Executive Summary Report

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1. STUDY OVERVIEW

Solar System bodies – including the Moon and Near-Earth Objects (NEOs) – contain a rich diversity of materials such as metals and volatiles that could be used as energy sources and as means to sustain human life, as humankind ventures deeper into space. Space agencies worldwide are considering such resources as potential raw materials for space infrastructure development, based on recent technological advances related to space in-situ manufacturing. Concepts, payloads and technologies have also been proposed to harness resources such as water, which is present in the form of ice in the Moon´s regolith and in some hydrated asteroids, for life support needs and energy and propellant production in the context of deep space exploration. In addition to this, private companies have formulated plans to extract mineral resources from asteroids or other celestial bodies for exploitation elsewhere in the Solar System. These operations would entail certain risks and third-party liabilities that need to be better analysed and characterised.

Such considerations motivated LSA and ESA to initiate this study with the financial support of the LuxImpulse and Discovery Preparation programmes.

The objectives of the study were to compile a list of potential space resource utilisation missions, defining risk criteria relevant to them and performing a preliminary risk analysis; and to propose a risk assessment methodology and inputs that entities wishing to carry out these missions should provide to a national authority for mission certification.

The study was completed in February 2019 and had a duration of seven months. It proceeded through two main iterations, one until the progress review three months after the study kick-off, and the other up to the final review.

In the context of this study, risk has been defined as the outcome of a project, e.g., a space mission, that can result in a liability, as a consequence of unwanted impacts on human life (on Earth or space), on assets (e.g. facilities) or on environments that are widely considered to be valuable, such as an ecosystem, a popular orbital location (e.g. LEO, GEO, Lagrange points, etc.), or a site with a historic significance for humankind (e.g. the Apollo 11 landing site).

In order to compile a list of realistic, albeit theoretical, mission scenarios to support the assessment of the risks that this type of mission would involve, the analysis considered different Solar System bodies, with an emphasis on Near-Earth Asteroids (NEAs) and the Moon as the most credible targets in a 2020s-2030s time horizon. This choice of the timeframe allowed to filter out technologies that might or might not be available to both missions and technological applications –say lunar outposts or fusion reactors- potentially driving the demand for certain space resources. It also allowed to better assess the most likely risks that need to be considered.

The mission scenarios covered a wide range of cases relevant to Space Resource Utilisation (SRU) missions in the timeframe considered in the study, i.e. the next two decades. The mission objectives were related to resource excavation, processing, extraction, storage and transportation and were addressed in different mission scenarios. The location for resource excavation, processing, extraction and/or storage is defined as the mission “target” and the location where the resource is delivered at the end of the mission -for later use or further transportation to another location- is called “destination”. With this in mind, accessibility (i.e., energy or delta-v) considerations consistent with the time horizon considered in this study led to focusing on the following space resource mission “targets” and “destinations”:

- The “targets” were the lunar surface and the Near Earth Asteroids (NEA), The lunar surface was considered for resource excavation, processing, extraction, storage and/or transportation in two of the scenarios in the second iteration. NEAs were taken as targets in three other scenarios either for resource excavation, processing, extraction, storage and transportation, or for direct transportation to another destination of a fragment (<10 m in diameter) or a similarly small NEA making orbital redirection a viable mission option.
- As for “destinations”, the lunar surface, Lunar Orbit, the Earth-Moon Lagrange point L1, Low Earth Orbit, and the Earth’s surface were considered in different scenarios.

The preliminary assessment of major risks associated to mission types carried out in the first iteration showed that total risk values tended to be lower for Moon scenarios (sc9 & 10), whereas they were more significant for NEA scenarios (sc1, 2, 3 & 4) where no orbital redirection is planned, and even higher for NEA scenarios (sc5, 6, 7 & 8) involving orbital redirection from the original orbit to a lunar or Earth orbit. These trends can be largely explained by the preliminary nature of the analysis based on “worst-case scenarios” and the cumulative effect of different risks that were taken into account, e.g., release of debris into valuable orbits, in-orbit collisions and uncontrolled Earth re-entry. For all of them, at each step effective risk mitigation measures were identified, which might need to be considered by the mission operators as a prerequisite for certification to be granted.

Among these major risks, the study analysed the case of the risk of potential change of a NEA orbit due to accidental debris release leading to a change in momentum and hence a modification of the orbit. However the analysis showed that for this mechanism to be really effective the mass ejection would have to be very anisotropic and specific; most of the mass flow would need to be in a direction that is closely aligned to the tangential component of the NEA’s orbital velocity vector, and mass flow rate (mass amount and ejection speed) would need to be significant to change the orbital momentum, in the same way as a high-power and precisely operated rocket engine would. Nevertheless, it can be all but be ruled out that that could happen accidentally -or even intentionally- in a realistic operational SRU mission scenario.

In the second iteration of the study the scenarios were used to refine the methodology and test it, and to extract more general lessons on the scenarios themselves and the way they are related to the risks.

Among the latter are the following:

- The scenario involving large NEA (e.g. Eros, the target in sc4 which has a diameter of about 10 km) have a comparatively lower risk value due to the larger escape velocity; this limits risks related to the release of debris that could lead to a significant increase in the micro-meteoroid background level as a result of the operations on the surface of the NEA. This is also applicable to the potential pollution of orbital locations that are valuable for future space operations. A more detailed analysis in this second iteration also leads to lower risk in scenarios were orbital redirection is considered; due to energy considerations, the redirection of very massive objects would be unfeasible with the technology available in the next two decades. The operation can only be an option when considering very small objects, or fragments of larger ones, of diameters of a few meters at most. In those cases, however, the risks are much lower, as most of the objects of that size would burn in the atmosphere in the event of an uncontrolled atmospheric re-entry. This greatly reduces the severity and likelihood of extensive damage or threat to human life on the Earth's surface.

- In the scenarios where a relatively small NEA -such as 4660 Nereus, about 130-m in diameter - is chosen as the target (in scenarios 7 & 8), some of these risk trends invert due to the lower escape velocity; but, still, mitigation techniques can be identified such as the use of encapsulation methods to prevent the release of debris during the resource excavation, etc.
- The careful evaluation of other risk factors in this second iteration also leads to a risk reduction when considering the risk of releasing toxic materials or Nuclear Power Sources (NPS) on the surface of Solar System bodies. This is because choices exist at spacecraft and operations levels to eliminate or greatly reduce the risks. The same logic applies to the risk of a catastrophic impact on Solar System bodies and the crossing of Earth orbits in the case of NEA redirection.
- Other risk factors were dismissed, such as forward planetary protection, given the type of targets (biologically inert by all scientific standards and COSPAR class) that are considered in the scope of the study i.e. NEA and the Moon. Similar arguments apply to limit background planetary protection risk in scenario 8 (Earth-Moon).
- In the case of the lunar orbit, pollution by debris from surface is considered low. In scenario 4, where the Earth-Moon L1 Lagrange point is the destination, proximity operation has been given a low weighting factor as a result of the relatively high gravity environment on the Moon; it is also likely that gravity perturbations lead to a relatively fast orbital decay.

In summary, a structured approach to identify and analyse the risks associated to a given Space Resource Utilization mission has been developed, and later tested through the use of theoretical mission scenarios. In the process, specific risks have been addressed and general lessons have been extracted. The analysis showed that the risks that SRU missions can cause in the time horizon considered in the study (i.e., the next two decades) are unlikely to pose significant issues, and the risk trend showed that more detailed analysis can lead to risk reduction. Uncertainties can be understood, and mitigation actions can be recommended at spacecraft of mission operations level. In fact, this is the norm in well-developed industrial and commercial sectors. For instance, in civil aviation, where the conclusions of thorough analyses, e.g. accident or mishap investigations, are used to inform the certification agencies that grant commercial companies permission to operate.

