THE ECONOMICS OF THE CONTROL OF THE SPACE DEBRIS ENVIRONMENT

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ABSTRACT

It is investigated whether cost estimation can be used as an instrument to support the selection of suitable space debris mitigation or remediation measures. Several long-term simulations of the evolution of the future space debris environment are combined with cost estimation. The costs of damages to satellites are compared to the costs of measures like post mission disposal (PMD) and active debris removal (ADR). As a parameter variation the damage costs are estimated based on two different approaches. It is shown that the cost estimations are in a reasonable order of magnitude which allows cost-benefit comparisons for different scenarios.

1 INTRODUCTION

Within this study the main goal was to determine to which extent it is possible to control the stability of low Earth orbits (LEO). Due to the fact that the highest density of space debris is located at about 900 km altitude it is also the region with the highest collision risks. In terms of the inclination mainly the Sun-synchronous satellites at about 98° and objects at about 82° are likely partners for catastrophic collisions, where due to the “head-on” character of the collision a great amount of energy is released which will fully fragment both objects. When the generated fragments in turn cause catastrophic collisions these are called feedback collisions. Currently such catastrophic collisions happen relatively seldom and so do not pose a great risk. However, assuming that the space programs are not being adjusted in the future (launch rates remain the same, limited post mission disposal), which means doing business as usual (BAU), in the future the increase of satellites and debris objects in space may lead to an increased rate of collisions making it the driver of future debris generation. Numerous simulations show that almost all future collisions will occur in regions between 500 and 1,200 km altitude and inclinations between 80° and 105°. In 2009 about 1,090 satellites and rocket bodies have been in that region. In order to reduce this risk it may be necessary to actively remove objects from critical regions. Due to the fact that the majority of catalogued objects are inactive, hence are not able to de-orbit or re-orbit themselves, active removal missions might be a solution to remove this kind of objects. Methods for determining effective active removal missions are subjects to current studies. This involves analyzing possible removal targets beforehand. Because it is not possible to actively remove all objects, which are inactive, a few objects with the highest impact on the space debris environment have to be selected. For this purpose a priority list had to be compiled, ranking all objects, which pose the greatest risk of being fragmented and in turn have a big impact on the environment. Using these priority targets it was possible to run long-term simulations of the evolution of the future space debris environment. Using different removal scenarios it is possible to show the impact a removal of specific targets would have on the evolution of the environment. As a part of this study it has also been the goal to develop a cost model. With the analysis of the active removal targets basic facts for planning service satellites have been derived. This includes for example an estimate of the required delta-v and the fuel and payload masses. Following these estimates a prediction of the cost for the development, launch, and operation has been made [1]. A statement about the cost effectiveness of such missions can be made when comparing the costs of these removal missions with the costs that are generated by potentially lost satellites due to an increased collision risk. Based on these findings removal scenarios can be derived to efficiently reduce the collision risk in the critical regions.

A cost-benefit analysis related to the control of the future space debris environment was performed in three major steps. First, the priority targets were identified, which have to be actively removed in order to maximize mission effectiveness. A dedicated servicer satellite was then modeled in a statistical sense, giving its total mass based on regression analysis for individual subsystems and a propellant subsystem referring to the selected target from the priority list. This resulted in cost models providing all relevant costs associated with an active

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removal mission. The last step consisted in numerical simulations of the future space debris environment taking into account different mitigation and removal strategies. This allowed for the comparison of associated costs for each scenario.

The target object priority list was based on the satellite population in LEO in 2009, including non-operational satellites and rocket bodies. However, also active satellites were considered, as they may potentially lose their maneuvering capabilities during the mission and thus also become target objects. An individual risk analysis, based on flux computations, was performed for altitudes between 500 and 2,000 km and objects with mass greater than 100 kg. As the cross-section is required for each object in order to determine collision probabilities, a geometry model was used for those objects, where geometry information was not available a priori. Information was derived from the correlation of object mass and its geometrical dimensions using regression analysis. The probability of a fragmentation was computed within the long-term simulation tool LUCA (Long-term Utility for Collision Analysis), which applies an orbit tracing method for the estimation of collision probability. The priority criterion was then defined as the score resulting from the multiplication of object mass, fragmentation probability and the number of generated fragments in case of a collision.

