAAN and inclination

Now the list of risk-inducing objects has been obtained and data concerning their properties and orbital elements have been determined, the last step consists in selecting potential targets for an effective removal that could lead to secure the planned lunar mission. To do so, a concrete removal scenario must be proposed, thinking about current real objects launched into space. Therefore, the last step of this study aimed to identify the listed objects designed by modelling with the real objects that have been launched over the past years, by assimilating the data deduced from the baseline population and linked to the International designator of each real object. This is the subject of following sub-section 3.e.

e. Assimilation to existing objects (objects catalogued with their International designator)

It is possible from the result file of the 24 risk-inducing objects to assimilate them to current space objects that are catalogued by Space Agencies, using the International Designator. The International Designator is an identification number used at international level by Space Agencies and committees in order to track each of the objects that are currently present in space, whether due to launches, collisions or explosions.
Among these 24 objects, 18 objects could be assimilated to existing objects, i.e. to their name and International Designator. Information is summarized in the Table 8 below. Among the 6 remaining ones, 2 (green in Table 8) have been assimilated with the closest existing objects, but without certitude, therefore it is better not to consider them in short term; 2 (yellow in Table 8) have been assimilated to their name (rocket or satellite series), but many launches of the same object series were done in the same orbital region, so the selection of one particular object of the series could not be done (i.e. the corresponding International Designator could not be selected); and for the last 2 objects (blue in Table 8), no existing objects could be assimilated to their data (TLE and mass).

Table 8. List of identified risk-inducing objects with respect to their name and International designator (if could be assimilated)

Rec. ratio	Number in model	COSPAR ID	Name	Type	Owner country	Mass (kg)	Launch date
16%	413	?	SL-8 R/B	R/B	CIS	1430	?
15%	164	?	?	S/C	?	450	?
13%	2707	1982-003A	COSMOS 1333	S/C	CIS	803	1982/01/14
13%	207	?	?	S/C	?	2700	?
12%	968	1997-051C	IRIDIUM 33	S/C	US	661	1997/09/14
12%	108	2008-025E	SL-19 R/B	R/B	CIS	2370	2008/05/23
12%	960	1998-019D	IRIDIUM 59	S/C	US	661	1998/03/30
11%	3009	1993-036BNU	COSMOS 2251 DEB	frg	CIS	19.3	1993/06/16
11%	3089	1968-069A	ESSA 7	S/C	US	144	1968/08/16
11%	511	2003-049B	Chuang Xin 1	S/C	PRC	100	2003/10/21
11%	1236	1971-046B	SL-8 R/B	R/B	CIS	1420	1971/05/22
11%	1831	1983-113A	OPS 1294	S/C	US	728	1983/11/18
11%	2691	2004-028A	COSMOS 2407	S/C	CIS	803	2004/07/22
11%	439	2004-037A	COSMOS 2408	S/C	CIS	225	2004/09/23
11%	2397	1969-037A	NIMBUS 3	S/C	US	570	1969/04/14
11%	3098	1978-014A	KYOKKO 1	S/C	Japan	102	1968/02/04
11%	3096	1993-036R	COSMOS 2251 DEB	frg	CIS	56.9	1993/06/16
11%	4644	1970-025CA	THORAD AGENA D DEB	frg	US	15.6	1970/04/08
11%	172	1999-029C	Oceansat 1	S/C	India	1450	1999/05/26
10%	625	1999-025D	CZ-4B R/B DEB	MRO	PRC	50	1999/05/10
10%	10037	1999-025NQ	FENGYUN 1C R/B DEB	frg	PRC	1.82	1999/05/10
10%	2297	?	COSMOS (number ?)	S/C	CIS	1670	?
10%	1759	*1970-108A*	*COSMOS 385*	S/C	*CIS*	694	*1970/12/12*
10%	12630	*1967-034K*	*TRANSIT 15 DEB*	frg	*US*	0.167	*1967/04/14*

This list of objects (mainly the 18 objects that could be identified) can give a first idea of the kind of targets that may be selected for a removal process in the future, which is the aim of the second phase of the contract. The technology currently developed by ASTROSCALE PTE. LTD. may allow removing objects until a hundred kilograms. Therefore, in this case, satellites like ESSA 7, Chuang Xin 1 or Kyokko 1 may appear as potential targets for a first removal study case. Indeed, the criterion for the mass is satisfied, and it is easier to consider intact objects (spacecraft or rocket upper stage) since the shape has accessible data and is simpler than in the particular case of fragments. However, even if all these objects are in post-mission phase, so no more operational, a major problem to deal with while thinking about removal is the question of the ownership a state or company has on a particular spacecraft. This ownership continues even after the mission duration, and many social, political and economical issues may be considered. Therefore, discussions must be initiated with the owner entity. For more details, the owner country has been specified in Table 8 for each body that could be retrieved.

f. Suggestion for possible improvements to strengthen the reliability of the study

In order to simulate the environment in year 2045, the initial population file based on data as of May 1st, 2009 and explained in Section 2.a.i. has been used. However, this list of objects is the result of both the data from catalogues of objects and simulations performed to estimate future fragments. In other words, this file of year-2009 objects also gathers non-catalogued or non-existing objects. This file was therefore used as a support and basis in order to develop a strategy and a process to find out original objects for potential removal.
Since the aim of this study is to propose targets for an effective removal that may secure future commercial travels to the Moon, a new population file created from catalogued objects only must be created in order to give an easier access to real information, such as International Designator. For this purpose, keeping into mind the goals of Astroscale PTE. LTD., an initial population file has been created, listing all objects existing as of January 1st 2016. To complete this task, data were gathered both from Space-track catalogue (through *bulk catalogue*) [11] for TLE and from NORAD catalogue [12] for mass, launch date and others. This updated file will give a better and a more recent basis in order to get results that are more adapted to the final purpose of the all research, i.e. to define the targets to be removed.

Furthermore, as the technology developed by the company has become more concrete and is now close to feasibility, the precision and reliability of the results will become a priority. Therefore, it is recommended to increase the number of Monte-Carlo simulations as possible so as to be able to calculate the mean of all cases on a wider range of data and to compensate the randomness of the events (collisions, launches…) that are simulated.

g. Conclusive part

Concerning the results deduced from this study and provided to Astroscale PTE. LTD., the list of original objects that induce risks for the mission spacecraft in 2045 has been obtained. All the functions and the general process to go back from the colliding debris to their original parent objects have been implemented and defined, which allows performing a similar study whatever the case is. However, the input of the evolutionary model consists in the 2009 initial population file and a 2003-to-2010-launch-traffic file. Since then, the file for initial population as of year 2015 and a new file recording launch traffic until the end of year 2012 have been created and are ready to be delivered to the company according to the will and the orientation in the project of this one since more reliable results concerning the potentially risky objects are expected to be obtained. However, as explained in the first section, predicting future launch traffic remains a difficult task since new launches' frequency strongly depends on various parameters such as new regulation laws, the development of human activities, the needs of future missions, etc. Instead of using a repeated launch cycle over periodic years, analysing and understanding past launch frequency should be considered in order to evaluate the possibility to proceed to some extrapolation for the future. This is a point that should be carefully taken into consideration in order to increase the prediction level of the model, and must be considered as a recommendation from the author in case the company wants to follow the study.

Lastly, to improve the effectiveness of remediation process that could be decided according to the gotten results, a stronger criterion should be proposed and added in order to evaluate the removal emergency of each object. Until now, the main criterion to decide of the dangerousness of an object is to consider its recurrence ratio among the simulations. An improvement to bring is to keep the information of the collision probability proper to the generated objects in 2045, calculate the mean of the probabilities of the different Monte-Carlo simulations during the origin-search process, and associate this mean to the corresponding final original object. In this way, the prior objects to be removed would be chosen by considering both their recurrence ratio and the risk probability they induce in the future. This information would bring more strength to the results and to the decision that is made concerning debris remediation. It is recommended that this improvement will be made together with the increase of the number of Monte-Carlo simulations to be run.

It is also important to notify that this study has led to build a general process and create programming tools in order to be able to track objects and their origin. Therefore, the "generality" of the program makes this process applicable to various cases and many kinds of missions or trajectory studies.

4. Preliminary observations that motivated the study concerning ADR target selection and classification

a. Explanation of the whole research approach

This study, described from now to Section 8, tries to determine and understand the effects of remediation activities on the future evolution of the debris population around the Earth from low-Earth orbits (LEO) to geostationary orbits (GEO) by the use of the analytical Near-Earth Orbital Debris Environment Evolutionary Model (NEODEEM). The main purpose and the originality are here to dissociate the analysis of ADR impacts according to the future that is observed: it will be shown that a different time scale will lead to a different nature of the targets and a different criterion for the selection since the main phenomenon targeted here is the generation of fragments by collisions. Therefore, this paper presents a way to determine the selection criterion in the best adequacy to the focused period. To do so, this study was based on two complementary ways to understand the phenomena and mechanisms related to the evolution of space object population, using a "double-check" process.

First, NEODEEM simulates the environment over 100 years and 100 Monte-Carlo runs.

Then, among the initial population of year 2009, the objects supposed to be at the origin of the debris detected at a given time are tracked back in time into the simulations, using the collision-detecting program (tracking function) described in Section 2.b. The "given period" above mentioned for the presence of debris is based on a future as such that 2029 be considered a short-term scenario (Section 6), 2059 a midterm scenario (Section 7) and 2109 a long-term scenario (Section 5). This step produces three lists of targets for removal (one for each future), and simulations are run once again, through different scenarios involving the removal of particular listed targets in order to verify the appropriateness of the proposed scenarios. The analysis of the results is based both on the mean of the simulations and on the recurrence considering each run. Therefore, three studies were conducted one for each term, and a fourth one (Section 8) completed the work by establishing comparison between short, mid and long-term periods. This origin-identification approach leads therefore to the new question of the identity of potentially good candidates for removal. In other words, which objects may be the best targets to remove according to which scenario?

The research concerning the ADR target selection and classification is therefore motivated by the analysis of current real case investigation (Top priority targets from space agencies, SL-16 or SL-8 rockets). Therefore, in the study process, long-term ADR impacts have been evaluated as a first to compare with top agencies' lists. This first evaluation has led to deeper observations since a difference in the behavior of the population at different time scales could be noticed. In this way, it was decided to focus on two more particular studies concerning respectively mid-term and short-term analyses. To fully understand the approach of such research, the reader must consider the study of this Section 4 as the trigger that motivated the will to find out the most adequate criteria for target selection at long term (Section 5); and it must be understood that this long-term study consisted in the main support to notice the differences in the behavior of the population at other time scales, that is short term (Section 6) and mid term (Section 7). This is also why the propagation of the population was initially done over a long-term period, at 100 years. Thus, the same basis supports all the different time-scale studies.

This whole research does not pretend to give a solution for the crucial problem related to the knowledge of the riskiest debris currently in space. However, it tries to warn about the importance of the selection of target objects by showing various results obtained after the choice of particular objects, a particular area of intervention and a determined number of removable objects.

b. Motivations under the orientation of the whole research (preliminary study)

The aim is here both to underline the questions and the assumptions that have triggered this research concerning the removal conditions, and to justify its orientation (in terms of consideration for the altitude of the targets or the potential necessity to dissociate the removal effects at different periods of time). More precisely, references from agencies' requirements have been considered as a preliminary in order to propose criteria for the choice, the number, the area or the orbital zone of the potential ADR target objects.

The necessity to perform active debris removal has been clearly established [1, 2], as explained in Introduction through the graph of Fig. 1 [4]. The technology to do so is under development, as it was detailed in the previous part concerning the study jointly conducted with Astroscale PTE. LTD., Surrey University), and the main phenomenon under the expected growth of the population has been established thanks to the preliminary study of Section 2 with the effects of collisions (Figures 5 and 6). Therefore, using as a base support the results from these previous researches, the aim of this study is to take consideration of the number of removed objects, the importance of their on-orbit location, and various parameters presented later in order to point out which objects should be chosen so as to perform an efficient removal in terms of impact on the future LEO population.

As a first, in order to get a direction to investigate, the focus has been made on objects proposed by Space agencies. ESA is now developing the e.Deorbit mission whose objective is "to use a custom spacecraft to capture a heavy, ESA-owned item of debris and remove it from an altitude of 800 to 1000 km and a near-polar orbital trajectory" (ESA Space engineering technology website [10]). The target currently considered is the massive ENVISAT. In the point of view of JAXA, the heavy ADEOS 2, orbiting at 800 km in the high-populated region is in center of discussions [20]. In addition to these two objects, it has to be kept into mind that other objects have been launched in a recurrent way every year, mainly in the case of rocket bodies. The problem of these launchers is that their upper stages remain into their payload's liberation orbit. For example, the Russian rocket upper stages SL-16 or the SL-8 are frequently pointed out in terms of number of launches from the past to present. With such a consideration of agencies' lists or simple observations from launch history, this research theme has come naturally to mind: going beyond the focus on particular main target objects, the will is here to investigate the role of parameters that could lead to a better definition of "what" a target may be. Is the criterion the mass, the altitude, the probability of collision over the year, the number of removed objects or the fragments they may generate in the future? And is the effect of the selection the same whatever the period of observation? Precisely, it seems legitimate to wonder if the nature of a target should be selected according to the period on which the regulation will be done. In other words, the selection of a target should take into consideration the number of future generated debris, but also the period of impact (criterion that is linked to the altitude of the target). In order to deepen these questions, the present study has been raised, keeping also the motivation defined in Introduction and in Section 2.a.ii concerning the major impact of collisions in the evolution of the future population of space objects.

With such consideration, it is necessary to use all the possible tools in order to treat all criteria with the same care in terms of investigation in the effects over any periods. Mainly, with the particular role of collisions, and as extension of the fragments they produce, this study proposes to track directly the origin of the events that generate fragments, which will move the problem from the question of the appropriateness of the objects targeted in different ranking lists to the question of the identification of the best targets for an efficient removal at a selected period. This leads to the true objective of this research, presented more in details from Section 5 to Section 8, where the study, following its initial approach, is presented from long-term analysis (Section 5) to mid-term analysis (Section 7) through short-term analysis (Section 6). Section 8 concludes then by proposing a comparison of the criteria according to the period of action.

5. Selection and classification of ADR targets according to the resulting impacts of their removal on long-term evolution of LEO population

As explained at the end of Section 4.b., the aim is here to go further than the analysis of the impacts due to the removal of few targeted objects, and try to determine which objects should become targets for a better remediation at long term. To do so, a double-check process has been settled. This procedure consists in: first, tracking the parent objects of the long-term presence debris by using the tracking program and building the priority list of the resulting target objects; secondly, re-running different simulations with the analytical evolutionary model NEODEEM in order to verify the effectiveness of the removal of the listed objects on the evolution of the debris population in the far future.

The initial conditions and the simulation settings are as described in Section 2.a and Section 4.a, as well as the use of the tracking program (see description in Section 2.c) whose results came from the MC mean evaluated by considering the number of year-2109 fragments that an initial object may generate or may be responsible for in the future. Therefore, the object indicated at the top of the list would be the object that is expected to generate the more fragments in mean in year 2109. The number of fragments, when mentioned, must be considered as the arithmetic mean, on the number of MC runs, of the number of the resulting fragments in 2109 generated through all collisions directly or indirectly produced by the related parent object. All the objects expected to generate fragments were classified in a total list of 1255 objects (among the 20 788 catalogued objects in the initial population file of year 2009). Hereafter to simplify the reading, the classification for the very first ten parents is presented in Table 10, in which the objects at the top of the list are the most probable objects to generate the fragments of year 2109. Therefore, these top objects should correspond to the most adequate targets for removal according to the mean made on the hundred Monte-Carlo simulations. The top10 objects are presented in Table 10, after excluding the two explosion fragments present in 4^{th} and 10^{th} positions since the purpose of the ranking lists is to propose objects technologically and legally removable.

Item number	Target object	Mass (kg)	Incl. (deg.)	Altitude (km)	Number of generated fragments
877	COSMOS 952 (s/c)	4500	64.94	950	114.19
755	SL-16 (R/B)	8230	71	842	112.63
467	SL-16 (R/B)	9000	71	845	100.81
842	SL-16 (R/B)	8230	71.01	834	87.43
1350	SL-8 (R/B)	1420	82.92	975	84.27
819	SL-16 (R/B)	8230	71.02	841	76.72
820	SL-16 (R/B)	8230	70.88	849	74.31
660	SL-16 (R/B)	9000	99.65	997	72.8
816	SL-16 (R/B)	8230	71	836	67.08
1319	SL-8 (R/B)	1420	82.95	974	60.41

Table 10. List of the top 10 identified objects to be removed for efficient impacts at long term (results on 100MC-case mean).