2. INTRODUCTION

This document is submitted in fulfilment of tasks 1.1, 1.2, 1.3, 2.1, 2.2, 3.1 and 3.2 of ESA SoW, Technical Risk Assessment of Space Resources Utilization – TECSYS-180424-SOW, Issue 1, Revision 0 of 24/04/2018.

2.1. ACRONYMS

AU Astronomical Unit
BoM Beginning of Mission
CH4 Methane
COSPAR Committee On Space Research
EoM End of Mission
LH2 Liquid Hydrogen
LOX Liquid Oxygen
MM Micro Meteoroid
MOID Minimum Orbit Intersection Distance
NEA Near Earth Asteroid
NEO Near Earth Object
NPS Nuclear Power Source
PGM (Platinum Group Metal)
PHA Potential Hazardous
SRU Space Resources Utilization

3. CONTEXT AND ASSUMPTIONS

As humankind ventures deeper into space, space activities will require new energy sources and materials to fuel missions and to sustain human life. The Moon, Near-Earth Asteroids (NEAs) and other Solar System bodies contain such resources, like metals and water. Space agencies worldwide are considering the potential of those raw materials for space infrastructure development, based on recent technological advances related to space in-situ manufacturing. Concepts, payloads and technologies have also been proposed to harness volatiles like water, which is present as ice in the Moon´s regolith and in some hydrated asteroids, for life support needs, energy and propellant production, in the context of deep space exploration. Those activities are coordinated through the Global Exploration Roadmap, agreed among all major space agencies. The roadmap has as final target the sustainability of human presence in the Mars system in the next decades. In addition to this, private companies have expressed plans to extract mineral resources in asteroids or other celestial bodies for exploitation elsewhere in the Solar System. The potential commercial interest of these targets attracted private investors and start-up companies worldwide. These operations by either private or public entities would entail certain risks that need to be better analysed and characterised. This type of analysis could eventually support a certification process by a public authority. This would provide legal stability to private operators and investors while making the commercial entities accountable for their operations (and the externalities that they might involve), which could only help enforcing adequate safety and environmental impacts standards and hence protecting public interests.

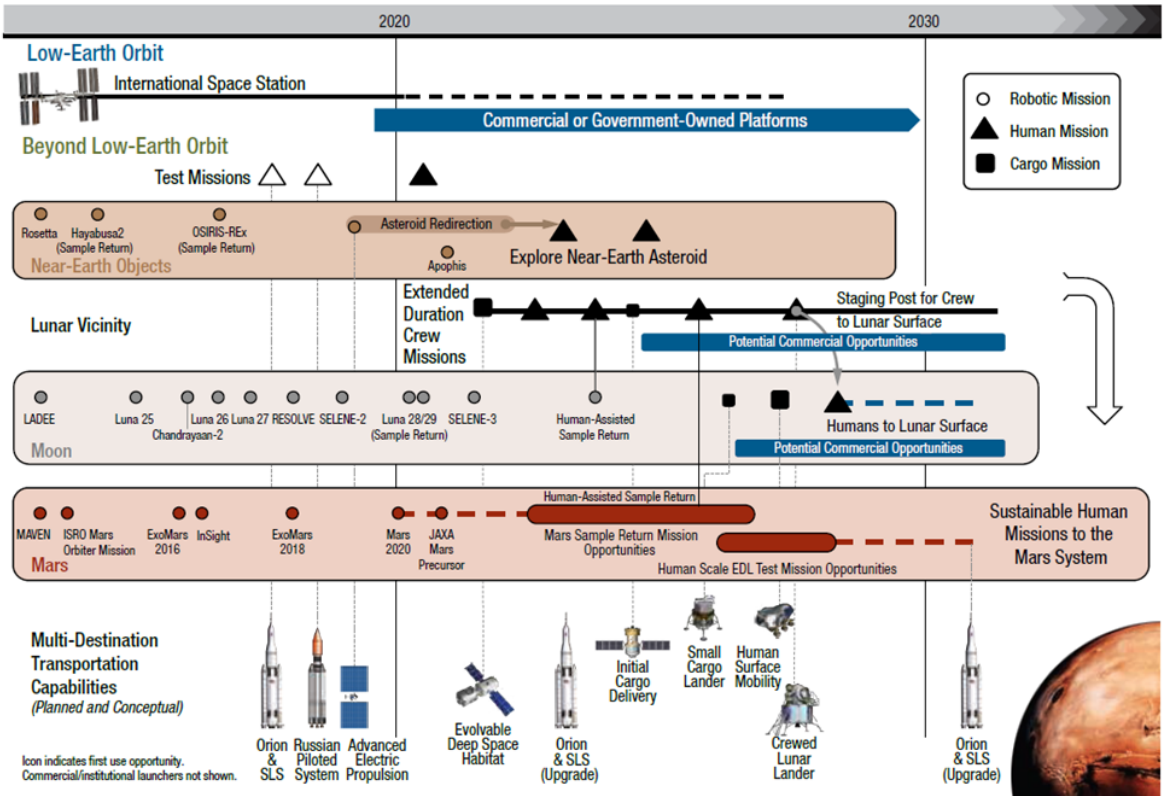


Figure 2.1-1 International Space Exploration Coordination Group (ISECG) mission scenario

3.1. OBJECTIVE OF THE STUDY

Objectives of the study (as stated by ESA):

- Compile a list of potential resource utilization missions, in different Solar System bodies, with a particular focus on Near-Earth Asteroids (NEAs) and the Moon in a 2020s-2030s time horizon;
- Define risk criteria relevant to the mission scenarios;
- Perform a detailed technical risk analysis for each of the mission scenarios and phase
- Define the content of the risk assessment report that entities wishing to carry out these missions should provide to a national authority for mission certification.

3.1.1. Study Iterations

The study was organised along two main iterations:

- The first iteration, lasting 3 months, up to Progress Meeting 1 (PM1), consisted of:
  1. a thorough literature survey;
  2. the compilation of a catalogue of SRU missions (in particular, of NEA and Moon missions);
  3. a technical trade-off analysis of mission scenarios; and finally,
  4. a preliminary assessment of major risks associated to mission types, and of risk avoidance strategies.
- The second iteration, from PM1 until the Final Review (FR), considered only a subset of five mission scenarios out of the initial ten; these mission concepts were selected in the trade-off analysis and agreed with ESA. The second iteration involved the following tasks:
  a. each of the mission scenarios was broken down into building blocks and critical phases
  b. risk criteria and guidelines on both severity and likelihood were defined, in order to identify the potential risks associated to each mission type and mission phase;
  c. a detailed mission and risks analysis was performed.

3.2. DEFINITIONS

Risk: a (mission) outcome that could result in a liability, as a result of unwanted impacts on economic or human activities, and/or significant (i.e. above natural background levels) long-term alteration of an environment or historical heritage that is widely considered to be valuable to humankind.

Mission Scenarios: conceptual study cases, used to a) analyse major and specific Risks (as previously defined) and their Severity and Likelihood: and b) test and validate the general Risk Assessment Methodology, which is the main outcome of this study.

Resource: Specific element, compound or material that is the subject of the SRU activity in the Mission Scenarios.

BoM: Beginning of Mission, first action considered in the Mission Scenario.

EoM: End of Mission, last action considered within a Mission Scenario.

Mission Parameters: Set of variables that define the Missions Scenarios uniquely, including the following:

- Target: locations where the resources will be extracted from, starting at BoM;
- Destination: location where the resource will be used at EoM;
- Resource: being considered in the scenario, and the
- Objective and Building Blocks: that are involved in the Mission Scenario.