It was assumed, that for an active removal mission a dedicated servicer satellite would be launched from Earth for each target on orbit. The servicer would then perform rendezvous and docking maneuvers, to approach the target. Then, the target would be grabbed by a recovery payload (for example a robotic manipulator or a net) and both, servicer and target would be maneuvered to a re-entry trajectory, having its perigee at 80 km altitude, through a retro-engine burn of the servicer. This results in an atmospheric burn-up of the target and the servicer satellite.

The cost of an active removal mission include the development, manufacturing, launch and operation cost of the servicer satellite. The development and manufacturing costs are based on regression analysis of scientific satellites and assume a BOL (begin of life) mass of 500 kg for the servicer satellite without fuel mass. The required fuel mass results from the orbit and the mass of the target object, as for different altitudes, a different delta-v is required to perform a de-orbit maneuver and the heavier a target is, the more fuel mass is required to perform a specific maneuver. After the computation of the required fuel mass, the resulting launch mass of the servicer satellite could be used to compute launch cost as an explicit function of the servicer mass.

Besides the development, manufacturing and launch cost, operation costs were also considered. However, as they are mainly due to staff labor time, which resulted in some 100,000 dollars for a single mission, an arbitrary upper boundary of 5 million dollars was defined to account for all operation costs, which still was a relatively small amount compared to the other costs.

For comparison analysis, damage costs were estimated, which consider only active payloads and take into account the cost which is required to replace a satellite in orbit which does not have any operational capabilities anymore. The failure probability obtained through a catastrophic flux analysis and was multiplied by the associated replacement cost to result in the so called damage cost. As economic loss is highest at mission start and approaches zero at mission end, the computed value was divided by a factor of two.

2 LONG-TERM SIMULATION

For the long-term simulations of the evolution of the space debris environment the software LUCA was used, taking into account launch rates of different space-faring nations, the number of payloads per launch, the number of generated mission-related objects per year, the yearly solid rocket motor firings and explosion rates (2 per year). Collisions are triggered based on individual collision risk for each object. A total of 200 Monte Carlo simulation runs were performed for each of the scenarios.

The future space environment was simulated [1]. The results are shown in Fig. 1. The main driver for the future evolution of the space debris environment is catastrophic collisions occurring on low Earth orbit. The figure is therefore limited to a section of the debris population in LEO, called the effective number of objects. Different results in Fig. 1 are shown. The highest increase of debris is expected if spaceflight activities continue in a business as usual (BAU) scenario. In this worst case scenario, no post mission disposal (PMD) maneuvers would be carried out (*BAU – no PMD*). The debris environment evolution is significantly lower, if a significant proportion of the potential collision partners are removed by PMD from orbits of high spatial density. If the disposal of spent spacecraft is performed by de-orbiting or re-orbiting with a success rate of 90 %, the resulting evolution of the debris environment is represented by the curve "*BAU – PMD (90 %)*" in Fig. 1. By introducing additional Active Debris Removal (ADR) maneuvers, further objects can be removed so that the future number of debris is decreasing. In Fig. 1 different variations of such maneuvers are shown. It is most effective, if the objects with the highest probability of collision are removed first according to their priority, independent of their national ownership. A curve is shown in which five objects are removed each year (*ADR – 5 international*). For some parameter variations, further ADR scenarios are shown. One graph shows for example the debris environment if ADR were to begin in the year 2028. It has also been simulated, which evolution takes place if, for example, Russian or European only objects are removed. Furthermore, even a hypothetical case is simulated in which it is shown how the number of debris would decrease if it would be possible to avoid any future catastrophic collisions using ADR (*ADR – Collision Mitigation*). The top and bottom curve in Fig. 1 indicate the possible width, how the future space debris population might evolve. Both curves themselves are unrealistic. The actual evolution will lie somewhere in between.