According to these first results, the most impactful objects on the evolution of the future debris population are one heavy spacecraft and 2 kinds of Russian rocket upper stages. The top priority one appears to be the Russian COSMOS 952 satellite that was launched on 30th December 1976. It is expected to be responsible for the generation of 114 fragments in 2109 (on the mean of 100 Monte-Carlo simulations). And each of these top10 objects is expected to generate, in mean, more than 60 fragments in 2109. Their presence in the top of the list is due to their high recurrence rate among the outputs of the simulations, recurrence which is itself implicated by their high mass and orbital conditions. Indeed, they are all present on inclinations and altitudes corresponding to highly populated regions. Figs. 21 and 22 present the orbital regions of the objects recorded in the enlarged top100 list.

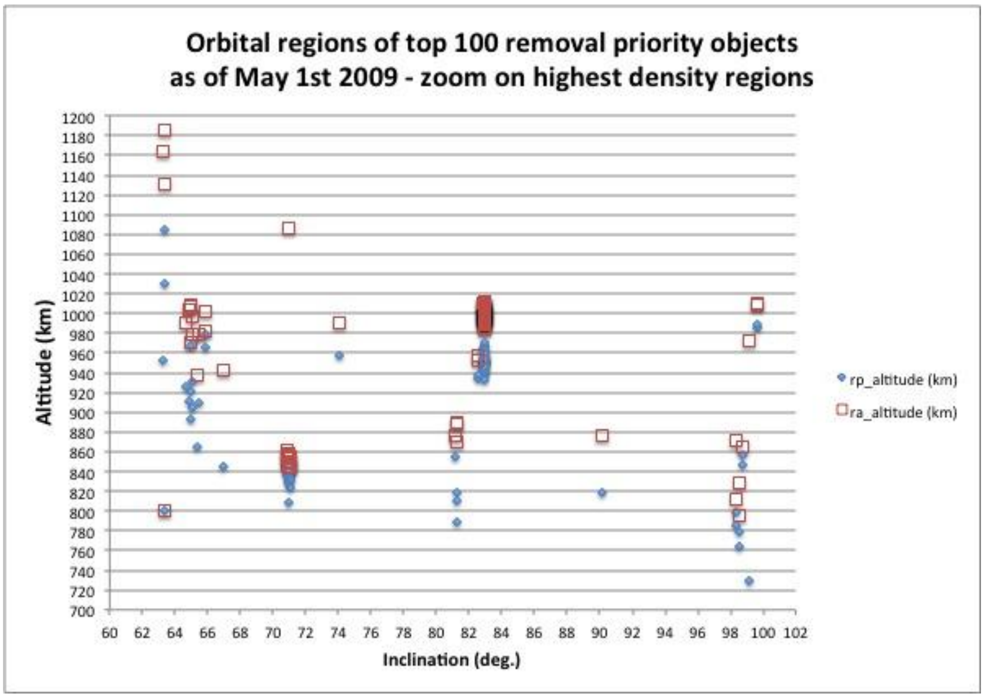


Figure 19. Orbital regions of Top100 targeted objects for long-term-impact removal: altitude vs. inclination (blue: perigee; red: apogee)

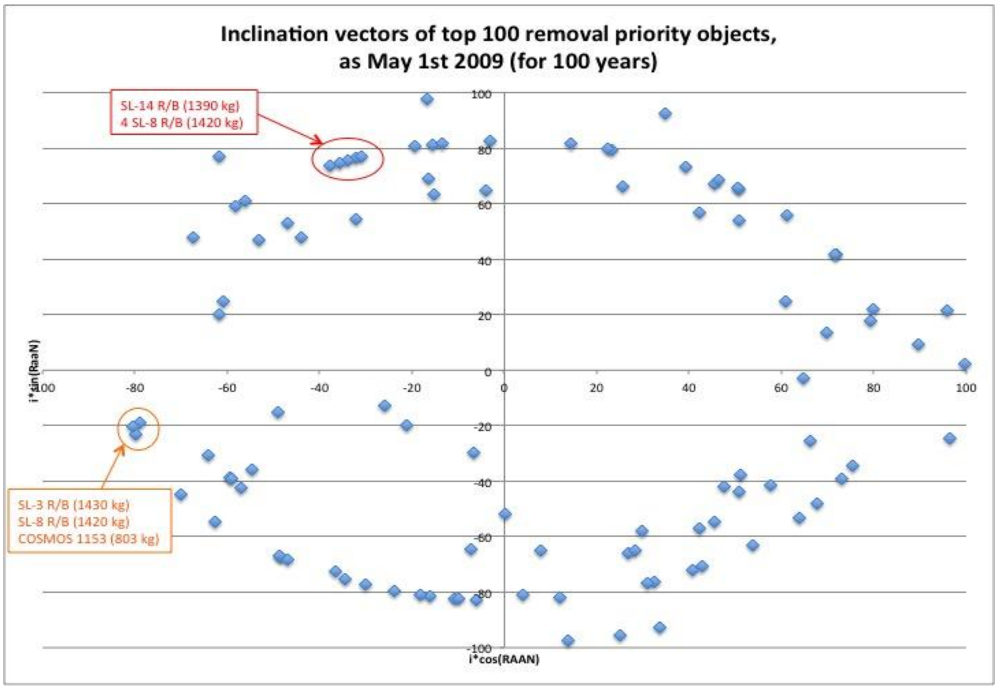


Figure 20. Orbital regions of Top100 targeted objects for long-term-impact removal: inclination vectors

From the above figures, it is easily noticeable that some of the main targets are grouped in the same orbital regions, mainly around 65°, 71°, 82° and 99° of inclination, for altitudes between 800 km and 1200 km. Some of them are also present in the same orbital plane, as it can be seen in Fig. 22. For example, four SL-8 rockets and one SL-14 rocket (upper-left corner of the graph) could be removed together in one time (one removal process). This group of objects is expected to generate 179 fragments in mean in 2109, therefore a possible multi-removal process in this case could be thought as an efficient way to decrease the debris population in this 100-year future. If the analysis is extended to the list of top100 objects, it appears that 33 SL-8 rockets and 10 SL-16 rockets are present in the classification.

Then, a double-check analysis has been done in order to verify the appropriateness of the top-priority list that was built thanks to the tracking program. To perform this verification and to better understand the role of the number of removed objects as well as the role of the position in the list, new simulations have been run thanks to NEODEEM after removing particular targets of the classification from the initial population. The simulations have been done until year 2109 to study the effects of targets' removal on the future evolution of the debris population according to different selection criteria. Three scenarios have been considered: one evaluates the impacts of the removal of the top1 object COSMOS 952 only; the second one concentrates on the removal of the 10 SL-16 rockets present in the top100 list of targets; and the third one focus on the removal of the 33 SL-8 rockets of the top100 list. All other conditions and assumptions for the simulations remain similar in the three scenarios. The results are presented in Fig. 23.

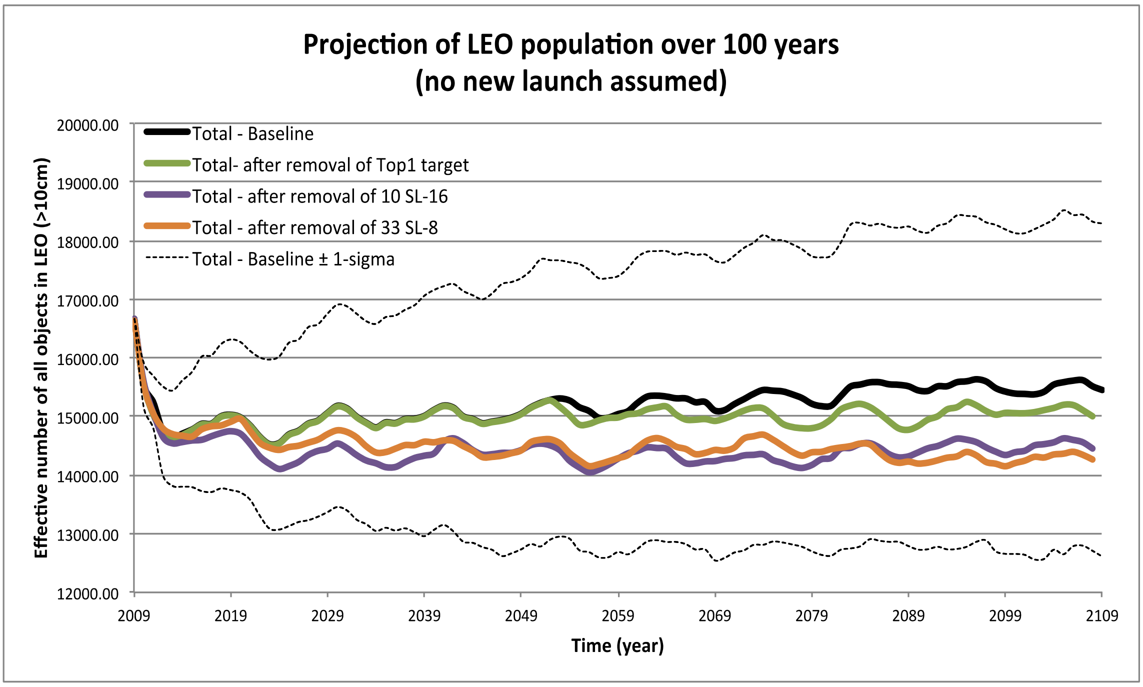


Figure 21. Impacts of removal scenarios on the far-future LEO objects population (evolution of the mean effective number of objects on 100 MC runs over 100 years) – under the assumption of no future launch

This figure shows, first of all, that the randomness introduced by the Monte-Carlo approach must be taken into account in this study. Indeed, the standard deviation calculated for the Baseline scenario encompasses the differences that can be observed between the other different scenarios, as presented in the following. In other words, it is impossible to make pertinent conclusions only from the mean of the results; in addition, it is therefore required to consider the outputs of each Monte-Carlo simulation in order to integrate the probability of occurrence for collision events and to compensate the underlined randomness suffered by the mean.

Based on the mean of the simulations, the tracking-program allowed to get reliable results since the removal of COSMOS 952, predicted to be the most appropriate target for a single-object removal, conducts to a better environment in the future in comparison with the baseline where no removal is performed, and this is also verified for other ADR scenarios (SL-16 in purple curve and SL-33 in orange curve). However, considering the previous problem of robustness in the approach, a more detailed comparison between the different removal scenarios is established.

First, concerning the number of objects, even if the removal of COSMOS 952 leads to better results than in the baseline scenario, looking carefully at Fig. 23 makes notice that this Top1st object only does not seem to be a stable choice in order to decrease the future population over 100 years. Indeed, after removal of COSMOS 952, the total population changes uncertainly, presenting a decrease at very short term before a slight stabilization over the period. It is then impossible to conclude on a true and solid impact of its removal continuously over 100 years, therefore the interrogation concerning the meaning in the removal of only one object is raised. But this is not the most striking point of this analysis at long term.

The most noticeable is that this analysis lets also understand the role of two criteria in a removal process. First, the impact of the number of removed targets is underlined since Fig. 23 shows that removing only COSMOS 952 leads to a future population higher in number than the population resulting after the removal of 33 SL-8 rockets or 10 SL-16 rockets. This means that, even if COSMOS 952 is the first object in the priority list of targets and the impact of its removal is higher than the removal of another object, it is less efficient than the removal of a great number of objects present in the same list, even coming after in the ranking. That is, the more the objects of the list can be removed, the more efficient the impact will be. But this fact is also linked to the uncertainty of the mean results: by removing more objects implicated in collisions, the probability to improve the environment is increased. Considering each Monte-Carlo output, removing the Top 1^{st} target leads to a weaker impact on the evolution of the environment in 58 simulations if compared with the removal of the10 SL-16 R/B, and in 53 simulations if compared with the removal of the 33 SL-8 R/B. Statistically, the removal of a higher number of objects is more efficient than a single-object removal at long term, which is in adequacy with the analysis based on the mean of the results. It must be noticed however that 58% and 53% rates represent a majority of the cases, but can't be qualified as very high rates. This is why the results must be considered with care and still in a statistical approach.

Then, the importance of the position in the priority list is also noticeable. Indeed, removing 33 SL-8 rockets and removing 10 SL-16 rockets reveal to have a comparable impact on the future evolution of the LEO population. This may be due to the fact that the SL-16 rockets are present in the very top of the list (7 are present in the first ten priority targets), whereas the SL-8 rockets appear later in the classification (only two rockets in the top 10). In addition, the weight should also be considered since the number of generated fragments depends on the mass of the colliding objects (according to NASA Breakup Model), and in this case, SL-16 rocket is much heavier than SL-8 rocket. This gives strength and coherence to the criterion lying under the list, given that SL-16 rocket bodies are predicted to account for more fragments in the 100-year future than the SL-8 rocket bodies. By looking at the results in each simulation, it appears that removing the 33 SL-8 R/B is more efficient than removing the 10 SL-16 R/B in 55 simulations. Here, the number of targets is once again underlined as a key factor, probably also to compensate the mass of the objects that are implicated in the collisions.

At last, it should be underlined that the effects of the above mentioned criteria clearly appears to be different according to the period of study. For example on Fig. 23, the gap between the three curves is very slight at short term, i.e. until year 2030, and starts to go increasing more and more until 2109. This means that the ranking may be a preponderant criterion at short term, whereas the number of removed objects may gain in importance at long term. This is an observation that justifies the necessity for the more precise investigation made at short and mid terms, as it was explained in Section 4 where the approach of the full study had been detailed. The analyses at short and mid terms are respectively presented in the following Sections 6 and 7. Moreover, in order to make the study complete, the comparison between ADR impacts at short, mid and long terms has been established, and the observations, together with the discussions that have been raised, are presented in Section 8.

6. Selection and classification of ADR targets according to the resulting impacts of their removal on short-term evolution of LEO population

Taking as basis the observations made through the study of the long-term period, the aim is here to focus on a restricted period and determine which objects should become targets for a better remediation at short term. To do so, a double-check process has been settled, exactly in the same way explained in Section 5 for the long-term study, that is tracking the parent objects of the short-term presence debris and building the priority list of the resulting target objects; then re-running different simulations to verify the effectiveness of the removal of the listed objects, and for this short-term study, the track of the fragments' origins has been performed here only over the first 20 years among the 100 years simulated.

The initial conditions and the simulation settings are as described in Section 2.a and Section 4.a, as well as the use of the tracking program (see description in Section 2.c) whose results came from the MC mean evaluated by considering the number of year-2029 fragments that an initial object may generate or may be responsible for in the future. Here again, the number of fragments, when mentioned, must be considered as the arithmetic mean, on the number of MC runs, of the number of fragments generated through all collisions directly or indirectly produced by the related parent object. All the objects expected to generate fragments were classified in a total list of 454 objects (among the 20 788 catalogued objects in the initial population file of year 2009). Hereafter to simplify the reading, the classification for the very first ten parents is presented in Table 11, in which the objects at the top of the list are the most probable objects to generate the fragments of year 2029. Therefore, these top objects should correspond to the most adequate targets for removal according to the mean made on the hundred Monte-Carlo simulations. The top10 objects are presented in Table 11, after excluding the four explosion fragments present in 2nd, 4th, 9th and 10th positions since the purpose of the ranking lists is to propose objects technologically and legally removable. Then, the 4th and 10th objects of this list, two SL-16 rocket upper stages, are notified in red colour because these objects are also present in the top10 list at long term, respectively at the 3rd and 7th positions. Therefore, these objects increase in the ranking at long term. Concerning the 7th object of this list, the SL-16 r/b number 816, it is marked in blue colour since it is also present in the Long-term list, but at the 9th position, so it decreases in long-term ranking.