4. MISSION SCENARIOS IDENTIFICATION & OUTLINE

The Moon, other planets and their satellites, comets and asteroids in the Solar System are rich in elements, minerals and hydrocarbons. However, the gravity of large celestial bodies makes exploitation comparatively less efficient and more costly in terms of energy. Accessibility considerations lead to focusing on the following Targets and Destinations (as previously defined) for SRU missions in this study: Earth Surface and Low Earth Orbit (Destinations); Moon Orbit, Lagrange Points (Destinations) and Surface (Target and Destination) and Near Earth Asteroid (Target and Destination).

The two most important physical considerations in determining the viability of mining a particular NEA are the time factor and the energy cost required for the mission. The ideal NEA for mining purposes would be one that is close to Earth (in energy terms, i.e., low mission delta-v) and allows a long mining season without requiring large amounts of energy to reach it or to return to Earth. The Apollos, Atira, Amors and Atens are groups of relatively accessible asteroids that could be targets for future SRU activities.

4.1. SPACE RESOURCES

In order to analyse realistic Missions Scenarios, different resources were considered. These were related to the main targets, NEA and the Moon, as follows:

NEA: These objects can be classified based on their mineralogical characteristics and on their whole-rock chemical compositions into: S-complex asteroids, they are similar of ordinary chondrite meteorites which contain iron, irons oxides, and different other types of silicates; C-complex asteroids, they are similar of carbonaceous chondrites that can contain water, carbon and organic materials; X-complex, some of them are pure metallic bodies, while others could be a mix of metal and silicates.

Moon: Silicates, in lunar highlands Regolith; Iron oxide, in lunar Mares Regolith; Imbedded atoms (Helium 3), in Regolith from solar wind and Water ice, in Regolith pores in permanently shadowed craters near the poles.

4.2. MISSION OBJECTIVES

Also with the aim of defining credible mission scenarios, a set of potential goals and functions have been assessed; these are called “Mission Objectives” or “Objectives” in the context of this study, and include the following categories:

Excavation: beside the simplest methods such as auger, scoop and drill (all made more difficult by a micro-g environment in NEAs and the dusty nature of the regolith), pneumatic and magnetic solutions can be worth considering. The excavation can be started after either anchoring (cables, clamps, tethers and hooks) or encapsulation (surface is covered in an enclosure such as a capsule, net or fabric that is not permeable to the material on the surface).

Processing: Fragmentation is the mechanical process of breaking down a NEA, or Moon rock, into smaller parts or fragments. This includes drilling, cutting, augers, shears and scoops. Rubblisation is similar to fragmentation but uses blasting material to perform the separation. Magnetic systems can be used to lift and collect fine metallic regolith and dust particles. Pneumatic systems use gas techniques to blow and collect tiny fragments, powders and dust particles.

Extraction: the extraction methods can be very different depending on the nature of the Resource and can be divided into physical or chemical methods. In carbonaceous chondrite, water can be extracted in different ways, depending on the physical state (free ice or bound water): 1) Heating (e.g. solar concentrators, laser or microwaves) and condensation for free ice 2) Vacuum distillation in space for bound water. Extracted water can be further processed by electrolysis to obtain propellant. Metals can be separated by means of magnetic or pneumatic extraction tools.

Storage: Water or other volatiles should be stored in pressurised containers such as pressure vessels. Processed resources would most likely be stored in sealed containers to prevent losses and avoid contamination.

Transportation: if not used in-situ, the resource should be transported to the final Destination, probably by means of dedicated hauling spacecraft.

4.3. PROPOSED MISSION SCENARIOS

4.3.1. First Iteration (Major Risk Analysis)

The scenarios proposed for the Major Risk Analysis are listed below, ordered by Resource taken into account. The mission parameters in the columns use the terminology adopted in this study and defined above. Major Risk Analysis is described in paragraph 5.

Scenario #		Scenario Name	Orbital Redirection	Resource	Objective	Destination	Target
sc	6	deviation to Lagrange point	YES	Water	Storage & Transportation	Lagrange (Earth-Moon)	Asteroid
sc	1	asteroid in situ	NO	Water	Storage	In-situ	Asteroid
sc	4	asteroid to Lagrange point	NO	Water	Storage & Transportation	Lagrange (Earth-Moon)	Asteroid
sc	2	asteroid to Moon orbit	NO	Water	Storage & Transportation	Moon Orbit	Asteroid
sc	8	deviation to Earth surface	YES	PGM	Extraction, Storage & Transportation	Earth Surface	Asteroid
sc	3	asteroid to Earth surface	NO	PGM	Extraction, Storage & Transportation	Earth Surface	Asteroid
sc	7	deviation to Earth orbit	YES	Sample	Storage & Transportation	Earth Orbit	Asteroid
sc	10	Moon in-situ	NO	Regolith	Excavation & Processing	In-Situ	Moon
sc	5	deviation to Moon orbit	YES	Metals	Extraction, Storage & Transportation	Moon Orbit	Asteroid
sc	9	Moon to Earth surface	NO	Helium 3	Extraction, Storage & Transportation	Earth Surface	Moon

Table 4.3-1 Proposed Mission Scenarios assessed during the first iteration

4.3.2. Second Iteration (Detailed Risk Analysis)

In the second iteration, the risk assessment methodology was tested with five study cases, the selected Mission Scenarios. Each of them was the subject of the detailed analysis in the second part of this study. These scenarios are listed in the table below.

Sc. #	Target	Destination	Resource	Objective	Orbit Redirection
4	NEA	Lagrange (Earth-Moon)	Water	Storage & Transportation	No
7	NEA	Earth Orbit	Sample	Storage & Transportation	Yes
8	NEA	Earth Surface	PGM	Extraction, Storage & transportation	Yes
10	Moon Surface	Moon Surface	Regolith	Excavation & Processing	No
9 (*)	Moon Surface	Lagrange (Earth-Moon)	Water	Storage & transportation	No

Table 4.3-2 Selected mission scenarios for the second iteration in the study

(*) as scenario 9 but modified

5. RISK ANALYSIS

5.1. MAJOR RISK ANALYSIS (FIRST ITERATION)

The following risks were identified during the first iteration, as relevant to the list of mission scenarios being considered:

ID	environment	Risk	Detail	Target	Destination
OS-01	**Outer space environment**	Increase the MM background population	Generation of fragments by excavation or processing of NEA surface materials, depending on the NEA's escape velocity	NEA	Moon & Earth Orbit, Lagrange & Surface
SS-01	**Solar system bodies surface and/or near environment**	Generation of fragments released in NEA orbit	Generation of fragment by excavation / processing of materials on NEA, depending on the NEA's escape velocity	NEA	Moon & Earth Orbit, Lagrange & Surface
SS-02		Forward planetary protection	Transfer of organisms from Earth to another celestial body	Mars, Europa	Moon & Earth Orbit, Lagrange & Surface
SS-03		Release of toxic material or NPS on solar system bodies surface	Unwanted release of toxic chemical or nuclear materials caused by a failure during surface operations on NEA, Moon	NEA, Moon	Moon & Earth Orbit, Lagrange & Surface
SS-04		Pollution of Moon orbital space	Pollution of the Moon orbital space caused by the transportation / insertion into Moon orbit of material extracted on the Moon itself or a NEA	NEA, Moon	Moon Orbit
SS-05		Catastrophic event on Solar System body	Caused by asteroid redirection. Level of risk may be related to extraction process	NEA	Moon & Earth Orbit, Lagrange & Surface
EO-01	**Earth orbital space**	Pollution of Earth orbit	Pollution of the Earth orbital space caused by the insertion into Earth orbit of material extracted on solar system bodies	NEA, Moon, Mars, Europa	Earth Orbit
EO-02		Crossing of Earth orbit	Generation of fragment caused by extraction of materials on a NEA that can cross Earth orbit	NEA	Moon & Earth Orbit, Lagrange & Surface
EA-01	**Earth atmosphere and/or surface**	Catastrophic event on Earth	Caused by asteroid redirection. Level of risk may be related to extraction process	NEA	Moon & Earth Orbit, Lagrange & Surface
EA-02		Re-entry of NEO fragments on Earth	Generation of fragment caused by extraction of materials on a NEA that can cross the Earth space and re-enter on earth atmosphere	NEA	Moon & Earth Orbit, Lagrange & Surface
EA-03		Re-entry of NEA and/or entry system on Earth	Caused by a failure during the re-entry phase	NEA	Moon & Earth Orbit, Lagrange & Surface
EA-04		Backward planetary protection	In case of failure during the re-entry phase the material extracted on the planetary body could re-enter in a non-nominal way in the Earth's atmosphere	NEA, Moon, Mars, Europa	Earth Surface
EA-05		Re-entry of toxic material	Caused by failure during the re-entry phase in case toxic materials are used	NEA, Moon, Mars, Europa	Earth Surface
EA-06		Re-entry of NPS	Caused by failure during the re-entry phase in case NPS are used	NEA, Moon, Mars, Europa	Earth Surface