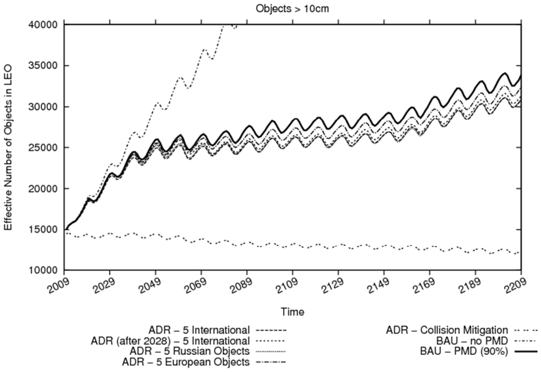

Figure 1. Simulated evolution of the space debris environment for different mitigation scenarios showing the effective number of objects greater than 10 cm [1]

The selection of the objects which are to be removed by ADR maneuver takes place by means of a priority list [1]. The creation of the priority list is based on the particle flux onto a target object which is present in the respective orbit region. The target object that is exposed to the highest particle flux has the highest probability of collision. Thereafter, the objects are prioritized. The top five of these objects are removed annually. If these objects are removed, the likelihood of catastrophic collisions decreases in the future. Thus the number of debris decreases accordingly. Would it be possible, in a hypothetical manner, to identify the high-risk objects so precisely that all future catastrophic collisions could be suppressed, then the debris number could be reduced significantly. To get closer to this ideal condition, it might be possible to support ADR maneuvers by precise conjunction analysis. In such an idealized case ADR could help considerably to stabilize the future space debris environment. Such optimization is not to be examined here. For the following cost analysis a flux based creation of the priority list will be used.

3 DAMAGE COSTS

If a particle collides with an operational satellite, this can lead to damage. The severity of the damage depends on the kinetic energy. The crucial factors, whether the satellite is damaged and how big the damage may be, are the diameter, the density and velocity of the projectile. If the collision occurs at the end of life of the satellite or thereafter, there is no damage. The mission has already amortized at this time. Thus, only collisions with operational satellites are considered in estimating the cost of damage.

The amount of the kinetic energy is responsible for determining whether a satellite is only damaged or even fails. For determining the cost of damage in a first step, a conservative approach has been chosen. As "damage" that case is considered if the satellite fails. Projectiles which fulfill this condition are objects of the centimeter population. Centimeter size objects have enough energy to terminate a satellite mission in low earth orbits at collision velocities in the order of 10 km/s. It is very likely that a satellite after such a collision is no longer functional. The likelihood of such an impact weighted by the replacement cost of the satellite is a measure of the damage costs per satellite.

For estimating the probability of failure, the knowledge of the cross-sectional area of the satellite is required. Based on various data on satellite dimensions and using regression analysis, typical cross-sectional areas of satellites were determined. This simple model uses satellite mass as an input parameter. The average mass of satellites is about 1.5 t. The cross sectional area for such a satellite is on average 9.35 m². The probability of failure is also depending on the operational lifetime of the satellite. Satellites have an average life of about seven years. This operational lifetime is assumed for all future satellites. Next, the future development of the space debris environment is simulated. For each future satellite a particle flux analysis is carried out. Therefrom, the probability of an impact of a projectile is determined. The damage costs are defined as loss of amortization. This results in damage costs which are 50 % of the replacement cost weighted with the probability of failure. Selecting "50 %" should take into account the fact that the damage can occur between the beginning or the end of the mission, which is, on average, after half the operational lifetime.