Item number	Target object	Mass (kg)	Inclination (deg.)	Altitude (km)	Number of generated fragments
937	Ariane 40 (R/B)	1760	98.58	787	61.35
24	NOAA 9 (s/c)	1420	98.73	855	48.90
1344	SL-8 (R/B)	1420	82.95	972	43.57
467	SL-16 (R/B)	9000	71	845	40.46
2361	? (s/c)	824	98.7	839	40.46
994	Iridium 74 (s/c)	661	86.45	746	37.86
816	SL-16 (R/B)	8230	71	836	35.61
1360	SL-8 (R/B)	1420	82.93	969	34.34
946	? (s/c)	945	86.39	775	33.95
820	SL-16 (R/B)	8230	70.88	849	33.26

Table 11. List of the top 10 identified intact objects to be removed for efficient impacts at short term (results on 100MC-case mean)

According to these first results, the most impactful objects on the evolution of the future debris population are mainly Russian rocket upper stages and some spacecrafts. However, the top priority one appears to be the French Ariane 40 rocket upper stage that was launched on 26th September 1993. It is expected to be responsible for the generation of 61 fragments in 2029 (on the mean of 100 Monte-Carlo simulations). And each of these top10 objects is expected to generate, in mean, more than 30 fragments in 2029. Their presence in the top of the list is due to their high recurrence rate among the outputs of the simulations, recurrence which is itself implicated by their high mass and orbital conditions. Indeed, they are all present at inclinations and altitudes corresponding to highly populated regions. Figs. 24 and 25 present the orbital regions of the objects recorded in the enlarged top100 list.

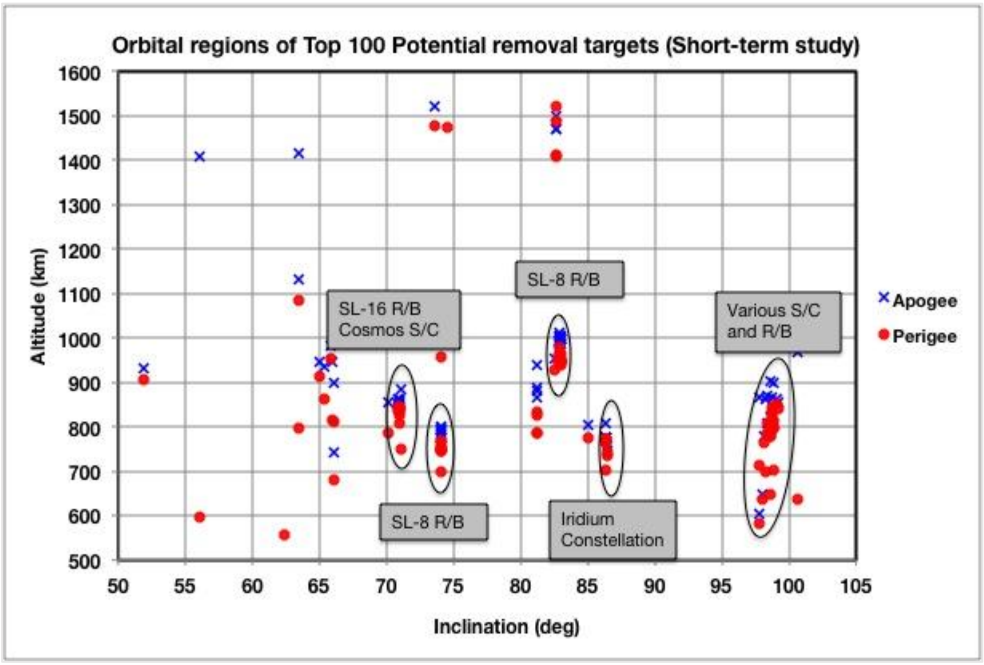


Figure 22. Orbital regions of Top100 targeted objects for short-term-impact removal: altitude vs. inclination

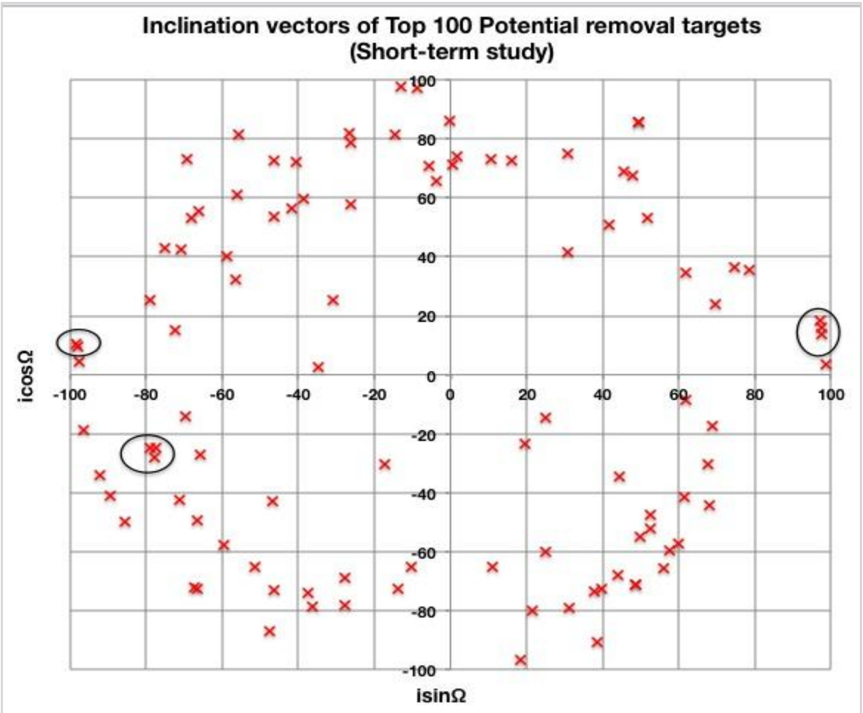


Figure 23. Orbital regions of Top100 targeted objects for short-term-impact removal: inclination vectors

From the above figures, it is easily noticeable that some of the main targets are grouped in the same orbital regions, mainly around 65°, 71~74°, 82~86° and 99° of inclination, for altitudes between 600 km and 1200 km. Some of them are also present in the same orbital plane, as it can be seen in Fig. 25, which may suggest a possible multi-removal process. This is the case mainly for objects present in very close area, such as the encircled ones. For example here, two targets can be observed around (-98 ; 10) coordinates (upper left corner of the graph), identified as CZ-2C rocket upper stage and an explosion fragment. For technological removal, it is better to focus on intact bodies. Therefore, looking at the upper right corner of same figure, three objects, identified as two spacecrafts and one rocket upper stage, could be removed together in one time (one removal process) since they are grouped around (97 ; 13~18) range of coordinates. This group of objects is expected to generate 58.42 fragments in mean in 2029, therefore a possible multi-removal process in this case could be thought as an efficient way to decrease the debris population in this 20-year future. A last group can be observed in the lower left corner of the graph, around (-78 ; -25) coordinates. Among these three targets, two are intact bodies, identified as SL-3 rocket upper stage and one spacecraft. These two objects are expected to generate in mean 45.57 fragments in year 2029. They might thus be potential good candidates for a multi-removal objective mission.

Then, a double-check analysis has been done in order to verify the appropriateness of the top-priority list that was built thanks to the tracking program. To perform this verification and to better understand the role of the number of removed objects as well as the role of the position in the list, new simulations have been run thanks to NEODEEM after removing particular targets of the classification from the initial population. The simulations have been done until year 2109 (to allow comparison with long term) and results are presented until 2029 here to study the effects of targets' removal on the future evolution of the debris population according to different selection criteria. Four scenarios have been defined: one evaluates the impacts of the removal of the top1 object Ariane 40 rocket upper stage only; the second one concentrates on the removal of 5 objects identified in both the top100 long-term list and short-term list of targets; the third one focus on the removal of 3 objects in the top100 list grouped in the same orbital zone (so potential targets for multi-removal process in a 98deg. inclination and 800km altitude area); and the fourth one analyses the effects of the removal of 5 objects in the top10 list. All other conditions and assumptions remain similar in the four scenarios. The results on the population after the different removal scenarios are presented in Fig. 26. Before moving to the analysis of the results, it is preferable to understand the motivation lying under the choice of each scenario. Therefore, the reason for the selection of these particular targets in the study of their removal impacts is explained from now.

- The first scenario has been established in order to determine the impacts of a possible removal of the first object appearing in the priority list since Ariane 40 is expected to generate itself more than 60 fragments in mean for year 2029. Therefore, the absence of this object from the population should give major information concerning the removal of one object. Indeed, in the situation when only one object could be removed, Ariane 40 should correspond to the best choice considering the number of fragments it may be responsible for in the future.

- For the second scenario, the lists of top100 targets for short term and long term have been compared in order to determine the evolution in the ranking of some objects that may appear in both of them. Indeed, after investigation, 19 objects could be identified to be common to both lists and increasing in the ranking (in terms of generation of fragments) while going to long term. Among them, the first five objects repeating in short and long term lists have been selected to study the multi removal of objects that are expected to generate more and more fragments from short period to long period of observation. This scenario was therefore established in order to better understand and compare the effects of removal at two different periods, but does not aim to evaluate implications of a multi-removal process (this is the purpose of the third scenario study). The characteristics of the selected objects are detailed in Table 12. One of these objects is an explosion fragment from SL-16 rocket; it has been kept in the scenario since the aim is here to evaluate the effects of the common presence in the two observation periods, rather than the technological feasibility of such a removal.

Target object name	Short-term rank	Nb. fragments Short term	Long-term rank	Nb. fragments Long term	Increase in nb. fragments
Expl. fragment	10	37.12	4	98.21	61.09
SL-16 (R/B)	6	40.46	3	100.81	60.35
SL-8 (R/B)	16	33.26	8	74.31	41.05
COSMOS 2237 (s/c)	43	21.88	14	59.98	38.10
Nadhezda 7 (s/c)	32	25.39	24	51.91	26.52

Table 12. Details concerning the first 5 objects common to short-term and long-term priority target lists (for Case 2 scenario)

- The third scenario aims to evaluate the effects of a multi-removal process by eliminating three objects located in the same orbital zone (98deg inclination and 800km altitude) at once. Since the technological feasibility of such a process must be taken into account, only intact objects have been selected. They are two spacecrafts and one rocket upper stage. Furthermore, since they are present in the top100 list of targets at short term, they might be potential good candidates for multi-removal: indeed, these three objects together are expected to generate in mean as many fragments as the top first object Ariane 40 is expected to produce. Then, their close location may allow removing them at once, which could be interesting for companies in terms of cost concerning launch and propellant consumption for future removal missions.

- Concerning the last scenario, the focus has been made on the significance of the objects' ranking positions, together with the number of objects to be removed. As for the study on the number of objects, it does not concern a multi-removal process investigation, but just the role of the number of removed objects in one year; this is why one explosion fragment is also present in this scenario. Therefore, five targets have been selected among the top10 list at short term. It is therefore meaningful to compare the results from this scenario both with the behaviour returned by the first scenario to understand the effect of the number of removed objects, and with the results given by the third scenario to point out the role of the ranking in the list.

Table 13 presents the four different scenarios simulated for the short-term analysis of removal processes targeting one or several objects either gathered as groups in purpose (case of the third scenario) or independently (case of the second and fourth scenarios). As for the category of an object in the "Type" column, 1 is spacecraft, 2 is rocket upper stage, and 4 is fragment.

Case	Name	Type	Inclination [degree]	Altitude [km]	Number of Fragments Generated	Mass [kg]
1	Ariane 40	2	98.58	787.26	61.35	1760
2	SL-16 Debris	4	70.94	947.36	37.12	2990
	SL-16	2	71.00	844.86	40.46	9000
	SL-16	2	70.88	849.16	33.26	8230
	Cosmos 2237	1	70.87	848.86	21.88	3170
	Nadezhda 7	1	82.90	987.26	25.39	818
3	OPS 7323 (DMSP 5B F3)	1	98.65	800.46	27.44	416
	PSLV	2	98.86	754.86	15.77	1000
	ERS	1	98.62	793.86	15.21	2300
4	Ariane 40	2	98.58	787.26	61.35	1760
	Delta 1 Debris	4	98.62	776.06	49.81	2290
	NOAA 9	1	98.73	855.46	48.90	1420
	SL-8	2	82.95	971.66	43.57	1420
	SL-16	2	71.00	844.86	40.46	9000

Table 13. Details on the removal targets selected in each of the 4 scenarios for short-term study

The impacts produced by each scenario simulation on the short-term future population are now presented and analysed more in details. The graph of Figure 26 presents the comparative projection of the LEO population over 20 years, according to the different removal scenarios.

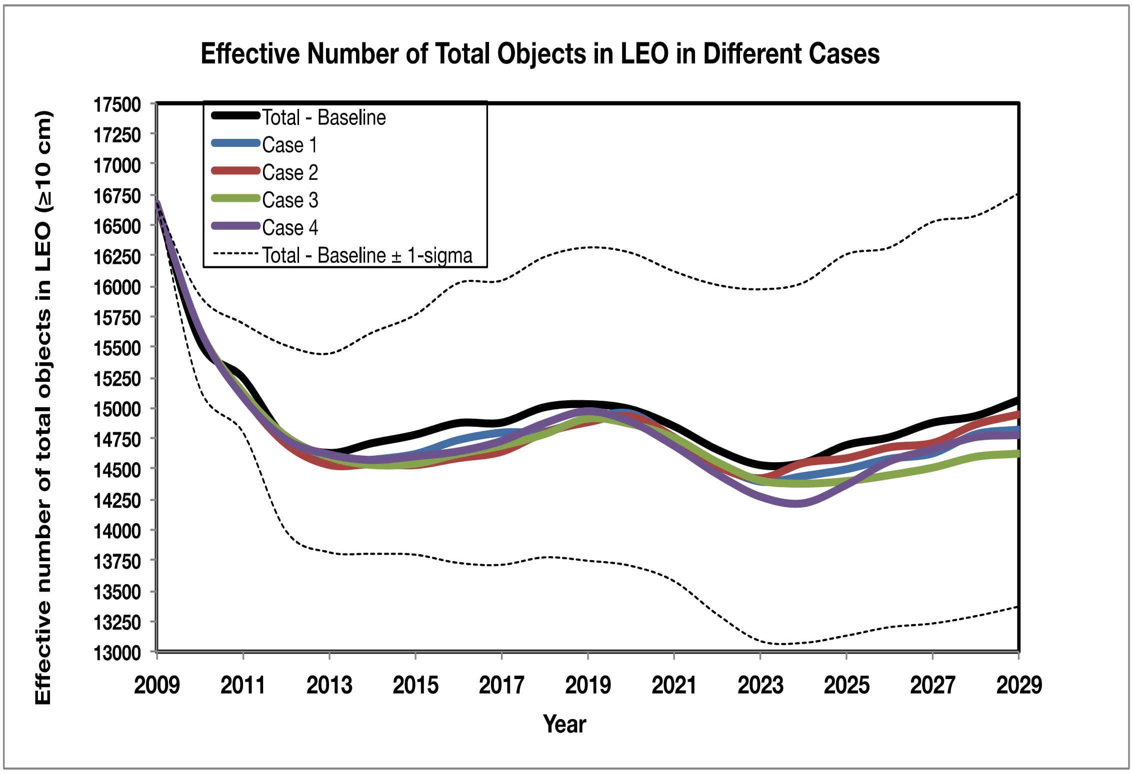


Figure 24. Impacts of removal scenarios on the close-future LEO objects population (evolution of the mean effective number of objects on 100 MC runs over 20 years) – under no future launch assumption

- **Case 1: removal of Ariane 40**
- **Case 2: removal of 2 SL-16; COSMOS 2237; Nadhezda 7; SL-16 debris**
- **Case 3: removal of OPS 7323; PSLV; ERS**
- **Case 4: removal of Ariane 40; Delta 1 debris; NOAA 9; SL-8; SL-16**

At first, this figure shows here again that the standard deviation from the baseline covers the differences made from the different scenarios. Therefore, the same care as in the long-term study must be taken in the analysis of the results from the MC mean. As a consequence, a more detailed investigation based on each simulation's output is conducted in this part.

Looking at the mean of the results, as in the case of long-term analysis, the scenarios including the removal of one or more objects lead to a slightly better future environment, compared to the baseline. Therefore, the reliability of the tracking-function is here again verified. Then, the graph shows that the removal of Ariane 40 only (blue curve), predicted to be the most appropriate target for removal in terms of generation of fragments and appearing as the first object of the list, leads to comparable effects as the removal of three (green curve) or five (red and purple curves) objects. This observation reveals a clear impact of the ranking position as a preponderant criterion in the selection of targets to improve the effectiveness of ADR at short term (more than the number of targets). This statement thus confirms the first observation underlined through the long-term analysis presented previously in this thesis.