Table 5.1-1 Risk Review

5.1.1. Severity and Likelihood

For each risk, values were assigned for “Severity” and “Likelihood” (both defined above) as defined in the following table:

Severity	Score	Likelihood
Catastrophic	5	Certain
Critical	4	Frequent
Major	3	Sometimes
Significant	2	Seldom
Negligible	1	Never

Table 5.1-2 Severity and Likelihood Score definition

Severity and Likelihood can each be related to three main sub-categories:

- **Severity**
  1. Risk effects on human beings: i.e. injuries and loss of life.
  2. Risk effects on assets: e.g. liability for induced damages, liability for financial loss.
  3. Risk effect on environment: e.g. pollution of useful sites/location, alteration of the heritage.
- **Likelihood**
  1. Spacecraft, for all the parameters pertinent to the Spacecraft design.
  2. Environment, for all the parameters dependent on the selected Target (NEA or Moon).
  3. Operations, for all the parameters related to the Spacecraft and to the selected Target (NEA or Moon).

Based on the above, the following quantities have been calculated:

- "Risk Index = Severity*Likelihood" for each risk,
- "Total Risk per Scenario = Summation of each Risk Index"
- "Total score per Risk = Σ of Cost Risk Provision of SCn", with n= 1, 2, … 10

The table below illustrates the Risk Index calculation.

Severity					
5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15
2	2	4	6	8	10
1	1	2	3	4	5
	1	2	3	4	5 Likelihood

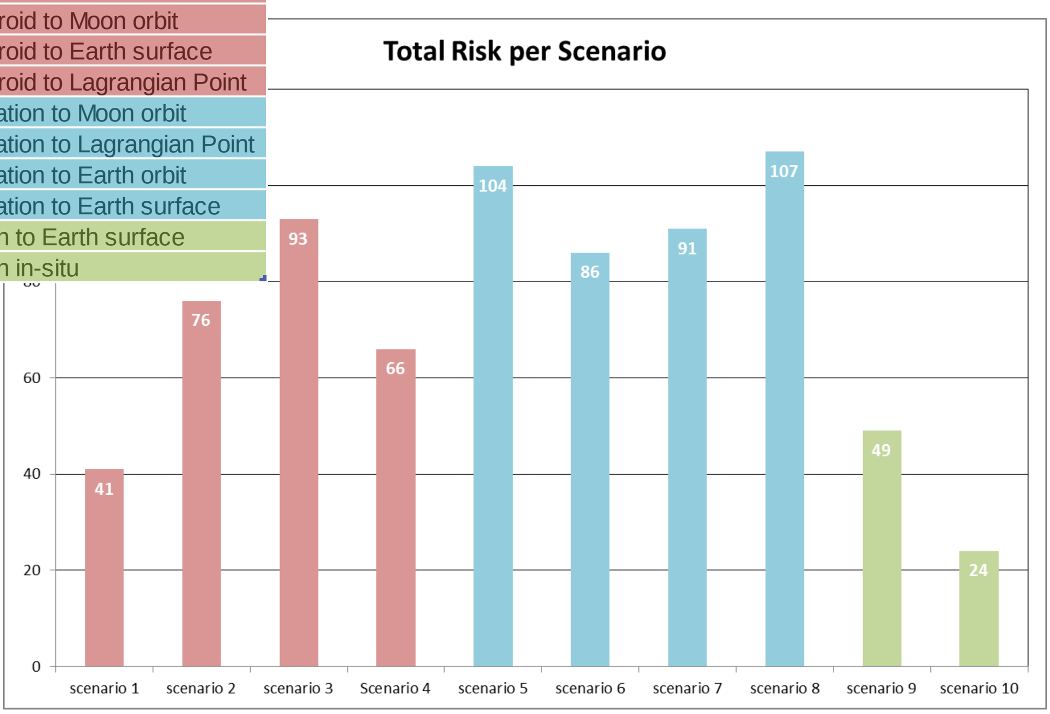
Table 5.1-3 Risk Index as a function of Severity and Likelihood

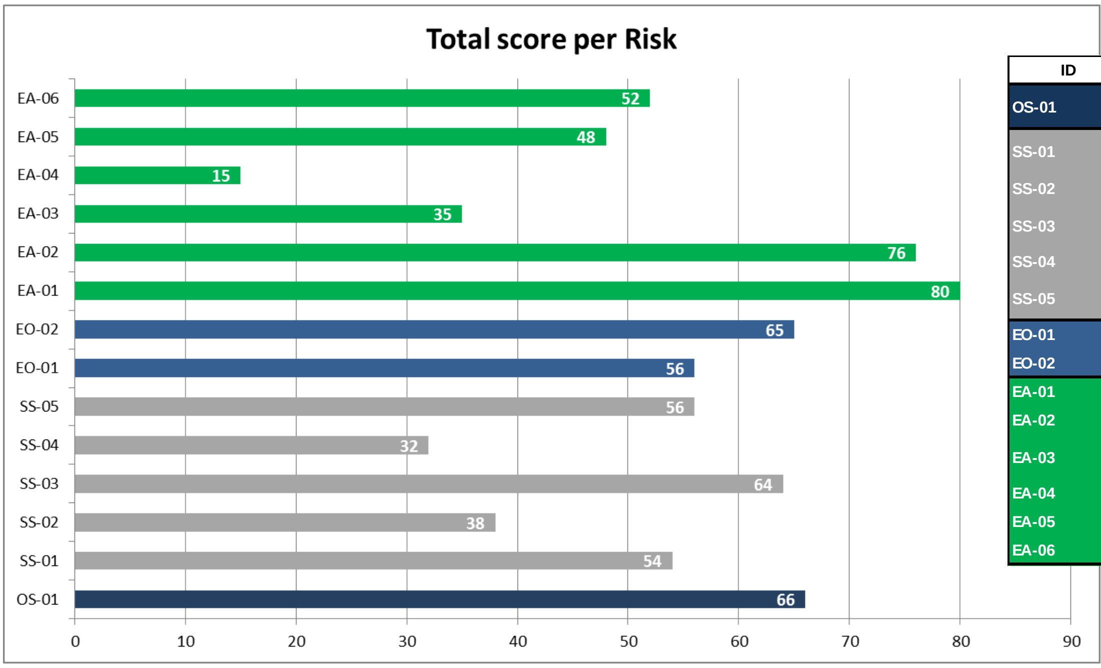
From these definitions, the Total Risk per Scenario and the Total score per Risk are calculated (see paragraph 5.1.2).