For an exemplary mission the approximate probability of failure is estimated, using the conservative damage model. A satellite of average size is placed in an orbit where the highest risk of collision exists. The selected orbit is circular with an altitude of 900 km and an inclination of 98°. Using MASTER-2009, the flux of centimeter size objects is calculated on a satellite with a cross-sectional area of 9.35 m^2 (referring to the population of the year 2012). The operational lifetime is at least seven years. The probability that the satellite collides during its lifetime with a centimeter object is about 1.6 %. (On all other orbits the risk is lower.)

The conservative model gives an approximate measure of the minimum cost that can be expected from damages. As a parameter variation, a more expensive damage model shall be applied, which takes into account higher financial risks. This model includes two additional contributions. One is damage caused by small particle impacts. The other is the implementation of insurance costs, to compensate for the losses.

In a second step, the more expensive damage model is applied. First, the extent of the additional contribution of penetrating small particles to the failure probability shall be estimated. A risk analysis concerning small particle impacts on all future satellites is very extensive and practically not feasible. Therefore, an investigation from [2] is used here as reference. The aim is to determine a reasonable order of magnitude of the additionally expected damages. For estimating the damage, only those particles are considered which have the capability to penetrate a typical satellite wall. From these, only those particles are considered for a risk analysis that hit electronic components. Subsystems that contain electronic components are considered particularly vulnerable. For this philosophy a simple vulnerability model was created in [2]. This model takes into account that most of the penetrating particles contribute only to a certain amount to the probability of failure of the satellite.

For an exemplary mission, a risk analysis is performed. The results are compared with the conservative damage model. The comparison results in a ratio that indicates how much the expected damage increases if small particle impacts are considered. Compared with the conservative model, the damage increases by a factor. In [2], the probability of failure was calculated considering small particle impacts for an exemplary satellite mission. For the calculation, a typical design of the satellite wall and a circular orbit at 900 km altitude at an inclination of 98° has been adopted. The resulting probability of failure for an unprotected satellite is given in Tab. 8 in [2]. It is compared with the probability of failure, which is caused by centimeter objects only. The comparison shows, that considering the small particle impacts the probability of failure will increase by a factor of 1.3. This factor is taken in a simplifying assumption for all satellite missions. The result is a rough estimate of the additional damage by small particle impacts.

The direct damage costs are arising directly from the particle impacts. If it should be taken into account that this damage should be compensated by an insurance, then additional insurance costs would incur. These costs are estimated very simplistic here. If for example the satellite owner wants to cover the risk over the entire duration of the mission, it will incur at least an insurance amount equal to the damage costs. A simplifying assumption for the calculation of insurance is therefore that the overall damage costs are doubled. The sum of losses and insurance costs should be regarded as an approximate measure of the maximum possible damage costs.

The future development of the space debris population was simulated up to the year 2200. One of the most important parameters of this simulation is the number of expected catastrophic collisions. The calculations have been executed according to the definitions used in [1]. For all future missions, damage costs have been calculated. Fig. 2 shows the cumulated costs of the business-as-usual (BAU) scenario from [1]. In this scenario, no mitigation measures are applied. The dark grey curve shows the cost that arises from damages to satellites caused by projectiles larger than 1 cm only. The middle curve shows additional damage costs caused by all smaller projectiles. Finally, the light grey curve adds insurance fees to the overall costs. The figure shows that damages will occur more often in the future in this scenario.

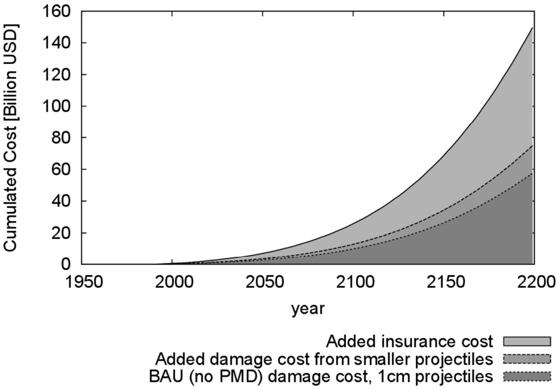

Figure 2. Cumulated damage cost to all future satellites versus time for the BAU scenario in constant US Dollars of the year 2012