Furthermore, an inversion in the curves can be noted around year 2023, near the end of the short-term period study. From this epoch, the third scenario (green curve) in which three grouped objects have been removed, becomes more efficient than the fourth scenario (purple curve) in which five objects in top10 have been removed and that was the most efficient until this date. The fourth scenario concentrates on the removal of very top objects in the classification, including the top first target, therefore the key role of the ranking was fully beneficial. However, while leaving this "short-term period", the selection criterion might change, and the focus might be done on the number of objects to be removed and present in a more populated region, as it is precisely the case of the objects selected in the third scenario. Indeed, the altitude of the generated fragments together with the density of objects of the region they reach may change the results according to the period of observation. For example, since the objects of the fourth scenario are all in the top of the target list for short term, it means that they generate fragments immediately at short term; therefore their removal presents an immediate effect on the population. However, in the original scenario (without removal), the expected generated fragments may fall rapidly since they are at low altitudes, and the effects of ADR on such objects don't persist at longer term. At the opposite, a more precise choice of targets among a particularly populated region, as it is the case of third scenario, may induce effects for removal at a post period due to a different behaviour of their generated fragments. This can also explain why, at the end of the period, removing only Ariane 40 leads to the same effects as removing 5 objects in top10 (including Ariane 40 itself). And this is also underlined in the more precise analysis of each simulation output, from which it appears that 50% of the simulations predict a better environment after removing Ariane 40 than the environment obtained after removing the Top5 objects of case 4.

Lastly, the second scenario, including the removal of targets present in both short-term and long-term lists, induces similar results on the population as the removal of top1 object. In 52 simulations, the second scenario leads to better environment than the scenario removing the Top 1st object, so the same impact on the future population can be expected in term of probability. It could be interesting to continue the investigation for this case by extending the scenario until 2109 at long term in order to determine if there might be a change in the behaviour of the population over a longer period. Indeed, since the objects of this scenario increase in the ranking at long term, it means that their removal should be more efficient for long term because their fragments might remain into space for a longer time than those generated only by the first object of the short-term list (the altitude of these five objects is higher than in other scenarios). This evaluation has been conducted, and will be fully presented in the comparative study detailed in Section 8, showing the impact of the altitude in other periods.

Therefore, the above analysis of the results at short term has the interest to lead to two conclusions: first, it underlines the crucial role of the ranking position for short-term effects in the removal process; then, it points out the necessity to conduct a comparative study at other time scales by taking into account different criteria, such as the altitude of objects in the case of multi-removal process or the implication in chain collisions in the case of one-object removal process. This question leads to the following section dealing with the impacts of removal over a different period of analysis: the mid-term period extending until year 2059.

7. Selection and classification of ADR targets according to the resulting impacts of their removal on mid-term evolution of LEO population

With the support of the observations made through the short-term and the long-term studies, the aim is here to focus on a transition period and determine which objects should become targets for a better remediation at mid term. To do so, a double-check process has been settled once again, with the same procedure as previously, consisting in: tracking the parent objects of the mid-term presence debris and building the priority list of the resulting target objects; then, re-running different simulations to verify the effectiveness of the removal of the listed objects on the evolution of the debris population in the mid-term future.

The initial conditions and the simulation settings are as described in Section 2.a and Section 4.a, as well as the use of the tracking program (see description in Section 2.c) whose results came from the MC mean evaluated by considering the number of year-2059 fragments that an initial object may generate or may be responsible for in the future. As the previous studies, here also the number of fragments, when mentioned, must be considered as the arithmetic mean, on the number of MC runs, of the number of fragments generated through all collisions directly or indirectly produced by the related parent object. Therefore, the object indicated at the top of the list would be the object that is expected to generate the more fragments in mean in year 2059. All the objects expected to generate fragments were classified in a total list of 568 objects (among the 20 811 catalogued objects in the initial population file of year 2009). Hereafter, the classification for the very first ten parents is presented in Table 14, the objects at the top of the list being the most probable objects to generate the fragments of year 2059. Therefore, these top objects should correspond to the most adequate targets for removal according to the mean made on the hundred Monte-Carlo simulations. The top10 objects are presented in Table 14, after excluding the two explosion fragments present in 4th and 6th positions since the purpose of the ranking lists is to propose objects technologically and legally removable. Then, the 2nd and 4th objects of this list, an SL-16 rocket upper stage and COSMOS 952 spacecraft, are notified in red colour because these objects are also present in the top10 list at long term, respectively at the 2nd and 1st positions. Therefore, these objects increase in the ranking at long term. Let notice that this SL-16 upper stage is also present in the top10 list at short term (6th position). As for the 1st and the 5th objects, corresponding to two other SL-16 upper stages, they are notified in blue colour because these objects are also present in the top10 list at long term, respectively at the 2nd and 9th positions; therefore, these objects decrease in the ranking at long term.

Item number	Target object	Mass (kg)	Incl. (deg.)	Altitude (km)	Number of generated fragments
467	SL-16 (R/B)	9000	71	845	207.84
755	SL-16 (R/B)	8230	71	842	121.90
1763	COSMOS 2082 (s/c)	3220	71.04	844	121.90
877	COSMOS 952 (s/c)	4500	64.94	950	85.20
660	SL-16 (R/B)	9000	99.65	997	72.10
1257	SL-8 (R/B)	1420	82.96	980	72.10
2097	SL-8 (R/B)	1420	82.97	974	67.51
185	SL-16 (R/B)	9000	70.98	845	64.43
817	SL-16 (R/B)	8230	71.02	841	60.89
3537	? (s/c)	3.96	69.97	907	56.98

Table 14. List of the top 10 identified intact objects to be removed for efficient impacts at mid term (results on 100MC-case mean).

According to these first results, the most impactful objects on the evolution of the future debris population are mainly Russian rocket upper stages (7 SL rockets) and three spacecrafts. The first two top-priority ones appears to be SL-16 rocket upper stages, which makes think about the study concerning long-term period where many SL-16 rocket stages were present. The mid-term epoch may be assimilated as a slight transition period from short term to long term. The very first target is expected to be responsible for the generation of more than 207 fragments in 2059 (on the mean of 100 Monte-Carlo simulations). And each of these top10 objects is expected to generate, in mean, more than 56 fragments in 2059. Their presence in the top of the list is due to their high recurrence rate among the outputs of the simulations, recurrence which is itself implicated by their high mass (except the last spacecraft) and orbital conditions. Indeed, they are all present at inclinations and altitudes corresponding to highly populated regions, just as it is the case for short and long term studies. Figs. 27 and 28 present the orbital regions of the objects recorded in the enlarged top100 list.

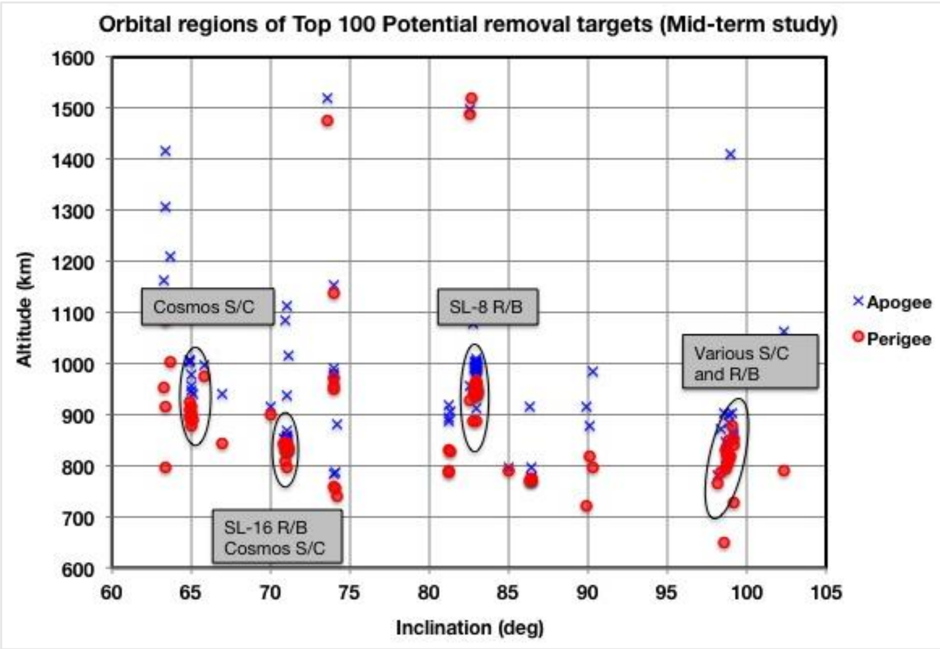


Figure 25. Orbital regions of Top100 targeted objects for mid-term-impact removal: altitude vs. inclination

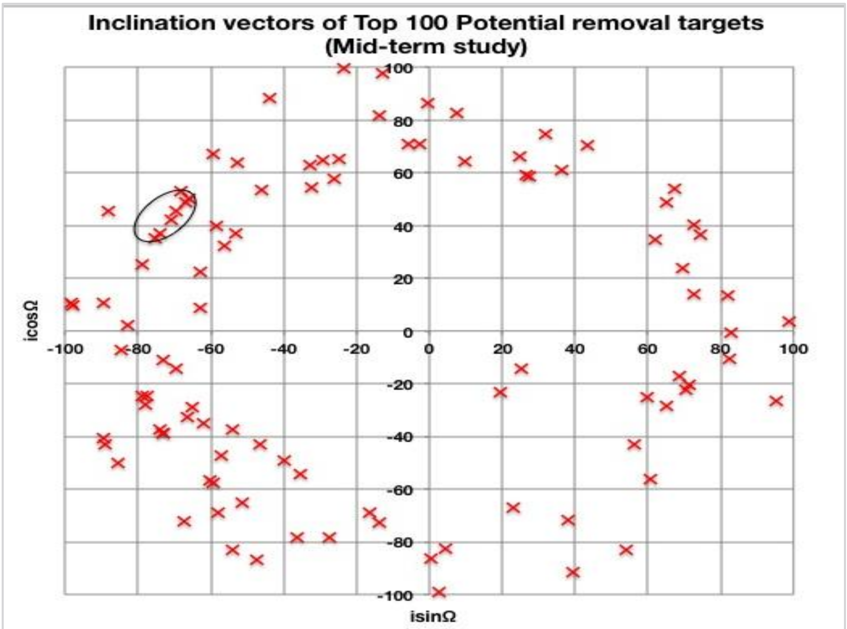


Figure 26. Orbital regions of Top100 targeted objects for mid-term-impact removal: inclination vectors

From the above figures, it is easily noticeable that some of the main targets are grouped in the same orbital regions, mainly around 65°, 71~74°, 82~83° and 99° of inclination, for altitudes between 700 km and 1200 km. Some of them are also present in the same orbital plane, as it can be seen in Fig. 28, which may suggest a possible multi-removal process, as it was also observable at short and long terms. This is the case mainly for objects present in very close area, such as the encircled one in the upper left corner of the graph. For example here, five targets can be observed around (-75 ~ -67 ; 35 ~ 48) coordinates, identified as one spacecraft COSMOS 991 and four rocket upper stages (3 SL-8 and one SL-14). Since they are all intact bodies, their removal is technologically interesting as a grouped removal in order to reduce the generation of fragments for year 2059. These five objects gathered together are indeed expected to generate 181.85 fragments in mean over the mid-term period.

Then, a double-check analysis has been done in order to verify the appropriateness of the top-priority list that was built thanks to the tracking program. To perform this verification and to better understand the role of the number of removed objects as well as the role of the position in the list for the mid-term period, new simulations have been run thanks to NEODEEM after removing particular targets of the classification from the initial population. The simulations have been done until year 2109 (to prepare a comparison all over the long term), and results are presented here until 2059 to study the effects of targets' removal on the future evolution of the debris population according to different selection criteria. Four scenarios have been established: one evaluates the impacts of the removal of the top1 object SL-16 rocket upper stage only; the second one concentrates on the removal of 5 objects in the top100 list grouped in the same orbital zone (so potential targets for multi-removal process in a 82deg. inclination and 1000-1400km altitude area); the third one focus on the removal of 5 objects identified in both the top100 long-term list and top100 mid-term list of targets; and the fourth one analyses the effects of the removal of 9 objects in populated area, common to top short, mid and long lists (combination of scenario 4 of short-term study and 3 of mid-term study). All other conditions and assumptions remain similar in the four scenarios. The results on the population after the different removal scenarios are presented in Fig. 29. Here again, before moving to the analysis of the results, it is preferable to understand the motivation lying under the choice of each scenario. Therefore, the reason under the selection of these particular targets to study their removal impacts is explained from now.

- The first scenario (named case 5) has been established in order to determine the impacts of a possible removal of the first object appearing in the priority list since this SL-16 upper stage is expected to generate itself more than 207 fragments in mean for year 2059. Therefore, the absence of this object from the population should give major information concerning the removal of one object and let understand whether the removal is as effective as it is at short term. Indeed, in the situation when only one object could be removed, SL-16 should correspond to the best choice considering the number of fragments it may be responsible for in the mid-term future.

- The second scenario (named case 6) aims to evaluate the effects of a multi-removal process by eliminating five objects located in the same orbital zone (82deg inclination and 1000~1400km altitude) at once. Since the technological feasibility of such a process must be taken into account, only intact objects have been selected. These objects are in fact the COSMOS 991 spacecraft and the four rocket upper stages identified previously through the analysis of the inclination vectors presented on Figure 23. They are all present in the same orbital region. Furthermore, since they are present in the top100 list of targets at mid term, they might be potential good candidates for multi-removal: indeed, these three objects together are expected to generate in mean as many fragments (20 fragments less) as the top first object SL-16 is expected to produce. Then, their close location may allow removing them at once, which could be interesting for companies to reduce costs concerning launch and propellant consumption for future removal missions, just as for the third scenario of short-term study.

- For the third scenario (named case 7), the lists of top100 targets for mid term and long term have been compared in order to determine the evolution in the ranking of some objects that may appear in both of them. Indeed, after investigation, 36 objects could be identified to be common to both lists and increasing in their ranking (in terms of generation of fragments) while going to long term. Among them, five objects have been identified as repeating in top10 midterm and top10 long-term lists. These five objects have thus been selected to study the multi removal of objects that are expected to generate more and more fragments from mid period (about 600 generated fragments in 2059) to long period (500 fragments still persist in 2109) of observation. This scenario was therefore established in order to better understand and compare the effects of removal at two different periods, but does not aim to evaluate implications of a multi-removal process (this is the purpose of the case-6 study). The characteristics of the selected objects are detailed in Table 15. One of these objects is an explosion fragment from SL-16 rocket; it has been kept in the scenario since the aim is here to evaluate the effects of the common presence in the two observation periods, rather than the technological feasibility of such a removal.

Target object name	Mid-term rank	Nb. fragments Mid term	Long-term rank	Nb. fragments Long term
SL-16 (R/B)	1	207.84	3	100.81
SL-16 (R/B)	2	121.90	2	112.63
Expl. fragment	4	113.08	4	98.21
COSMOS 952 (s/c)	6	85.20	1	114.19
SL-16 (R/B)	7	72.10	9	72.80

Table 15. Details concerning the first 5 objects common to mid-term and long-term priority target lists (for Case 7 scenario)

- Concerning the last scenario (named case 8), the focus has been made on the significance of the objects' ranking positions, together with the number of objects to be removed. As for the study on the number of objects, it does not concern a multi-removal process investigation, but just the role of the number of removed objects in one year; this is why one explosion fragment is also present in this scenario. Therefore, nine targets have been selected among the different top lists of targets, from short, mid and long terms. This scenario is a gathering of scenario 4 of short-term study (5 objects of the top10 short list) and case-7 study (5 objects of top10 mid and long term lists), with one object common to all three periods. It is thus meaningful to compare the results from this scenario both with the behaviour returned by the case-5 scenario to understand the effect of the number of removed objects, and with the results given by the case-6 scenario and the third scenario of short-term study to point out the role of the ranking in the list.

Table 16 presents the four different scenarios simulated for the mid-term analysis to study removal processes targeting one or several objects either gathered as groups in purpose (case of the case-6 scenario) or independently (case of the case-7 and case-8 scenarios). As for the category of an object in the "Type" column, 1 is spacecraft, 2 is rocket upper stage, and 4 is fragment.