5.1.2. Total Risk per Scenario & Total Score per Risk (first iteration)

In order to numerically assess possible trends, and analyse the variation of the values as the analysis becomes more detailed (in the two iterations), the total risk per scenario and the total score per risk were calculated. The plots below show the values for the first iteration:

ID	Name
scenario 1	asteroid in situ
scenario 2	asteroid to Moon orbit
scenario 3	asteroid to Earth surface
Scenario 4	asteroid to Lagrangian Point
scenario 5	deviation to Moon orbit
scenario 6	deviation to Lagrangian Point
scenario 7	deviation to Earth orbit
scenario 8	deviation to Earth surface
scenario 9	Moon to Earth surface
scenario 10	Moon in-situ





ID	Risk
OS-01	Increase the MM background population
SS-01	Generation of fragments released in NEA orbit
SS-02	Forward planetary protection
SS-03	Release of toxic material or NPS on solar system bodies surface
SS-04	Pollution of Moon orbital space
SS-05	Catastrophic event on Solar System body
EO-01	Pollution of Earth orbit
EO-02	Crossing of Earth orbit
EA-01	Catastrophic event on Earth
EA-02	Re-entry of NEO fragments on Earth
EA-03	Re-entry of NEO and/or entry system on Earth
EA-04	Backward planetary protection
EA-05	Re-entry of toxic material
EA-06	Re-entry of NPS

Figure 5.1-1 Total risk per Scenario and the Total score per Risk

Keeping in mind the rather simple assumptions used to quantify the severity and likelihood, and hence to compute numerical values for the Risk Index, any comparison of such values has to be handled with care. It should be stressed that these numerical estimates will not serve the purpose of comparing the level of risk for two given scenarios. However, given a larger number of scenarios, the risk index values might be useful to analyse drivers and general trends.

Thus, in these plots, only risk indexes can be compared, not the actual risks. With this in mind, and being aware of the limited number of scenarios analysed even in the first iteration (n=10) the plots show the following:

- Total Risk per Scenario
    1. Minimum value, for Moon scenarios (sc8 & 9)
    2. Medium value, for NEA scenarios (sc1, 2, 3 & 4) where no orbital redirection is foreseen
    3. Higher value, for NEA scenarios (sc5, 6, 7 & 8) where orbital redirection is foreseen
- Total score per Risk
    1. Minimum value, for backward and forward planetary protection, re-entry of entry system on Earth and pollution of Moon orbit (EA-04, SS-02, EA-03 and SS-4)
    2. Medium value, for Generation of fragments, re-entry of fragments on Earth, Release and re-entry of toxic material on Earth and Pollution of Earth orbit (OS-01, SS-01, EA02, EA-05, SS-03 and EO-01).
    3. High value, for Catastrophic event on Earth (EA-01).

These preliminary results show the strong dependence on the accuracy and level of detail of the analysis, as illustrated by a reduction in all the values in the second iteration when risks and missions were better understood. This risk index reduction has also been evident in the analysis when uncertainties have been reduced by using even rather simple physical and “back of the envelope” engineering models, rather than scoring based on limited knowledge of physical processes and subjective perception.

For instance, the “High” value for NEA scenarios (sc5, 6, 7 & 8) where orbital redirection is foreseen, together with the “High” value for risk “Catastrophic event on Earth (EA-01)” is mainly due to the fact the Severity value is 5 (i.e. the worst case scenario). However, at this stage, no actual assessment of severity as a function of the fragment (or small NEA) size was made; this modelling was not in the scope of the study. On the other hand, a value of 3 is assigned to likelihood on the basis of a (preliminary and, as such, subjective) valuation of reliability of choices at Spacecraft (e.g. electric vs. chemical propulsion) and Operation (e.g. Operational fail safe, any propulsion failure will generate free collision orbital evolution) sub-category level.

The “Medium” value for NEA scenarios (sc1, 2, 3 & 4) where orbital redirection is not foreseen, together with the “High” value for risk “Catastrophic event on Earth (EA-01)” is, mainly, due to the fact the Severity was assigned a value of 5 (as before) but as for Likelihood, a value of 1 may be granted because a simple dynamical model (momentum conservation law and Newton’s third law) shows that changing the orbit of a NEA as an unwanted consequence of the Operation assumed in the scenarios is very hard to do and hence an unlikely event.

“Minimum” value, for Moon scenarios (sc8 & 9) is mostly due to the comparatively more intense gravity field: even if the Moon´s gravity is low compared to Earth’s, it is sufficient to avoid the release of fragments in the Moon and/or Earth orbit. Still, this preliminary assessment also needs backing from numerical modelling to justify a low value of Likelihood and more detailed assessment of Severity on potential consequences e.g. to assets and human life in the cislunar space. On the other hand the Moon regolith is quite aggressive and an encapsulation method has to be taken into account for the Moon surface environment.

The “Medium” values for the risks “Generation of fragments”, “re-entry of fragments on Earth”, “Release and re-entry of toxic material on Earth” and “Pollution of Earth orbit” (OS-01, SS-01, EA02, EA-05, SS-03 and EO-01) are due to the values assigned to Severity, of either 3 or 4, depending on the risk; and to values given to Likelihood i.e. either 1, 2 or 3, depending of the scenario. This is driven by the availability of suitable choices to mitigate risks at Spacecraft, Environment and Spacecraft levels (e.g. restriction in use of toxic materials, choice of the target mass and hence escape velocity, and Encapsulation).

The “Minimum” values for the risks “backward and forward planetary protection”, “re-entry of entry system on Earth” and “pollution of Moon orbit” (EA-04, SS-02, EA-03 and SS-4) is due to low severity value for NEA in line with the COSPAR scale, and the available choices at Spacecraft (mission reliability, quality assurance, including TRL and redundancy policy) and Operation (Encapsulation for NEA redirection to Moon orbit) sub-categories.

5.2. DETAILED RISK ANALYSIS (SECOND ITERATION)

5.2.1. Severity, Likelihood and Building Blocks

The definition of Severity and Likelihood was reviewed and updated in the second Iteration, in order to apply more objective criteria. For this purpose, measurable quantities associated to Likelihood and Severity scoring have been identified and linked to the existing norms where possible (see Table 5.2-1). This has also been the basis to define the scope and the format of the information to be submitted to a relevant national authority.

In order to estimate the severity associated to the risk the methodology summarised hereafter has been adopted:

- **Risk identification:** the risk list previously identified in the "first iteration" (see 5.1), has been reviewed and consolidated.
    - For the evaluation of the Index assigned to each identified Risk, and for the evaluation of the overall mission scenario Risk Index (for the evaluation of the First Iteration see 5.1.1), the following equation are applied:

      $Rsc\_I = Ssc\_S * L\_S$ (to be evaluated for each Risk sub-category)

      $R\_I = \Sigma\ Rsc\_I$ (to be evaluated for each Risk)

      $MS\_R = \Sigma\ R\_I$ (to be evaluated for the overall Mission Scenario)

      Where:

      R_I (Risk Index) = "Risk Index" in 5.1.1
      R_{sc}_I (Risk sub-category Index)
      S_{sc}_S (Severity sub-category Score)
      L_S (Likelihood Score)
      MS_R (Mission Scenario Risk) = "Scenario Total Risk" in 5.1.1

  Severity and Likelihood values have been assigned to each sub-risk according to **Error! Reference source not found.**Table 5.1-2. The approach is detailed below:

- **Severity drivers:** For each potential risk, the **severity drivers** have been identified: the measurable quantity that can be used to establish a **severity metrics**. When possible these drivers are related to existing norms and laws.