4 POST MISSION DISPOSAL

In the following figures, the costs of two different debris mitigation scenarios are shown. The first scenario is based on the conservative assumption that only projectiles larger than 1 cm cause damage to satellites. The second scenario considers the more expensive assumption including damages of small particles and insurance costs. For both scenarios, passive post-mission-disposal (PMD) measures are applied to 90 % of all active satellites (as defined in [1]). The high percentage of properly equipped satellites is a rather optimistic assumption; actual values are likely much lower than that. It is also optimistically assumed that all currently active satellites are equipped with additional propulsion systems and fuel for PMD maneuvers, even those launched years ago. The cost estimation of PMD is based on the assumption that the additional delta-v for the maneuver requires more fuel and thus an enlargement of the on board propulsion module. This causes additional hardware costs and increasing launch costs. Furthermore costs of the increase of the systems complexity due to higher requirements for reliability are considered.

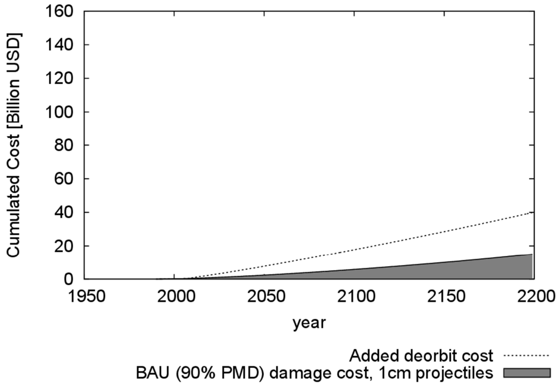

Figure 3. Cumulated cost versus time for the post mission disposal (PMD) scenario (with a success rate of 90 %) considering a conservative damage cost model in constant US Dollars of the year 2012

Figure 3 shows the cumulated damage costs that occur in the PMD scenario. As expected, they are much lower than without PMD because of the severely reduced number of collision partners. Even with the additional fuel and subsystem cost for the PMD maneuver displayed by the dotted curve, the overall costs are still lower.

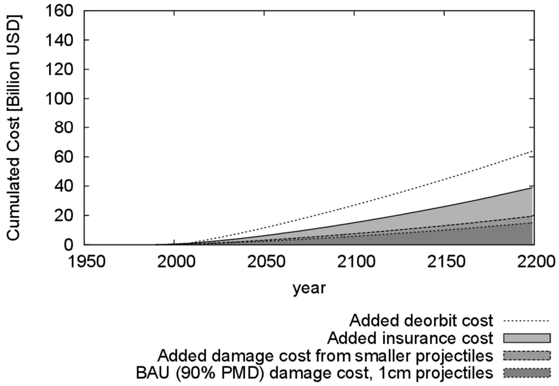

Figure 4. Cumulated cost versus time for the post mission disposal (PMD) scenario (with a success rate of 90 %) considering a more expensive damage cost model in constant US Dollars of the year 2012

Like in the BAU scenario, damages from smaller projectiles and insurance costs can be taken into account for the PMD scenario. This is shown in Fig. 4. Even though the assumptions in the PMD scenario should be regarded as an unrealistic best case, the simulations show that post-mission disposal measures are a highly effective and cost-efficient way to stabilize the LEO population and reduce costs in the long run. Comparisons of the overall costs of the BAU and PMD scenarios are shown in Fig. 5 and Fig. 6, both without and with smaller projectiles and insurance costs, respectively. In Fig. 6, a break-even point can be seen around the year 2100, where the higher investment for PMD measures pays off through largely reduced damage costs. The overall costs in 2200 are reduced to approximately 43 % of the corresponding BAU scenario (68 % without smaller projectiles and insurance).