Case	Name	Type	Inclination [degree]	Altitude [km]	Number of Fragments Generated	Mass [kg]
5	SL-16	2	71.00	844.86	207.84	9000
6	Cosmos 991	1	82.99	974.96	55.31	803
	SL-8	2	82.97	951.66	47.11	1420
	SL-14	2	82.60	1492.76	30.25	1390
	SL-8	2	82.91	975.86	26.23	1420
	SL-8	2	82.94	974.26	22.95	1420
7	SL-16	2	71.00	844.86	207.84	9000
	SL-16	2	99.65	996.86	72.10	9000
	SL-16 Debris	4	70.94	947.36	113.08	2990
	SL-16	2	71.00	842.36	121.90	8230
	Cosmos 952	1	64.94	949.76	85.20	4500
8	SL-16	2	71.00	844.86	207.84	9000
	SL-16	2	99.65	996.86	72.10	9000
	SL-16 Debris	4	70.94	947.36	113.08	2990
	SL-16	2	71.00	842.36	121.90	8230
	Cosmos 952	1	64.94	949.76	85.20	4500
	Ariane 40	2	98.58	787.26	61.35	1760
	Delta 1 Debris	4	98.62	776.06	49.81	2290
	NOAA 9	1	98.73	855.46	48.90	1420
	SL-8	2	82.95	971.66	43.57	1420

Table 16. Details on the removal targets selected in each of the 4 scenarios for mid-term study

The impacts produced by each scenario simulation on the mid-term future population are now presented and analysed more in details. The graph of Figure 29 presents the comparative projection of the LEO population over 50 years, according to the different removal scenarios.

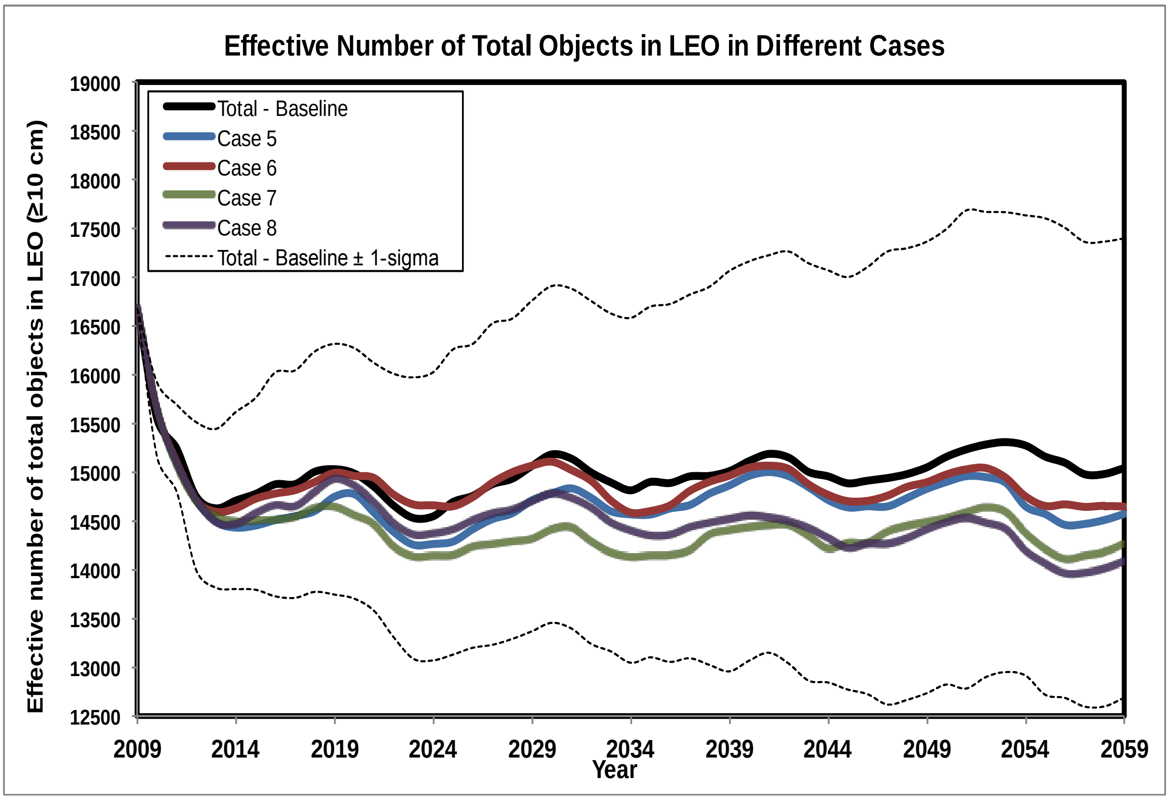


Figure 27. Impacts of removal scenarios on the mid-term-future LEO objects population (evolution of the mean effective number of objects on 100 MC runs over 50 years) – under no future launch assumption
- Case 5: removal of SL-16
- Case 6: removal of 3 SL-8; COSMOS 991; SL-14
- Case 7: removal of 3 SL-16; SL-16 debris; COSMOS 952
- Case 8: removal of 3 SL-16; SL-16 debris; COSMOS 952; Ariane 40; Delta 1 debris; NOAA 9; SL-8

The randomness of the Monte-Carlo approach is here again taken into consideration and the same analysis as in the previous studies is conducted to avoid conclusions based on non-robust results.

At first, this figure helps to verify the reliability of the results given by the tracking-program, just like in the previous analyses by observing efficiency of removal scenarios compared to the baseline; this comforts the use of the tracking method for any study, independently of the period of observation. Moreover, the graph shows that the removal of top first object SL-16 upper stage only (blue curve), predicted to be the most appropriate target for removal in terms of generation of fragments and appearing as the first object of the list, does not clearly lead to stabilize the mid-term population anymore (as it was the case at short term for the top1 target), and does not appear to be the most efficient scenario in terms of reduction in the number of future objects since case 7 (removal of 5 objects in mid and long term lists) and case 8 (removal of 9 objects) lead to a lower effective number of LEO objects in 2059. This first observation invites to think about a transition towards the number of removed objects as a preponderant criterion for target selection, more than the ranking position in the priority list. Furthermore, the change in the behavior of scenarios 5 (one object removed) and 8 (9 objects removed) precisely occurs around year 2029, so at the end of the short-term period. This statement therefore confirms the first conclusion underlined through the long-term analysis presented previously in this paper considering the mid-term period as a transition scale between short term (for which the ranking was a decisive criterion) and long term (where the number of removed objects and the possibility of multi removal seemed to be more valuable criteria for an efficient selection).

Then, a second observation should be noted and comes as a confirmation of the previous finding: another inversion in the curves, this time between the curves of case 7 and case 8, occurs around year 2045, so during the mid-term period. Both of these two cases evaluate the influence of the removal of several objects, 5 for case 7 and 9 for case 8. Until 2045, the case-7 scenario appeared as the most efficient in lowering the number of objects in the LEO population along the period, even if it represented the removal of fewer objects. This is because this scenario focuses on objects from top10 at mid and long terms; therefore the priority is here made on the ranking. After 2045, Scenario 8, by combining the criteria of number of removed objects (9 objects) and classification (object from top 10 short, mid, long lists), becomes more efficient since it strengthens the case-7 scenario by a grouping effects while adding 4 supplementary targets in a very populated area. Therefore, the necessary number of objects to target is taken into account here to reply the requirements of an optimum removal process towards long-term perspectives.

Lastly, it must be underlined that both the case-7 scenarios and the case-8 scenarios lead to a slight decrease of the population at mid term, which is not the result of the two other cases where less objects (only one in case 5) are considered or where the ranking is not taken into account (case 6). This relative efficiency of cases 7 and 8 is due to the fact that both of these two efficient scenarios take into account targets at long term, so they extend the range of investigation by beneficing the knowledge of future risks in advance.

Therefore, the above analysis of the results at mid term has the interest to confirm the observations made at short and long terms, and to reach the conclusion of an evolution in the preponderance of selection criteria over the time scales, seeing the mid term as a transition period from short to long terms. However, to fully understand the behaviour of the LEO population in the future, it seems necessary to extend these results all over the observation period, that is over the long-term period in order to get a wider view of the population propagation and be able to establish meaningful comparisons. This question will be fully raised in Section 8 dealing with the comparative study on the impacts of removal over 100 years, until year 2109.

8. Comparative study between short, mid and long terms to define adequate criteria for an efficient targets' selection at each period

As explained at the end of Section 4.b. and Section 5, the aim is here to go further than the analysis of removal impacts on a restricted period, and try to establish comparison in the behavior of future LEO population after performing ADR between the three previous studied periods. The aim is here to determine the role of selection criteria and the role of time in an ADR process so as to be able to decide on targets to be removed according to the future in question. The purpose is to make a choice and a decision that match, as precisely as possible, the considered period before removal.

In this Section, two analyses must be considered. First, the impacts of ADR targets at short and mid terms are evaluated over a larger period, i.e. over long term, in order to understand whether a change in the behaviour of the population can be observed; the period of observation and analysis is therefore extended, which also allows proceeding in a second step to a more meaningful comparison with the long-term study. Then, the combination of different removal scenarios coming from the three precedent independent studies is observed all over the hundred-year period in order to look at possible best scenarios in term of efficiency at all terms, allowing to "kill two birds with one stone" (i.e. to have impacts not only on the selected period, but also on another one). This is why, in the following, some cases have been chosen among the previous scenarios proposed and are presented more in details for comparison. Mainly, the focus has been made on the following six cases:

- The 1st object of top100 list at Long term (COSMOS 952 s/c)
- The 1st object of Top100 list at Short term (Ariane 40 r/b) (previous case 1)
- The 10 SL-16 r/b in Top100 list at Long term
- The 33 SL-8 r/b in Top100 list at Long term
- 5 objects common to Top10 lists at Short and Long terms (previous case 2)
- 5 objects common to Top10 lists at Mid and Long terms (previous case 7)

The particular study of these cases has been decided according to the previous analyses made respectively at long, short and mid terms. Mid-term analysis revealed that Case 7 was particularly efficient at mid-term, therefore the will to see the impacts all over the period was strong, mainly thinking that this case gathers targets of both mid and long terms. Short-term analysis revealed that removing several objects (Case 2) or just the Top1st object had similar results at short term; then the purpose here is to enlarge the period of observation in order to detect potential change in this result over all the period, taking into mind that, as underlined in long-term analysis, the number of objects stars playing a key role from the transition period of mid term. The other cases have been conserved both because they had strong impact at long term, and because they appeared to be ideal support for the comparison between all terms in view of the evolution of the future population that could be observed over 100 years as described in the dedicated Section 5.

The following Figure 30 gathers the results concerning the evolution of future LEO population according to the six cases presented before. Concerning the cases related to short and mid term studies, the period has simply been enlarged (compared to the results shown in the corresponding Sections 6 and 7).

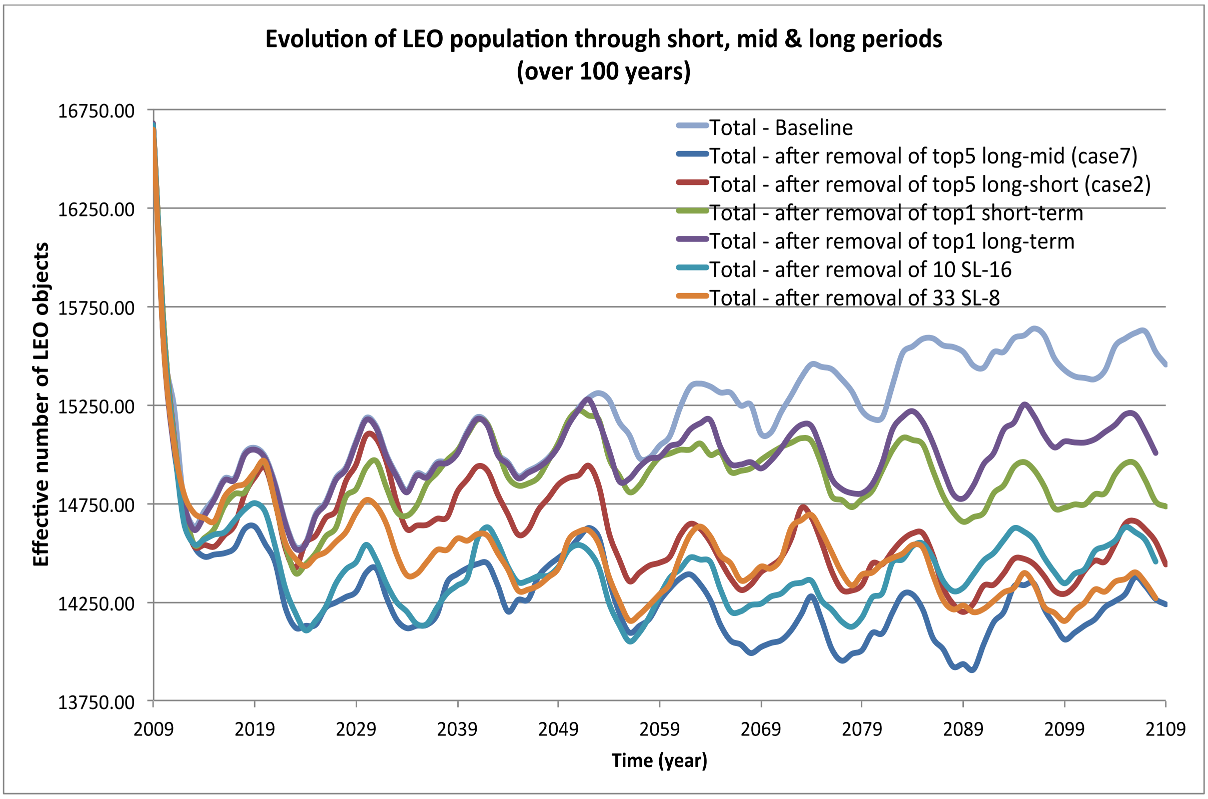


Figure 28. Impacts of removal scenarios on the long-term-future LEO objects population (evolution of the mean effective number of objects on 100 MC runs over 100 years) – under the assumption of no future launch – Most meaningful scenarios for comparison selected from short, mid and long term studies

From Fig. 30, the evolution of the LEO population after the different ADR scenarios can be observed over all the hundred-year period. Here again, the same statistical problem leads to consider both the results coming from the mean of the simulations and the results returned by each Monte-Carlo output. With such an approach, some scenarios clearly appear to be good strategies to stabilize the population over all the period or a particular term (cases of removal of several objects), whereas the others (cases of one-object removal) don't bring satisfying results on this point. Mainly, after year 2019, removing only one object, even the first target in the priority list, is not enough to stabilize the future population, represented in purple and green curves on the graph.
Statistically, removing the Top 1st object at Long term (COSMOS 952) leads to less efficiency on the future population in 52 simulations if compared to the removal of 5 objects common to Top Long and Short terms, in 54 simulations if compared to the removal of 5 objects common to Top Long and Mid terms, and in 58 simulations if compared to the removal of 10 SL-16 stages. The results are therefore coherent in both approaches.
However, it can be noticed that a combination of strategies from different terms leads to the best expected results and seems to produce the best impact on the evolution of the population, as shown by the dark blue and the red curves on the graph. These scenarios correspond respectively to the removal of the top 5 objects common to mid and long term lists, and to the removal of the top 5 objects common to short and long term lists. Moreover, the removal of only 5 objects present both in the mid-term list and in the long-term list is even more efficient than removing 33 SL-8 rocket bodies (orange curve) if the whole period is considered. This first observation may lead to a potential interest in terms of cost for removal techniques engaged by companies, by reducing the necessary propellant mass and the number of maneuvers for rendezvous with the targets for example.

A second observation is that the focus on targets detected at the previous period leads to impactful results on the following period, that is selecting targets at short term helps to increase removal impacts at mid term; and selecting targets at mid term helps to increase removal impacts at long term. This behavior can be noticed by looking at the dark blue curve representing Case 7. This removal scenario clearly appears to be the most efficient one all over the period, but the clear difference with the other scenarios really occurs from year 2060 (mid term) until the final year. This scenario includes the removal of targets present in both mid and long-term lists, which illustrates the above conclusion. Statistically, this scenario is better than the removal of objects common to Top Long and Short terms in 54 simulations, and than the removal of 10 SL-16 stages in 52 simulations. Therefore, same conclusions can be raised, mainly due to the high altitude of the objects and the total mass implicated in the detected collisions.