- **Severity sub-categories:** In order to more accurately take into account the potential effects associated to each risk, the initial single severity score was divided in three sub-categories. These categories are related to the potential impact of a given risk at three levels i.e. human life, assets and environment (as per 5.1.1).
    - **Effects on human beings:**
        - Defined as the **risk of causing injuries and loss of human life both by direct effects on the Earth or in space, or indirectly by leading to** a conflict or humanitarian crisis.
    - **Effects on assets:** e.g. liability for induced damages, liability for financial loss.
        - Defined as effects on assets including potential damages to assets on Earth or in space.
    - **Effects on the environment** e.g. pollution of useful sites/location, alteration of the heritage.
        - Negative impacts on top of direct effects on economy or human beings, which the pollution of the environment can cause, actions that can led to a **degradation of the original environment** are considered as posing a risk in themselves, therefore in this category the risk of modifying the environment ***per se*** is estimated.

- **Severity scoring approach**: The severity drivers have been used to define proper metrics associated to the various severity sub-categories (comparable scoring among the severity sub-category).

Each step of the methodology is detailed in the following sections and summarised in Figure 5.2-1.

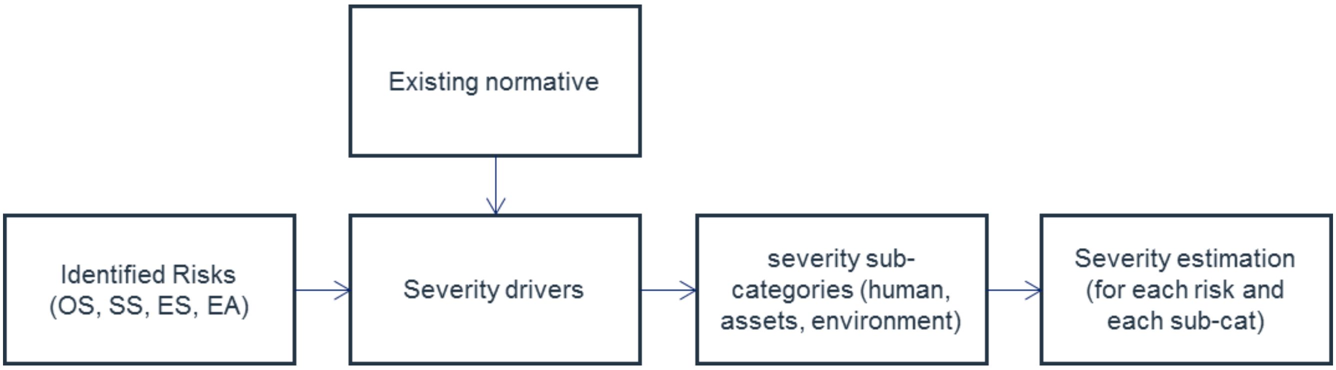


Figure 5.2-1 Severity estimation methodology

The estimation of the Severity of each risk may be related to a significant and measurable quantity the **Severity driver**. When possible the estimation of **Severity sub-category** is linked to existing norms. For what concerns the score estimation of the **Severity sub-categories** which cannot be directly related to existing normative, or which cannot be easily verified quantitatively, a more qualitative, but traceable, approach is adopted. Then the significant figure is used to estimate the severity related to each of the sub-categories. Table 5.2-1 lists the Severity drivers.

severity estimation drivers		main existing reference normative
OS-01	number of fragments (d > 1 cm TBC)	UN 1967 Outer Space Treaty
SS-01	number of fragments (d > 1 cm TBC)	UN 1967 Outer Space Treaty
SS-02	level of risk is related to the categories for target body/mission type as defined in the COSPAR Planetary Protection Policy	COSPAR Planetary Protection Policy
SS-03	ammount of released material	UN 1979 Moon Agreement
SS-04	number of fragments (d > 1 cm TBC)	UN 1979 Moon Agreement
SS-05	kinetic energy of the impact	UN 1979 Moon Agreement, UN 1972 Liability Convention
EO-01	number of fragment (min diameter function of orbit) * lifetime of the fragment	ISO IS24113, ECSS-U-AS-10, ESA/ADNMIN/IPOL
EO-02	number of fragments (d > 1 cm TBC)	ISO IS24113, ECSS-U-AS-10, ESA/ADNMIN/IPOL
EA-01	kinetic energy of the impact and/or total Casualty Area of re-entering fragment	ISO IS24113, ECSS-U-AS-10, ESA/ADNMIN/IPOL
EA-02	total Casualty Area of re-entering fragment	ISO IS24113, ECSS-U-AS-10, ESA/ADNMIN/IPOL
EA-03	total Casualty Area of re-entering fragment	ISO IS24113, ECSS-U-AS-10, ESA/ADNMIN/IPOL
EA-04	level of risk is related to the categories for target body/mission type as defined in the COSPAR Planetary Protection Policy	COSPAR Planetary Protection Policy
EA-05	amount of released material	COSPAR Planetary Protection Policy
EA-06	ammount of released material	ISO IS24113, ECSS-U-AS-10, ESA/ADNMIN/IPOL

Table 5.2-1 Severity drivers

Table 5.2-2 reports all the identified risks, classified according to the threatened environment, and split according to the three risk sub-categories. In particular, in the “Risk Sub-Category Index” column the sub-category applicable to the given risk is identified (colour code: red for human, blue for assets, green for environment; white means that that category is not involved in that particular risk).

ID	Threatened environment	Risk	Detail	Target	Destination	Risk Sub-Category		
						HUMAN	ASSET	ENV.
OS-01	Outer space environment	Increase the MM background population	Generation of fragment caused by mining of materials on NEA, depending on the NEA escape velocity (escape of regolith material from the Moon very unlikely)	NEA	Moon & Earth Orbit, Lagrange Point, Moon & Earth Surface			
SS-01	Solar system bodies surface and/or near environment	Generation of fragments released in NEA orbit, which could prevent the future exploitation of the NEA on which the mining has been performed	Generation of fragment caused by mining of materials on NEA, depending on the NEA escape velocity (escape of regolith material from the Moon very unlikely)	NEA	Moon & Earth Orbit, Lagrange Point, Moon & Earth Surface			
SS-02		Forward planetary protection	Transfer of organisms from Earth to another celestial body, level of risk is related to the categories for target body/mission type as defined in the COSPAR Planetary Protection Policy	Mars, Europa, others TBD	Moon & Earth Orbit, Lagrange Point, Moon & Earth Surface			
SS-03		Release of toxic material or NPS on solar system bodies surface	Unwanted release of toxic materials or NPS caused by a failure during the surface operation on NEA, Moon	NEA, Moon	Moon & Earth Orbit, Lagrange Point, Moon & Earth Surface			
SS-04		Pollution of Moon orbital space	Pollution of the Moon orbital space caused by the transportation / insertion into Moon orbit of material extracted on solar system bodies	NEA, Moon, Mars, Europa, others TBD	Moon Orbit			
SS-05		Catastrophic event on Solar System body	Caused by asteroid redirection. Level of risk may be related to extraction process, which could impart momentum to the asteroid, can result in a change of orbit making casing an impact on solar system bodies (eg: Moon, Mars, etc)	NEA	Moon & Earth Orbit, Lagrange Point, Moon & Earth Surface			
EO-01	Earth orbital space	Pollution of Earth orbit	Pollution of the Earth orbital space caused by the insertion into Earth orbit of material extracted on solar system bodies	NEA, Moon, Mars, Europa, others TBD	Earth Orbit			
EO-02		Crossing of Earth orbit	Generation of fragment caused by extraction of materials on a NEA that can cross Earth orbit	NEA	Moon & Earth Orbit, Lagrange Point, Moon & Earth Surface			
EA-01	Earth atmosphere and/or surface	Catastrophic event on Earth	Caused by asteroid redirection. Level of risk may be related to extraction process, which could impart momentum to the asteroid, can result in a change of orbit making it hazardous for impact on Earth	NEA	Moon & Earth Orbit, Lagrange Point, Moon & Earth Surface			