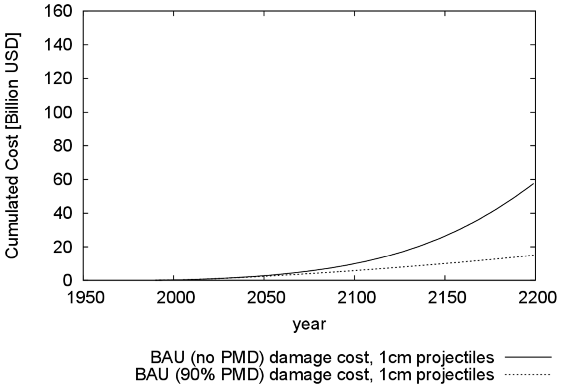

Figure 5. Comparison of the BAU with the PMD scenario considering a conservative damage cost model

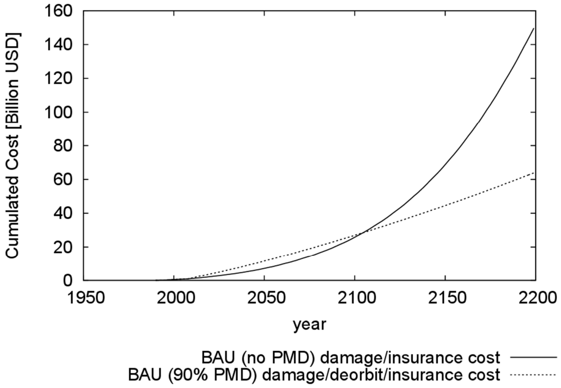

Figure 6. Comparison of the BAU with the PMD scenario considering a more expensive damage cost model

5 ACTIVE DEBRIS REMOVAL

In further mitigation scenarios, on top of the PMD measures five additional satellites are removed each year through active debris removal (ADR) missions which are defined in [1]. It is assumed that for each of the five objects, a satellite is launched that docks with the target and performs a de-orbit maneuver. Both the target and the ADR satellite are re-entering into the atmosphere. For the simulation, each year the five most high-risk historical objects have been identified based on their mass and collision probability and chosen as targets for active removal. The costs of such a mission are estimated to be approximately 140 million US dollars per target (700 million USD per year) for the first year (2010). After that it is assumed that the following removal satellites can be produced with higher cost efficiency. Starting in 2011, the active removal costs for a year are given as 80 per cent of the previous year's costs. In this scenario, active removal missions are executed for ten years to remove historic objects that do not have PMD capabilities. After that, all active removal activities are ceased in favor of PMD.

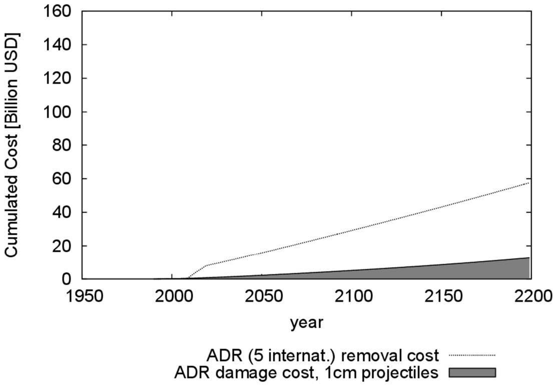

Figure 7. Cumulated cost versus time for the active debris removal (ADR) scenario (combined with PMD) considering a conservative damage cost model in constant US Dollars of the year 2012

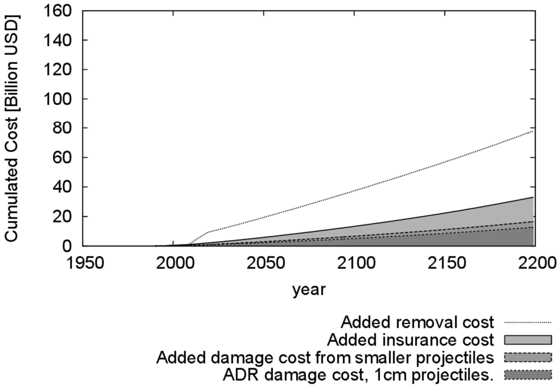

Figure 8. Cumulated cost versus time for the active debris removal (ADR) scenario (combined with PMD) considering a more expensive damage cost model in constant US Dollars of the year 2012