Finally, it can be argued that two scenarios bring the most efficient impact whatever the future is (short, mid and long terms) all over the period of study, in terms of stabilization of the LEO population. These scenarios are the removal of the five objects that are commonly present in the Top priority lists of mid and long terms (Case 7), and the removal of the ten SL-16 rocket bodies of the top list at long term (that are also present in all lists of the different periods). Performing these removal strategies is expected to stabilize the future population at any term and in a stable way, in the conditions of this study, knowing no new launches and no future explosions. By stabilization, it is meant here that the population keeps decreasing through the periods of observation, or at least remains stable all over the long term, without any period of increase. For example, the removal of the 33 SL-8 seems less efficient all over the period than the removal scenario of Case 7 because of the behaviour of the population at mid term (slight increase); in the same way, the removal of the 10 SL-16 is less efficient than the removal scenario of Case 7 because of its increasing trend at long term. Even if all the scenarios remain within the standard deviation of the mean baseline, such observation and statement are expressed here because the statistical analysis made on the evolutionary model underlined the convergence of the mean results (concerning the number of objects and occurring collisions) beyond 60 MC runs, while this study has used 100 MC simulations to generate its mean results.

The reasons lying under the observations on the effectiveness of the scenarios have been investigated and are now underlined in the following. Two elements must be considered: the presence of objects implicated in chain collisions (mainly the case of objects present in the common top lists), and the altitude of the objects.

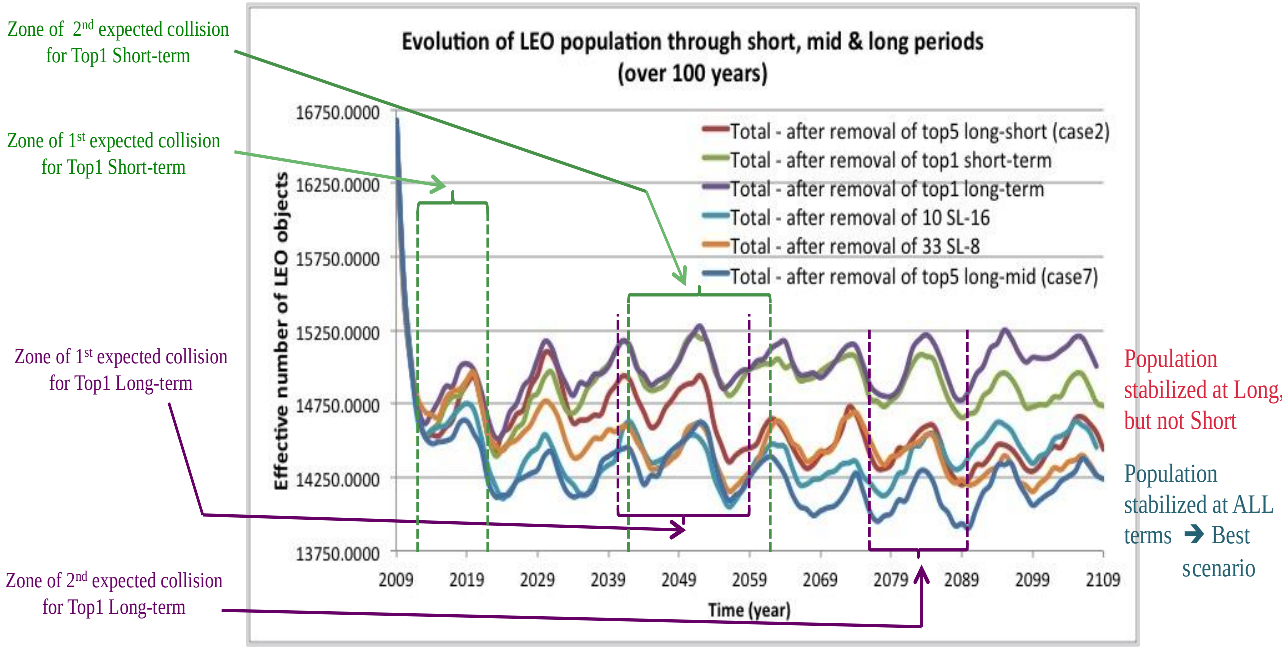


Figure 29. Impacts of removal scenarios on the long-term-future LEO objects population (evolution of the mean effective number of objects on 100 MC runs over 100 years) - under the assumption of no future launch – Analysis of occurring events within the scenarios

By looking at Fig. 31, focusing on the one-object removal scenarios (purple and green curves), that target the Top 1st object in long-term list and the Top 1st object in the short-term list, it is noticeable that their effects are comparable over all the period, and even a bit better for the removal of the short-term target from 2089, whereas the removal of Top 1st object for long term, COSMOS 952, should lead to better results (but a particular care must be given to this point considering the small significance of the difference compared to the Baseline standard deviation); statistically, the scenarios involving COSMOS 952 and Ariane 40 have same impacts, with a better resulting environment in COSMOS-removal case in 51 simulations. After investigation, this observation is not contradictory (in terms of relation between position in the period ranking and the impact of the removal on the same period); the reasons are now presented.

In fact, the main reason may rely on the implication of the above quoted objects in chain collisions over the time. By “chain collisions”, it is meant a natural process in which an initial collision will induce a multiplication of new collisions in the future due to the generation of new fragments over and over again, fragments that will, at their turn, collide with each other. By analyzing more in details the different Monte-Carlo simulations in these two case-scenarios, it has been discovered that the Top 1st object in the long-term list

(COSMOS 952) was expected to collide in five simulations over the hundred that were run, but was at the origin of a chain collision in only one simulation. In the four other simulations, the fragments it generates do not collide anymore. However, in the case of the Top 1st object in the short-term list (Ariane 40), it has been noticed that it may collide in six simulations in the short-term study, and in ten simulations in the long-term study. Among them, it is expected to generate chain collisions in three simulations. Thinking about the definition of a chain collision process, compared to a simple-collision case, the probability to generate more and more fragments in the future becomes higher because a collision is at the origin of at least one or several fragments or in worst case a cloud of objects. Therefore, the number of objects in space increases, raising the risk of a new collision. But in the case of a single collision, the object collides once, and no more consequences will follow. The phenomenon of chain collision is a real threat for the future. Therefore, the fact that the top 1st object at short term is implicated in chain collisions within three simulations instead of only one for the top 1st object at long term may explain why its removal seems more efficient, since the probability that it really induce chain collisions becomes higher than for COSMOS 952, leading to a greater risk-thinking impact on the future population due to modeling evaluation. Furthermore, in all cases, the collision dates are very close, as detailed on Fig. 31, therefore all the debris generated don't have enough time to decrease in altitude and fall down, which reinforces the risk of a perpetuation in the collision process. Concerning the list itself, the 1st position of COSMOS 952 in the long-term ranking, is due to the combination of two characteristic parameters: its high mass (4500 kg) and its high altitude (950 km). According to the NASA Breakup model, its mass enables to generate more fragments in one collision (more than Ariane 40 with its 1760 kg), and the high altitude keeps its fragments in space for a longer time.

This conclusion also underlines the importance of a new criterion for target selection through the recurrence of chain collisions in the Monte-Carlo simulations. This conclusion also underlines the importance of a new criterion for target selection through the recurrence of chain collisions in the Monte-Carlo simulations. The opportunity is taken here to discuss on the appropriate use of the ranking list when determining removal strategies and/or candidates. One could note that the efficiency to perform the removal of targets selected from the different lists at the different periods had been underlined since the results are always better than the Baseline's conditions. However, the results do not totally show that removing the first target of one list is the most appropriate measure to limit the impacts on the environment. Indeed, results from picking out one object hazardously from the initial population and observing the evolution of the environment in the future were not shown in this article. The reason is that, as illustrated through the comparison made between the two Top 1st objects at long and short terms, the strategy consisting in looking only at the results given by the list may not be enough to establish a robust decision. The aim of the ranking list as it was built here is not to prove the efficiency of one particular object's removal, but rather to point out the phenomena lying under a degradation of the environment according to the time we are looking at. And the list must also help to give a first idea of possible targets to be investigated more in details inside the simulations so as to overcome statistical issues. In other words, it should help to eradicate improbable candidates and focus on the most risky ones, as a first sorting. Since the number of objects to consider and simulate is huge, one tool can't be sufficient, therefore the measure consisting in the build of a ranking list and then the check of some scenarios more in details should be thought as a whole process .To conclude this point, the analysis of several ranking lists must be done (and was done in this study) to underline the criteria to be considered according to the observation period or time of action. For example, at long term, more than focusing on one object as an optimal target, it is better to directly think about the number of objects to remove. At the opposite, if the will is to secure the near future, it is possible to see some good impacts with the removal of one good selected object, and this object can be chosen from the ranking list.

Lastly, looking at the case concerning the removal of objects common to different-period top-lists, it appears that these objects increase in the ranking until long term, as it was detailed in the previous corresponding Sections 6 and 7 for short and mid-term studies (Cases 2 and 7). To illustrate this point, several SL-16 rocket bodies and Nadhezda 7 s/c are present in the common top ten lists of short term and long term; and several SL-16 rocket bodies and COSMOS 952 are present in the common top lists of mid term and long term. All these objects increase in position in the ranking at long term because their altitude is high (987 km for Nadhezda 7, 950 km for COSMOS 952, around 900 km for the SL-16 r/b). However, objects present only in one list, such as Ariane 40 r/b (first target at short term), reveal much lower altitudes (787 km for Ariane 40). A higher altitude of the removal targets induces a longer time in space for the fragments generated after collision of these target objects, therefore the presence of these high-altitude objects is perfectly justified in the ranking at the following period. The fact that was underlined previously concerning the best efficiency of the scenario proposing the removal of top 5 objects in mid-long term lists is therefore justified by this last observation, confirming the key role of altitude in the selection of targets for impacts at different terms. This fact also confirms the same efficiency noticed for the scenario concerning the removal of the ten SL-16 r/b since they are also at high altitude and are very heavy objects (9000 kg) with a recurrence in all top lists, whatever the period of observation is.

This comparative analysis between all periods of action helped to reach several conclusions and ideas concerning the role of different criteria for the selection of targets.

First, the ranking position of the targets appears to have the main impact at short term, whereas the number of objects to remove is a best criterion for long-term impacts. This is because the consideration of a short-term period allows thinking about a single-object removal as a possible efficient strategy to stabilize the population.

Then, the optimal efficiency relies on a combination of strategies coming from the different terms, that is considering the period preceding the period of action: short-term targets are the best selection for impacts at mid term; mid-term targets constitute the best selection for impacts at long term. A “pre-period” evaluation seems therefore necessary to increase the performance of a removal process. Moreover, to reach a total efficiency at all terms in one time, the best scenario seems to be the process that implies targets present in the ranking of all lists from short term to long term, with an increasing position over the all period, which gives a key role to the factors of chain-collision event and altitude in the selection of the targets. The consideration of chain collisions mainly concerns the case of a single-object removal, in order to compensate the low efficiency of a one-object removal; as for the altitude, it is rather a determinant criterion for a several-object removal scenario in terms of long presence in orbit of the generated fragments.

9. Conclusion

Summary of the whole Doctoral research

Through this whole study, main directions have been established in order to better understand the phenomena lying under the evolution of the near-Earth population in different targeted futures. To do so, two tools were developed and used. One is NEODEEM, the space environment evolutionary model that enabled to simulate the future population of objects at a given epoch. The other one is the debris' origin tracking program that was specially created for the purpose of this research by enabling a back-in-time detection of the initial objects expected to generate the most fragments in the targeted future. These tools are complementary and, used together, form a process that facilitates the verification of both the simulation and the identification steps. The study is also strengthened since the verification aims to compensate the randomness of the results originally obtained through a Monte-Carlo method.

With such a process, studies of various natures can be conducted. Specially, two kinds of studies were made here, presenting two different objectives.

The first one consisted in securing a future lunar mission whose manned spacecraft is planed to be launched in 2045. Therefore, a securing process was thought about, and the removal of potential objects colliding with the spacecraft is scheduled well before the launch, in 2020. The process tried thus here to define the population in 2045, to calculate the collision risks on the Earth-Moon trajectory at this date, and to find out the objects of year 2020 that may be responsible of the generation of the detected colliding objects. The purpose is in this context to evaluate the phenomena and their origins (parent objects) in a restricted area corresponding to the lunar trajectory and at a particular time in the future. Finally, the list of the objects prior to be removed in 2020 could be established, giving thus the time to think about a removal process efficient to avoid future collisions at the time of the mission.

The second study is of different nature, with the care to look for more general results by gathering three sub-studies. It mainly tries to raise the question of the importance of selection for targets or removal scenarios in adequacy with the period of action or the future that is considered. In this study, the efforts are made on the understanding of the major mechanisms at the origin of the population growth and on the difference of behavior at different terms, leading to the need for a different criterion that orientate the selection of a remediation process. A particular attention is given to the definition of the most adequate removal scenario considering both the selected period and the motivation of the entity willing to perform the remediation process. It resulted that the number of the objects to be removed had a huge importance at long term, but nearly no consequences at short term. At the opposite, the ranking of the targets is a key factor for short-term effects, but progressively looses importance while going to long-term evaluation. Finally, for a positive impact at all terms (from short to long terms, through mid term), it appears that the scenario combining the removal strategies of several objects from mid and long term ranking-lists is the most efficient since it leads to a continuous decrease of the population all over the period. Therefore, the top-priority lists of targets for each period could be established, but even more precious result lies on the ability to identify the most efficient combination of scenarios or selection criteria in order to produce concrete impacts on the population targeted at a desired future. More than imposing a new list of priority objects, this study rather looked for a reliable way to define criteria in the selection process. With this approach, it demonstrated the need to adapt the analysis to time, and also helped to point out weaknesses of evaluative methods, like the Monte-Carlo approach that brings randomness within the results. A complementary analysis (looking at each simulation) was therefore adopted to compensate this point with the tools at disposal. Moreover, still with the care to bring more precision to current methods, it should be a promising approach to combine an index based on the collision probability and mass product with an index based on this study's method (the expected number of generated fragments). Indeed, the consideration of both criteria may help to compensate the weaknesses present in each method. For example, considering only the collision probability cross mass product don't enable the prediction of the population evolution at different futures nor the effects after the removal; but this index may help to compensate the dependency from Monte-Carlo randomness that this Doctoral research's method suffers.

The whole research helped to raise conclusions concerning the adequacy of removal processes for a given period of time, a particular area of action or a defined space mission. A wide range of criteria, selection methods or scenarios can now be investigated and proposed so as to fit as well as possible the requirements or the goal each entity is willing to reach, always in the objective of improving the future space environment before the situation becomes uncontrollable.

Perspectives

From the list of targets obtained in the lunar mission study, a more precise idea concerning the area of the potential candidates and their structure characteristics (mass and size) has been gotten. With these parameters, the next step consists in the elaboration of a concrete removal scenario depending on the currently feasible technology at disposal. Astroscale PTE. LTD. is now developing an ADR mechanism gathering a mother-boy concept craft. The mother, as the main body, is used to reach the target's orbit and a neighbor position. Then, after the analysis of the target's tumbling and behavior, the boy is launched from the mother to the target and attaches this one thanks to an adhesive material fixed on one side. This allows the boy to conduct the descent of the target from its orbit by using its own propulsion engines. This complex scenario is still under development in the company.

Concerning the study about the effects of targets' selection, other removal scenarios are now under consideration, still analyzing the effects from a combination of various strategies. The aim is to find out a process enabling to propose an efficient solution at all terms, but the way to adapt the strategies to multiple conditions is long and complex. Taking as a strong support the observations, data, results and conclusions raised until now thanks to this study, the next step is to go further and to investigate new criteria. For example, instead of ranking the targets according to the Monte-Carlo mean number of expected fragments, the recurrence of the parent objects (meaning its frequency of appearance in the simulations) should be considered, mainly to give more importance to the phenomenon of chain collisions that was underlined in Sections 5 and 8.

Finally, the environment evolutionary model is kept being improved, with the care to update it regularly as new observations or questions are raised. Now, the program has been updated by taking into account the potential changes in solar and geomagnetic activities, together with the definition of the collision model that is adopted. As future work, a study concerning the effects of the launch model on the precision of the evolutionary model will be conducted. The results are expected to allow a better modeling of future launches in order to increase the confidence level of the model.

In this way, the will and the necessity to improve rapidly the situation of the space environment invite us to think more carefully about the means at our disposal to impact the future, and bring the motivation to develop stronger and more precise tools to give clear orientations for future studies.