ID	Threatened environment	Risk	Detail	Target	Destination	Risk Sub-Category		
						HUMAN	ASSET	ENV.
EA-02		Re-entry of NEO fragments on Earth	Generation of fragment caused by extraction of materials on a NEA that can cross the Earth space and re-enter on earth atmosphere	NEA	Moon & Earth Orbit, Lagrange Point, Moon & Earth Surface			
EA-03		Re-entry of NEA and/or entry system on Earth	Caused by a failure during the re-entry phase	NEA	Moon & Earth Orbit, Lagrange Point, Moon & Earth Surface			
EA-04		Backward planetary protection	In case of failure during the re-entry phase the material extracted on the planetary body could be re-enter in a non-nominal way on the Earth surface. According to the planetary body from which the material has been extracted different level of risk can be identified:	NEA, Moon, Mars, Europa, others TBD	Earth Surface			
EA-05		Re-entry of toxic material	caused by failure during the re-entry phase in case toxic material are used (e.g.: hydrazine)	NEA, Moon, Mars, Europa, others TBD	Earth Surface			
EA-06		Re-entry of NPS	caused by failure during the re-entry phase in case NPS are used	NEA, Moon, Mars, Europa, others TBD	Earth Surface			

Table 5.2-2 Risk table and associated severity sub-category

In order to have comparable scoring among the three severity sub-categories it was decided to adopt the same risk table for all the three severity categories defining the range of scoring associated to each category, as shown in Table 5.2-3.

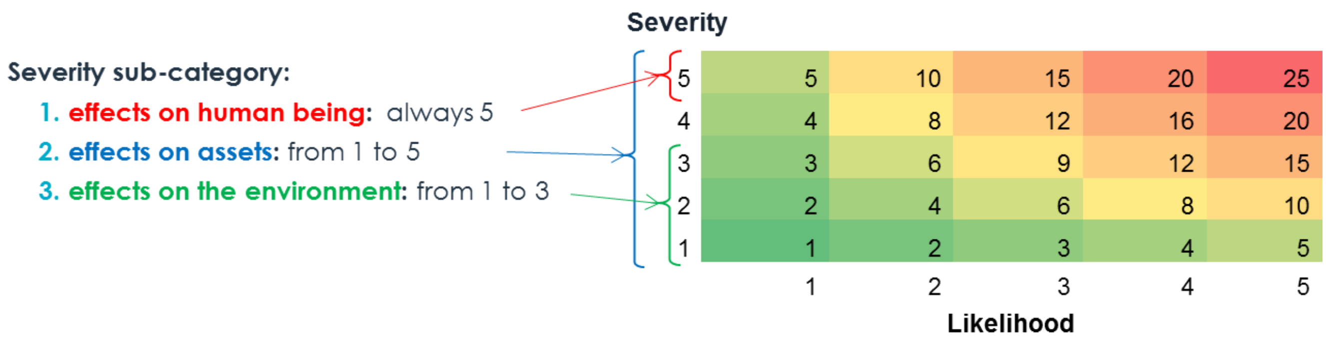


Table 5.2-3 Scoring ranges vs severity sub-category

Hereafter the approach to the scoring criteria is presented. The criteria/quantities associated to the severity sub-categories are reported as follows: starting from the severity main drivers identified before, the scoring for each severity sub-category is assigned according to the measurable, perceptible quantity as reported in Table 5.2-4.

- **Human:** For human casualties caused by operation in space we need to consider the principle of perceived risk, even one casualty caused by space activity will be perceived by the public opinion as an unacceptable risk and could have a significant impact on future space activities. Therefore, for the severity score the maximum value will always be assumed, i.e. 5. If the assessment of the main driver shows that a human casualty is potentially possible, then the score associated will be 5, and otherwise it will be 0.

- **Assets:** the scale is weighted on the entity of financial collateral damage and goes from 1 to 5. The financial collateral damage has to be established starting from the severity driver identified for each risk.

- **Environment:** The scale is weighted on the level of the environmental damage. Values range from 1 to 3, since the effects related to the environment in terms of economic value (asset) and threat to life (human) are already taken into account by the previous categories, where relevant, and this comes on top. For what concerns the environment risks, the measurable criteria have to be linked to the treated environment (i.e. a damage of the Earth environment is not the same than damage on a planetary body).

Severity typology	Scoring criteria	0	1	2	3	4	5
Human	Number of injured / casualties	N/A					1 or more casualties
Assets	Estimated economic loss	N/A	<1 M€	1-5 M€	5-10 M€	10-50 M€	>50 M€
Environment	risk related, see detailed description	N/A	Low impact	Medium impact	High impact		

Table 5.2-4 Scoring criteria

The Likelihood is strictly dependant on the characteristics of the Mission that shall be realised. In order to define a general approach encompassing a wider range of space projects, a shortlist of Mission Building Blocks has been selected.

The Building Blocks for each category are:

- **Spacecraft**
  - Reliability
  - Planetary Protection Policy
  - Propulsion System
  - Re-Entry System
  - Toxic/Nuclear Material on board
- **Environment**
  - Target Escape Velocity
  - Target Earth crossing distance (MOID)
  - Target Soil Particle Size
- **Operations**
  - Surface Operation
  - Critical Operation
  - Target Redirection

Each of the Building Blocks listed above can assume different values, depending on the choices done in the Mission Design. As an example the values assumed for the building blocks of the Environment category is shown below.

Environment	Building Block	Building Block	Building Block	Building Block	Building Block
	Target Object Escape velocity	Target Earth Crossing distance (MOID)	Target Soil Particle Size	-	-
Block Value 1	Not Applicable	Not Applicable	Not Applicable	-	-
Block Value 2	<0.1 m/s	<0.05 Au	Dust/Regolith	-	-
Block Value 3	0.1<x<10 m/s	0.05<x<0.1 Au	Compact soil	-	-
Block Value 4	>10 m/s	>0.1 Au	Unknow density	-	-
Block Value 5	-	-	-	-	-

Table 5.2-5 Environment Building Block values

To each Building Block, for every Risk described on Table 5.2-2, a "weighting factor" is associated that represents how the selected value of the Building Block affects the likelihood of each risk.

The following ranking has been associated to each Building Block:

Ranking	MITIGATION					No impact	INTENSIFICATION				
	Global	Strong	Average	Light	Poor		Poor	Light	Average	Strong	Global
	-5	**-4**	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**5**

Table 5.2-6 Building Block Ranking

In the table above, the values in red represent the contributions that increase the likelihood of a particular risk, and the ones in green represent the contributions to mitigating the likelihood of the same risk.

As an example, the Building Block ranking is shown below for the Environment category and for Risk OS-01, Increase the MM Background Population.

Environment	**Building Block 1**		**Building Block 2**		**Building Block 3**		**Building Block 4**		**Building Block 5**	
	Target Object Escape velocity	weighting factor	Target Earth Crossing distance (MOID)	weighting factor	Target Soil Particle Size	weighting factor	-	weighting factor	-	weighting factor
Block Value 1	Not Applicable	0	Not Applicable	0	Not Applicable	0	-	0	-	0
Block Value 2	<0.1 m/s	3	<0.05 Au	0	Dust/Regolith	1	-	0	-	0
Block Value 3	0.1<x<10 m/s	2	0.05<x<0.1 Au	0	Compact soil	0	-	0	-	0
Block Value 4	>10 m/s	1	>0.1 Au	0	Unknow density	1	-	0	-	0
Block Value 5	-	0	-	0	-	0	-	0	-	0

Table 5.2-7 OS-01 Risk Building Blocks Ranking

The Likelihood of a Risk is the composition of the different contributions of each applicable Building Block. To evaluate this contribution, for each scenario, the "weighting factor" of a particular Building Block is modified by the influence of all the other "weighting factors" of all the other Building Blocks which contribute to the definition of the overall single scenario.