Fig. 7 shows the cumulated damage costs for the ADR scenario which are slightly lower than in the PMD scenario, since five high risk objects are removed each year. Fig. 8 shows the overall costs with added small projectile damage and insurance. It can be seen that, even with a learning factor, the removal costs for the ADR missions are high compared to PMD. Fig. 10 shows that ten years of active debris removal between 2010 and 2020 will delay the break-even point by about forty years. Therefore, active debris removal should be used mainly for historical high-risk objects for which there is no other way of removal. All future satellites should be equipped with PMD capabilities to lower the LEO collision risk in a more cost-efficient way.

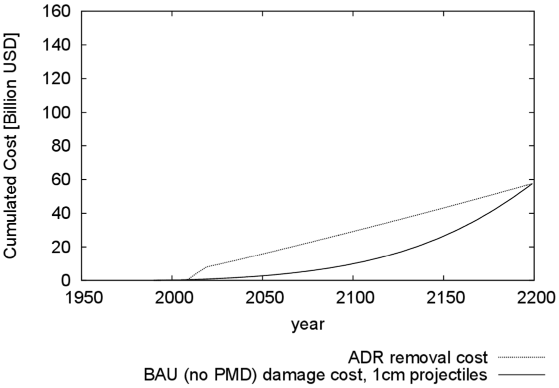

Figure 9. Comparison of the BAU with the ADR scenario (combined with PMD) considering a conservative damage cost model

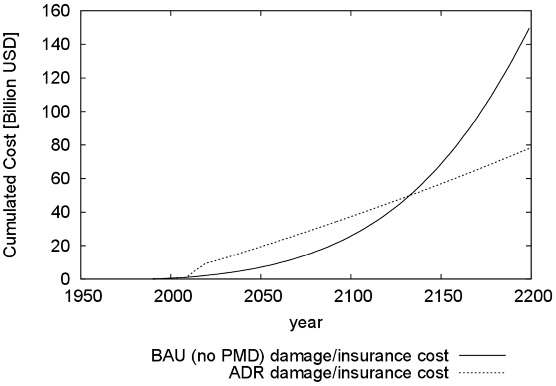

Figure 10. Comparison of the BAU with the ADR scenario (combined with PMD) considering a more expensive damage cost model

6 CONCLUSION

The aim of this investigation is to estimate the order of magnitude of costs of various scenarios. In particular, the ratio of losses compared to the cost of mitigation or remediation measures is estimated. It turns out that these measures may be worthwhile. In some cases a break-even point can be shown. The simulations confirm that the removal of objects is an effective measure to stabilize the future space debris environment. This can be done by PMD (De-orbiting and re-orbiting) or through ADR.

ADR here means to take into account the loss of the removal system after the maneuver. For this, the measure seems to be relatively expensive. De-orbiting with an on-board propulsion system would be cheaper. This propulsion system must be enlarged and its reliability should be increased. ADR is necessary to remove historical objects that have no functioning propulsion system. ADR may in the future be required to de-orbit satellites, whose propulsion system has failed. ADR can be effective if it is possible to identify high-risk objects precisely. This may be worth the high cost of such missions. The cost of ADR may be reduced if it is possible to reuse the removal system. The cost of such a scenario has not been investigated here. The reusability, however, requires the ability to remove completely different types of objects. Furthermore, a permission is required to remove objects which belong to different owners (nations). This is necessary because those objects that are on the top of the priority list have to be removed first.

7 ACKNOWLEDGEMENT

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8 REFERENCES

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