APPENDICES

APPENDIX A: Identifying the origin of collision fragments – example case of the 90th Monte-Carlo simulation

As results of the 90th simulation, the following list of collision fragments generated after 2020 has been obtained.

Item number	Generation year	Type (coll. frg)	Mass (kg)	Size (m)	a (km)	e	i	Status
2.3877000e+04	2.0230000e+03	5.0000000e+00	9.8160000e-02	1.1275800e-01	7.3070100e+03	1.2120000e-03	9.0927100e+00	3.0000000e+00
3.1991000e+04	2.0410000e+03	5.0000000e+00	3.5522000e-02	1.0951800e-01	7.7744300e+03	6.5982000e-02	1.0526600e+01	3.0000000e+00
2.8017000e+04	2.0250000e+03	5.0000000e+00	5.2891300e+00	5.6911200e-01	7.3611700e+03	4.3500000e-04	9.1369200e+00	3.0000000e+00
3.0143000e+04	2.0380000e+03	5.0000000e+00	1.3183400e-01	1.0152300e-01	7.3932700e+03	1.9274000e-02	1.0869600e+01	3.0000000e+00
2.4456000e+04	2.0230000e+03	5.0000000e+00	1.0114000e+00	1.8490200e-01	7.3606900e+03	6.2800000e-04	9.0922900e+00	3.0000000e+00
2.9363000e+04	2.0330000e+03	5.0000000e+00	1.2796700e-01	1.7586600e-01	7.3409500e+03	3.0024000e-02	1.0809200e+01	3.0000000e+00
2.6469000e+04	2.0250000e+03	5.0000000e+00	3.5075800e-01	1.0895700e-01	7.3486600e+03	1.9280000e-03	9.0920100e+00	3.0000000e+00
2.7544000e+04	2.0250000e+03	5.0000000e+00	3.3370500e+00	2.0270600e-01	7.3391600e+03	6.5100000e-04	9.1152300e+00	3.0000000e+00
2.6386000e+04	2.0250000e+03	5.0000000e+00	1.3135100e-01	1.0579400e-01	7.2939600e+03	3.6900000e-04	9.0334200e+00	3.0000000e+00
3.2071000e+04	2.0410000e+03	5.0000000e+00	2.8866700e-01	1.2192600e-01	7.6033600e+03	3.3077000e-02	1.0642900e+01	3.0000000e+00
3.0598000e+04	2.0380000e+03	5.0000000e+00	2.2289700e-01	1.2423200e-01	7.2265700e+03	2.2190000e-03	1.0856700e+01	3.0000000e+00
2.5107000e+04	2.0250000e+03	5.0000000e+00	7.8446100e-01	1.0178200e-01	7.0329300e+03	6.5370000e-03	1.0688100e+01	3.0000000e+00
2.8009000e+04	2.0250000e+03	5.0000000e+00	1.0106500e+01	5.4452900e-01	7.3671300e+03	8.8700000e-04	9.0737600e+00	3.0000000e+00
2.9585000e+04	2.0330000e+03	5.0000000e+00	4.4985100e-01	3.0669300e-01	7.1841100e+03	7.6590000e-03	1.0804600e+01	3.0000000e+00
2.3677000e+04	2.0230000e+03	5.0000000e+00	7.3806000e-02	1.0151200e-01	7.1473700e+03	1.2561000e-02	9.1082900e+00	3.0000000e+00
2.9279000e+04	2.0330000e+03	5.0000000e+00	3.8160400e-01	1.5582900e-01	7.1998800e+03	1.3010000e-02	1.0802700e+01	3.0000000e+00
2.9317000e+04	2.0330000e+03	5.0000000e+00	8.0891400e+00	1.6448400e-01	7.1472800e+03	1.0390000e-03	1.0804900e+01	3.0000000e+00
2.9040000e+04	2.0330000e+03	5.0000000e+00	2.1364700e-01	1.2152800e-01	7.0792500e+03	9.1900000e-04	1.0802800e+01	3.0000000e+00
3.2420000e+04	2.0410000e+03	5.0000000e+00	1.8777100e-01	5.3742800e-01	8.2611600e+03	5.3467000e-02	1.0666600e+01	3.0000000e+00
2.3996000e+04	2.0230000e+03	5.0000000e+00	6.0564900e-01	1.2128100e-01	7.3661900e+03	2.0200000e-04	9.0942500e+00	3.0000000e+00
2.7356000e+04	2.0250000e+03	5.0000000e+00	1.0945200e+00	1.7140200e-01	7.5102100e+03	2.0834000e-02	9.1232700e+00	3.0000000e+00
3.2244000e+04	2.0410000e+03	5.0000000e+00	9.4841000e-02	1.7136500e-01	7.3733600e+03	4.5448000e-02	1.0635100e+01	3.0000000e+00
2.7629000e+04	2.0250000e+03	5.0000000e+00	2.1500300e+00	2.2255700e-01	7.3477000e+03	9.8900000e-04	9.1067400e+00	3.0000000e+00
2.4820000e+04	2.0230000e+03	5.0000000e+00	6.2681700e-01	5.3689100e-01	7.5359500e+03	2.5317000e-02	9.0915100e+00	3.0000000e+00
2.5673000e+04	2.0250000e+03	5.0000000e+00	4.6073500e-01	1.5059100e-01	7.0325100e+03	2.1590000e-03	1.0688500e+01	3.0000000e+00
2.7654000e+04	2.0250000e+03	5.0000000e+00	3.7500900e-01	2.2922300e-01	7.3684800e+03	1.5000000e-03	9.0708800e+00	3.0000000e+00
3.2147000e+04	2.0410000e+03	5.0000000e+00	4.7374800e-01	1.3762300e-01	7.4957800e+03	4.7794000e-02	1.0639400e+01	3.0000000e+00
3.1591000e+04	2.0380000e+03	5.0000000e+00	3.3775900e-01	5.6044600e-01	7.7857500e+03	7.0059000e-02	1.0808800e+01	3.0000000e+00
3.0625000e+04	2.0380000e+03	5.0000000e+00	2.3406000e-01	1.2609000e-01	7.2323600e+03	1.2100000e-04	1.0846300e+01	3.0000000e+00
2.6960000e+04	2.0250000e+03	5.0000000e+00	1.9208100e-01	1.3410300e-01	7.3840800e+03	4.2260000e-03	9.0863300e+00	3.0000000e+00
2.6456000e+04	2.0250000e+03	5.0000000e+00	2.9934500e-01	1.0847900e-01	7.3289700e+03	5.9000000e-04	9.0941800e+00	3.0000000e+00
2.7352000e+04	2.0250000e+03	5.0000000e+00	1.4336200e-01	1.7077400e-01	7.5827300e+03	3.0352000e-02	8.9623000e+00	3.0000000e+00
2.7323000e+04	2.0250000e+03	5.0000000e+00	1.0010200e-01	1.6701500e-01	7.7761700e+03	5.5882000e-02	9.1565400e+00	3.0000000e+00
2.8028000e+04	2.0250000e+03	5.0000000e+00	2.9125400e+00	6.1233100e-01	7.5179800e+03	2.2440000e-02	9.0983700e+00	3.0000000e+00
2.6650000e+04	2.0250000e+03	5.0000000e+00	1.5799000e-02	1.1648400e-01	8.1886100e+03	1.1503700e-01	9.3426300e+00	3.0000000e+00
2.3807000e+04	2.0230000e+03	5.0000000e+00	4.9800100e-01	1.0842200e-01	7.3696600e+03	2.0800000e-03	9.0913600e+00	3.0000000e+00
2.6803000e+04	2.0250000e+03	5.0000000e+00	1.0412200e-01	1.2432400e-01	7.4579100e+03	1.5209000e-02	9.1225000e+00	3.0000000e+00
2.4625000e+04	2.0230000e+03	5.0000000e+00	1.5542300e-01	2.4604400e-01	7.1981000e+03	1.4530000e-03	9.0918400e+00	3.0000000e+00
2.7347000e+04	2.0250000e+03	5.0000000e+00	9.2268300e-01	1.7015200e-01	7.3470000e+03	3.6300000e-04	9.0982300e+00	3.0000000e+00
2.3705000e+04	2.0230000e+03	5.0000000e+00	8.7478000e-02	1.0288500e-01	7.3356400e+03	1.6110000e-03	9.0936600e+00	3.0000000e+00
3.0621000e+04	2.0380000e+03	5.0000000e+00	9.0442000e-02	1.2583000e-01	7.2596500e+03	1.7357000e-02	1.0869700e+01	3.0000000e+00
2.7110000e+04	2.0250000e+03	5.0000000e+00	1.1123200e-01	1.4556000e-01	7.1490400e+03	1.1499000e-02	9.0059500e+00	3.0000000e+00
2.7246000e+04	2.0250000e+03	5.0000000e+00	1.7283800e+00	1.5836700e-01	7.3368400e+03	8.1400000e-04	9.0925300e+00	3.0000000e+00
3.0675000e+04	2.0380000e+03	5.0000000e+00	8.3162000e-01	1.2961900e-01	7.2455100e+03	1.9490000e-03	1.0856500e+01	3.0000000e+00
2.6858000e+04	2.0250000e+03	5.0000000e+00	1.2489600e-01	1.2749700e-01	7.3467200e+03	1.1780000e-03	9.1588300e+00	3.0000000e+00
2.6040000e+04	2.0250000e+03	5.0000000e+00	1.1065100e+01	2.7714400e-01	7.1415600e+03	6.4370000e-03	1.0690200e+01	3.0000000e+00

Collision fragments that may collide with the lunar spacecraft in 2045

As detailed in the third section, the 90th simulation case predicts 46 collision fragments potentially dangerous that are generated after 2020. To determine the original objects, the collisions that occur during the simulation are investigated. In this case, 16 collisions occur, but after proceeding to year identification with the previous file, only 7 collisions are detected as origin for the above presented fragments. The file of their 14 corresponding colliding objects is also presented hereafter.

Collision year	Catas/non catas	Coll_alt (km)	nb generated frg	Item1 number	Item1 type	Item1 status	Item1 mass (kg)	Item1 size (m)	Item2 number	Item2 type	Item2 status
2.0220000e+03	0.0000000e+00	7.6481110e+02	2.0000000e+00	1.2870000e+03	2.0000000e+00	2.0000000e+00	1.4200000e+03	4.0600000e+00	1.1045000e+04	4.0000000e+00	2.0000000e+00
2.0220000e+03	1.0000000e+00	9.8654243e+02	6.0000000e+00	2.1910000e+03	1.0000000e+00	2.0000000e+00	8.0300000e+02	2.4400000e+00	2.4990000e+03	1.0000000e+00	2.0000000e+00
2.0240000e+03	1.0000000e+00	7.4113030e+02	4.0000000e+00	9.7300000e+02	1.0000000e+00	2.0000000e+00	6.6100000e+02	5.3200000e+00	1.4170000e+03	2.0000000e+00	2.0000000e+00
2.0240000e+03	1.0000000e+00	9.7209094e+02	1.8000000e+01	1.3020000e+03	2.0000000e+00	2.0000000e+00	1.4200000e+03	4.0600000e+00	1.3430000e+03	2.0000000e+00	2.0000000e+00
2.0320000e+03	1.0000000e+00	7.6408455e+02	5.0000000e+00	1.2074000e+04	4.0000000e+00	2.0000000e+00	1.0800000e+00	1.8900000e-01	2.8242000e+04	2.0000000e+00	2.0000000e+00
2.0370000e+03	1.0000000e+00	8.6132732e+02	6.0000000e+00	1.1330000e+03	1.0000000e+00	2.0000000e+00	2.2500000e+03	4.5900000e+00	2.7789000e+04	5.0000000e+00	3.0000000e+00
2.0400000e+03	1.0000000e+00	8.0367908e+02	5.0000000e+00	7.5600000e+02	4.0000000e+00	2.0000000e+00	5.5300000e+02	8.6000000e+00	1.5822000e+04	4.0000000e+00	2.0000000e+00

List of the collisions that generate the fragments colliding with the spacecraft in 2045

Item number	Generation year	Type	Status	a (km)	Lifetime	Size (m)	Area (m^2)	Mass (kg)	Coll year
1.2870000e+03	2.0200000e+03	2.0000000e+00	2.0000000e+00	7.1424216e+03	1.0110000e+03	4.0600000e+00	1.2916300e+01	1.4200000e+03	2.0220000e+03
1.1045000e+04	2.0200000e+03	4.0000000e+00	2.0000000e+00	7.1522149e+03	1.0110000e+03	2.1100000e-01	3.5000000e-02	1.3900000e+00	2.0220000e+03
2.1910000e+03	2.0200000e+03	1.0000000e+00	2.0000000e+00	7.3648080e+03	1.0110000e+03	2.4400000e+00	4.6739000e+00	8.0300000e+02	2.0220000e+03
2.4990000e+03	2.0200000e+03	1.0000000e+00	2.0000000e+00	7.3649767e+03	1.0110000e+03	1.8000000e+00	2.5534000e+00	8.1800000e+02	2.0220000e+03
9.7300000e+02	2.0200000e+03	1.0000000e+00	2.0000000e+00	7.1296328e+03	1.0110000e+03	5.3200000e+00	2.2250600e+01	6.6100000e+02	2.0240000e+03
1.4170000e+03	2.0200000e+03	2.0000000e+00	2.0000000e+00	7.0873937e+03	1.0110000e+03	3.9500000e+00	1.2266200e+01	8.9200000e+02	2.0240000e+03
1.3020000e+03	2.0200000e+03	2.0000000e+00	2.0000000e+00	7.3537042e+03	1.0110000e+03	4.0600000e+00	1.2916300e+01	1.4200000e+03	2.0240000e+03
1.3430000e+03	2.0200000e+03	2.0000000e+00	2.0000000e+00	7.3484521e+03	1.0110000e+03	4.0600000e+00	1.2916300e+01	1.4200000e+03	2.0240000e+03
1.2074000e+04	2.0200000e+03	4.0000000e+00	2.0000000e+00	7.1571670e+03	1.0110000e+03	1.8900000e-01	2.8000000e-02	1.0800000e+00	2.0320000e+03
1.1330000e+03	2.0200000e+03	1.0000000e+00	2.0000000e+00	7.2519349e+03	1.0110000e+03	4.5900000e+00	1.6540900e+01	2.2500000e+03	2.0370000e+03
7.5600000e+02	2.0200000e+03	4.0000000e+00	2.0000000e+00	7.5277071e+03	1.0110000e+03	8.6000000e+00	4.1647800e+01	5.5300000e+02	2.0400000e+03
1.5822000e+04	2.0200000e+03	4.0000000e+00	2.0000000e+00	7.2069926e+03	1.0110000e+03	1.3900000e-01	1.5100000e-02	5.3900000e-01	2.0400000e+03
2.8242000e+04	2.0270000e+03	2.0000000e+00	2.0000000e+00	7.1527943e+03	1.0000000e+00	4.4900000e+00	1.5798200e+01	1.1900000e+03	2.0320000e+03
2.7789000e+04	2.0250000e+03	5.0000000e+00	3.0000000e+00	7.3102279e+03	2.0100000e+02	2.8049900e-01	4.3559000e-02	2.3379650e+00	2.0370000e+03

List of the objects at the origin of the above seven collisions

In the above file, among the fourteen objects at the origin of the identified collisions, one is the result of another collision due to other original objects. More precisely, this object is the last one in the file: its generation year is 2025 (circled in red) and its type is 5, which indicates it is a collision fragment. Then, in the same file, four objects induce two collisions in 2024 (underlined in red square), thus one of these two collisions generates the object of year 2045 (in fact, the collision altitude is also known, and is used to determine precisely which collision is the generating one). In this way, since the four objects at the origin of the year-2024 collisions are already present in the file, it means they are part of the objects to be removed, and their removal will automatically delete the object generated in 2045. Without this red-circled 2025-generated object, the resulting year-2037 collision (circled in blue) cannot occur, and the second object implied in this collision does not represent a threat anymore, and can be ignored. In this way, the final list of collisions' original objects is limited to 12 objects (the above list without the two blue-circled objects).

APPENDIX B: Complementary analysis through a brief reflection on the stability of the ranking criterion among the simulations (complement for Parts 4 to 8 concerning target-selection studies)

After the presentation of the general results gathered in this study, this last section must be considered as a complementary discussion on the robustness of the Monte-Carlo method and the validity of the mean results on which the study relies. Mainly, the concern is raised about the appropriateness of the ranking lists in terms of reliability as well as dependence on the MC runs. This reflection might not have major impact on theoretical discussion concerning the nature of removal candidates, but may appear as a necessity if a more concrete approach is envisaged (e.g. taking a decision to validate an ongoing or to-be-done removal scenario).

Respecting the original purpose of this study, that is to underline the major role of the selection criterion as a measure to build up an efficient list of removal targets, only first elements are presented here, as an introductive reflection. To do so, the evolution of the Top10 objects among the MC simulations has been investigated. Since the whole process lies on 100 runs, the investigation is long; therefore the analysis has been done by following, over all the simulations, three objects of the Top10 list at short term (20 years) only. The observation of their movement in the ranking inside each simulation is expected to give information on the stability concerning the composition of the list and the validity of the underlying criterion. The objects chosen to conduct the analysis are: the first target Ariane 40 R/B; an explosion fragment classified at 2^{nd} position (Fragment n°707); and the explosion fragment n°701 classified at the 10^{th} ranking position in the mean Top 10 list at short term (presented in Section 4). The results are detailed in the following Table.

Object	Ranking in the Mean Top10 list	Number of MC runs where the object is present in the Top 10	Corresponding ranking position in the Top10-list of each run where the object is present
Ariane 40 (R/B)	1^{st}	13	3^{rd} ;: 1^{st} ; 2^{nd} ; 1^{st} ; 1^{st} ; 4^{th} ; 2^{nd} ; 3^{rd} ; 1^{st} ; 1^{st} ; 2^{nd} ; 3^{rd} ; 1^{st}
Fragment n°707	2^{nd}	9	2^{nd} ; 1^{st} ; 1^{st} ; 3^{rd} ; 2^{nd} ; 1^{st} ; 2^{nd} ; 2^{nd} ; 2^{nd}
Fragment n° 701	10^{th}	13	6^{th} ; 10^{th} ; 10^{th} ; 9^{th} ; 8^{th} ; 10^{th} ; 7^{th} ; 9^{th} ; 10^{th} ; 10^{th} ; 10^{th} ; 9^{th} ; 10^{th}

Movements in the rankings of three objects chosen in the mean Top 10 list of targets at short term – Evaluation of presence in the Top 10 ranking at each run and position in the runs where they appear in the list

As it can be observed from the Table, the first object Ariane 40, as determined by the mean number of fragments it may generate over the 100 MC runs, enters inside the first ten risky objects' list in 13 simulations over one hundred. And in these lists, it is present between the first and the fourth positions, so always at the head of the classification. Fragment n°707, second object in the mean list, is present in the Top 10 ranking of 9 simulations over one hundred, within the first and the third positions when present. Its recurrence among the simulations is lower than Ariane 40, but this result is compensated by the stability of its position in a list when it appears. As for the last object in the mean Top10 list (Fragment n°701), it is also detected as a Top10 object in 13 simulations over one hundred.

Two observations must therefore be underlined. First, the objects present in the Top10 list after looking at the mean number of fragments they may generate are not present in the Top 10 lists of all the simulations, but only in 13% maximum of the simulations. This means that, in other runs, they are present at much lower positions, so their risk is not as high as it is expressed when looking only at the mean. However, the number of fragments they generate is sufficiently high to make them enter the final composition of major risky objects. And this is linked to the second observation that concerns the position in the ranking when the object is present in a list. Indeed, the ranking can be considered as stable since the movements are not huge between the lists, once again when the object is detected.

This first analysis has the interest to raise concerns about the recurrence of the collision phenomena within the simulations, but should be extended to other periods of observation (mid and long terms), as well as the enlarged Top priority list of targets.

APPENDIX C: Main improvements and corrections made for the environment evolutionary model NEODEEM (programming and description)

About the modifications made in the program NEODEEM

The new version is called **NEODEEM_K++M4flux_gmindex_debgen**
It was initial modified on 2016/08/04 by Melissa Zemoura.
The last modification dates on 2016/10/26 by Melissa Zemoura.

Purpose of the modifications:

This version was created to enlarge the range of possible studies with the environment model while propagating the future space population by including the possibility now to **evaluate the effects of solar and geomagnetic activities on the evolution of future NEO population**, together with the **different configurations of collision events**. Until now, NEODEEM was run only with a constant solar flux, a constant geomagnetic index and only one type of collision geometry configuration. It is now **possible to use various solar flux files and geomagnetic index files** to make these criteria **change with time, and to choose between 3 kinds of collision geometries.**

The jointed research led with JAXA for IADC Working group, internal task IT32.1, also motivated these changes. The aim was to investigate the consequences of considering many solar and geomagnetic predictions instead of the best prediction available as it was commonly done until now. Indeed, the prediction of solar and geomagnetic activities is considered as one of the major sources of uncertainties in evolutionary models, and needs to be reassessed. Furthermore, the different possible geometries for collision configuration are also major changes in the way to think about fragments' generation through the NASA breakup model. In this case, the three possible scenarios consist in respectively: a standard configuration (only body-to-body including appendages for spacecrafts); a body-to-body configuration that does not take into account appendages into collision surface of spacecrafts; and a partial collision modeling allowing three geometries at different probability of occurrence (body-to-body, body-to-appendage, appendage-to-appendage geometries).

New created programing files:

- *GeomagIndex.h*
- *GeomagIndex.cpp*

→ Allow reading of geomagnetic index files (functions "readkp" and "readfile" and class "GeomagIndex")

Changes in existing programing files:

- *readfile.h*
  → added structure for geomagnetic index and readfile class
- *readfile.cpp*
  → added structure and class for GeomagIndex
- *Jacchia-Roberts.h*
  → function *JacchiaRoberts(**double kp**, double…)* l. 25 and 31
  → added ***double kp*** as private l.39
- *Jacchia-Roberts.cpp*
  → *const double kp* in comment
  → added same arguments ***double _kp*** to functions *JacchiaRobertsAtmosphere::JacchiaRoberts*
- *Collision.h*
  → added a call to ***std*** library to allow random generation of probability
  → added function *detect_ratio(…, **bool ratio_area, bool ratio_mass**),* where:
  Standard scenario: ratio_area = false & ratio_mass = false
  B2B_noapp scenario: ratio_area = true & ratio_mass = false
  Partial_coll scenario: ratio_area = true & ratio_mass = true
  → added function *spheres_ratio(…, **double Pfactor**)* that is called by function *detect_ratio*

- *Collision.cpp*
  → defined function *detect_ratio(…, **bool ratio_area, bool ratio_mass**)*
  → defined function *spheres_ratio(…, **double Pfactor**)*
  → added call to ***uniform_int_distribution*** and ***normal_distribution*** of *std* library, together with call to ***generator*** functions
- *PMD.h*
  → added functions ***operate_sa_gm*** & ***evaluate_sa_gm*** to include the update of gmindex value in atmospheric drag model (added for both SmallSatPMD and PMD classes)
- *PMD.cpp*
  → added functions ***operate_sa_gm*** & ***evaluate_sa_gm*** to be called in NEODEEM.cpp for PMD and Small satellite PMD parts (gmindex update)
  → inside these two functions, corrected previous version's miss in the call of PMD: now, only satellites without natural reentry are concerned by PMD operation
- *Removal.h*
  → modified function ***cumExpFrg*** to include the update of gmindex value in atmospheric drag model (one additional input in argument)
- *Removal.cpp*
  → modified function ***rm.cumExpFrg*** to be called in NEODEEM.cpp for the **Removal mode** named **cumExpFrg** part (gmindex update)
  → inside these two functions, corrected previous version's miss in the call of PMD: now, only satellites without natural reentry are concerned by PMD operation
- *NEODEEM.h*
  → added *include "GeomagIndex.h"*
  → defined the 5 possible modes for solar flux and geomagnetic index, known as: Low, Medium, High, Random and User_def
  → defined the 3 possible modes for collision geometries: Standard, B2B_noapp (excluding appendages) and Partial_coll.
- *NEODEEM.cpp* *Start::Future* part
  → added Geomagnetic index related class and structure
  → added reading functions *flux.readfile* & *gmindex.readfile* & *gmindex.readkp* according to the flux and index selected modes
  → added *body.planet.set_kp* to update the geomagnetic index at each year and month
  → added a "switch case" for the call to collision detection function according to the collision scenario defined in *setup.ini* file (function *detect_ratio*)
  → added a call to gmindex in PMD part to update the geomagnetic index value
  → added a call to gmindex in Removal part to update the geomagnetic index value (only for **cumExpFrg removal mode** through a modification of *rm.cumExpFrg()* function)
- *NEODEEM.cpp* *init* part
  → added the definitions of all modes for solar flux and geomagnetic index (precised in *setup.ini* file)
  → added the definitions of all modes for collision geometries (precised in *setup.ini* file)
- *Planet.h*
  → added *set_kp* function and *kp_gmindex*
- *Planet.cpp*
  → added function *PlanetaryEqns::set_kp* to update the index
  → added call to *JacchiaRoberts(kp_gmindex,…)* in *atm_drag* function
- *Utilities.h*
  → added the definition of the ratios on area and mass for LEO and LEO-crossing objects as given by IADC
- *Setup.ini* *[NEODEEM]* part
  → added FluxMode = XXX & GeomagMode = XXX
  → added CollisionMode = XXX

<u>Use of the program:</u>

In *Setup.ini*, the user can define the mode of solar flux and geomagnetic activity (respectively designated in the file by FluxMode and GeomagMode) while replacing XXX either by:

- Low (low solar activity)
- Medium (medium solar activity)

- High (high solar activity)
- Random (random solar activity)
- User_def (scenario defined by the user, constant or any values chosen by the user)

For the Random scenario, a number of files equal to the number of Monte-Carlo simulations to be run must be provided, and the random file is chosen randomly according to the MC number.

It is also necessary to provide solar flux and geomagnetic files, named and written as follows:

- For solar flux:
  → "solar_flux_f107-XXX.dat", where XXX is low, medium, high, random-MC or nothing
  → in the file, data are Year, Month, solar flux
- For geomagnetic index:
  → "geomag_index-XXX.dat", where XXX is low, medium, high, random_MC or nothing
  → in the file, data are Year, Month, kp_index

Lastly, it must be precised that NEODEEM uses the kp index for geomagnetic activity.When only the Ap index is known, a mathematical relation has been determined by Melissa to transform Ap to kp. This relation is a polynomial equation of order 6. Then, a Matlab function called true_kp.m has been created to write the values of kp that corresponds to existing Ap value of the conversion table (can be found on http://www.ngdc.noaa.gov/stp/GEOMAG/kp_ap.html, and is given in details in the following part of this appendix).

Furthermore, the mode of collision (designated in the file by CollisionMode) must also be defined while replacing XXX either by:

- Standard
- B2B_noapp
- Partial_coll

An example of use is provided through the "setup-example.ini" file at the end of this appendix.

Information for the user concerning new input files

Files that need specific attention:

To use the new version of NEODEEM at its upmost level, i.e. by taking the liberty to include variations in the solar and/or the geomagnetic activities, it is necessary to add two text files into the executable environment.

Of course, it is also possible to use this version with constant solar and geomagnetic activities, thus the corresponding parameters just have to be the same inside the files.

The purpose is here to explain the use of the files for changing solar and geomagnetic activities; therefore, the following must be carefully red, mainly concerning the format of the files in order to avoid errors in the reading of the files by the program.

File gathering the solar activity related parameters:

This file is called by the *readfile* function dedicated to solar activity in NEODEEM.cpp program. **It must be named** "solar_flux_f107-A.dat", where A is low, medium, high, random-X (X corresponds to the MC number to generate the random case) or no precision (user's file).

Then, concerning the format, this file is a **3-column** file; the number of rows is let to the user's liberty since the rows corresponds to year and month of the flux. The data are presented as follows:

1st column = **Year**

2nd column = **Month** (from 1 to 12)

3rd column = **Flux** (expressed in 10^4 Jy)

Therefore, there must be 12 rows by year, except for the very first year (free).
Year is expressed in general numbers; Month is expressed in general number from 1 to 12; and flux is in the appropriated unit.
As for the format, the file **must be written** under **Unicode UTF-8 (CRLF)** to be readable by the *readfile* function of NEODEEM.
Moreover, the **space between the columns must be** a space coded as **0x0020 in Unicode**.

File gathering the geomagnetic activity related parameters:

This file is called by the *readfile* function dedicated to geomagnetic index in NEODEEM.cpp program. **It must be named** "geomag_index-A.dat", where A is low, medium, high, random_XXX (XXX corresponds to the MC number to generate the random case; contrary to the solar flux file, it must be a three-digit number, e.g. 001 for first MC, 051 for fifty-first MC…) or no precision (user's file).

Then, concerning the format, this file is a **3-column** file; the number of rows is let to the user's liberty since the rows corresponds to year and month of the flux. The data are presented as follows:

1st column = **Year**

2nd column = **Month** (from 1 to 12)

3rd column = **Geomagnetic index kp** (expressed within range of values from 0 to 9)

Therefore, there must be 12 rows by year, except for the very first year (free).
Year is expressed in general numbers; Month is expressed in general number from 1 to 12; and geomagnetic index must be the kp index in the [0 ; 9] range of values. A more precise definition is provided here: http://www.ngdc.noaa.gov/stp/GEOMAG/kp_ap.html.
When only the Ap index is known, a mathematical relation has been determined by Melissa to transform Ap to kp. This relation is a polynomial equation of order 6. Then, a Matlab function called true_kp.m has been created to write the values of kp that corresponds to existing Ap value of the conversion table.
The relation is like below:

Interpolated relation between Ap and kp:
--> Deduced equation for kp = f(Ap): **polynomial equation of order 6**

y = 2E-07 x^6 - 2E-05 x^5 + 0.0008 x^4 -0.0144 x^3 + 0.1027 x^2 + 0.0235 x

with R-squared regression coefficient R^2 = 0.9993.

This interpolation was done by using the data of the Geomagnetic indices conversion table:
http://www.ngdc.noaa.gov/stp/GEOMAG/kp_ap.html

As for the format, it is the same as for the solar flux file. The file **must be written** under **Unicode UTF-8 (CRLF)** to be readable by the *readfile* function of NEODEEM.
Moreover, the **space between the columns must be** a space coded as **0x0020 in Unicode**.

Example of *setup.ini* file

```
[NEODEEM]
RunMode = future
launch = true
special_launch = false
explosion = false
collision = true
collision_avoid = false
lcMin_m = 0.1
originalBase = false
FluxMode = XXX
GeomagMode = XXX
CollisionMode = XXX

startMC = 1
endMC = 1

[Future]
isBase10 = false
baselineFileName = iadc_baseline_20130101_it32_1.dat
baseline10FileName = iadc_baseline_20130101_it32_1.dat
insertionFileName = iadc_launchlist_2005-2013_it32_1.dat
breakupFileName = explosionLEO_2002-2009.dat
isPMD = true
PMD_lifetime_year = 8
Megacon_lifetime_year = 5
PMD_rate = 0.6
PMD_MassLimit_kg = 50.0
isPMD_SmallSat = true
PMD_SmallSat_lifetime_year = 2
#Removal=-------------------------------------------------
isRemoval = false
isRmMassLimit = false
rm_mass_min_kg = 500
rm_mass_max_kg = 4000
num_rm = 5
removalMode = three_region
#rm_cum_year = 1

rm_h_min1_km = 900.0
rm_h_max1_km = 1000.0
rm_inc_min1_deg = 82.0
rm_inc_max1_deg = 84.0

rm_h_min2_km = 700.0
rm_h_max2_km = 1000.0
rm_inc_min2_deg = 98.0
rm_inc_max2_deg = 100.0

rm_h_min3_km = 700.0
rm_h_max3_km = 1000.0
rm_inc_min3_deg = 62.0
rm_inc_max3_deg = 64.0

[SmallSat]
isIndividualLaunch = false
IndividualLaunchFileName = data
SmallSat.num_IndividualLaunch_year = 50
```

```
isGroupLaunch = false
GroupLaunchFileName = ParentObjects_2003-2010.dat
event_GroupLaunch_year = 20
num_GroupLaunch_one_event = 5


[StartProjection]
year = 2013
month = 1
day = 1
hour = 0
min = 0
sec = 0.0
zone = 0.0
gregorian = 1

[EndProjection]
year = 2213
month = 12
day = 31
hour = 0
min = 0
sec = 0.0
zone = 0.0
gregorian = 1

[Propagator]
atmosphere = jacchia
```

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