This influence is modelled by adding to the former Building Block “weighting factor” the product of two “weighting factors” (normalised), see APPENDIX A :.

In order to take into account that a contribution may increase or mitigate the likelihood of a particular risk, the sign of the product has to be modified as in **Error! Reference source not found.**. A sign "+" increases the starting value, leading to a worse situation, and a sign "-" decreases the starting value, leading to a better situation.

In this way, for each Building Block the "Likelihood driver" is computed, taking into account the influence on a particular Building Block of all the other Building Blocks. This is done by summing all the influences of all the Building Blocks that contribute to the definition of the scenario being analysed. In this sum, the relevant sign is applied to each term, and the formula evaluates the absolute impact of each Building Block by normalising the weighing factor and, then, multiplying the ratio between each pairs of Building Block that are applicable to the considered scenario.

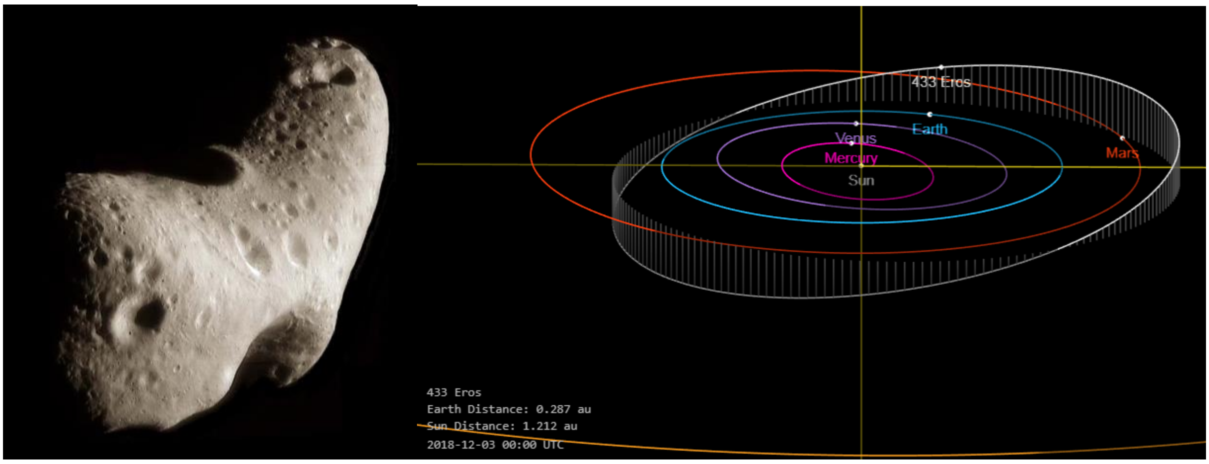
Based on the methodology described here above, and the mission analysis summarised in 5.2.2 the Total Risk per Scenario and the Total score per Risk has been calculated (see paragraph 5.2.3).

5.2.2. Mission Analysis

The Mission Scenarios are analysed in this section. It must be underlined that the NEA for scenarios 4, 7 and 8 have been chosen because detailed data are available about them and, thus, they are considered good candidates to test the methodology; they have not been chosen because they are considered good candidates for the mission in any particular way. In the following the main Building Blocks per each scenarios mission analysis are listed.

Sc. #	Target	Destination	Resource	Objective	Orbit Redirection
4	NEA	Lagrange (Earth-Moon)	Water	Storage & Transportation	No

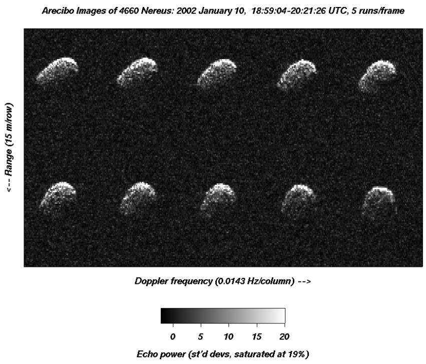
- EROS

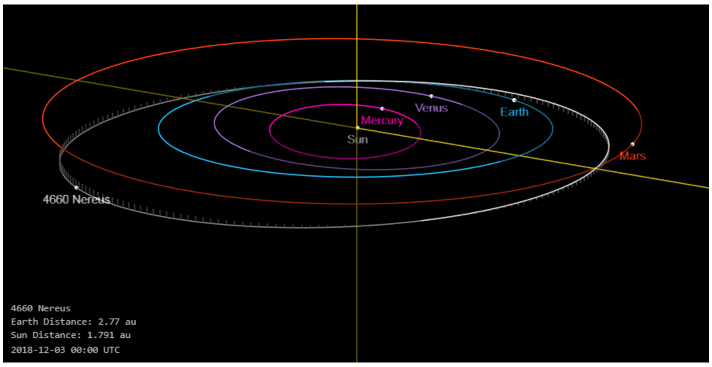


  - Spacecraft
    - Chemical Propulsion
  - Environment
    - Target Escape Velocity > 10 ms^{-1}
  - Operations
    - Extraction
    - Earth-Moon Proximity Operation

Sc. #	Target	Destination	Resource	Objective	Orbit Redirection
7	NEA	Earth Orbit	Sample	Storage & Transportation	Yes (*)
8	NEA	Earth Surface	PGM	Extraction, Storage & transportation	Yes (*)

- 4660 NEREUS

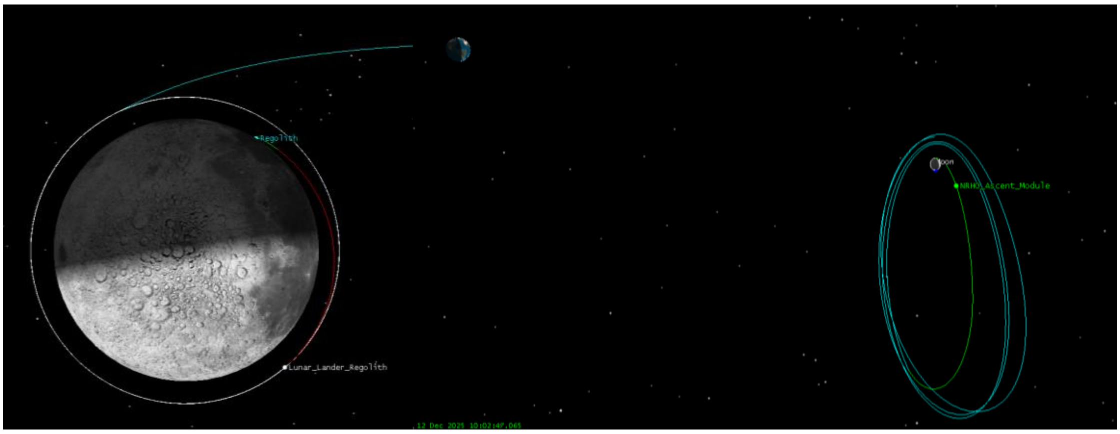




- Spacecraft
  - Electric Propulsion
  - Re-entry System (only for Scenario n. 8)
- Environment
  - Target Escape Velocity < $1 ms^{-1}$
- Operations
  - Extraction
  - Earth-Moon Proximity Operation

(*) or for direct transportation to another destination of a fragment l<10 m in diameter.

Sc. #	Target	Destination	Resource	Objective	Orbit Redirection
10	Moon Surface	Moon Surface	Regolith	Excavation & Processing	No
9 (**)	Moon Surface	Lagrange (Earth-Moon)	Water	Storage & transportation	No

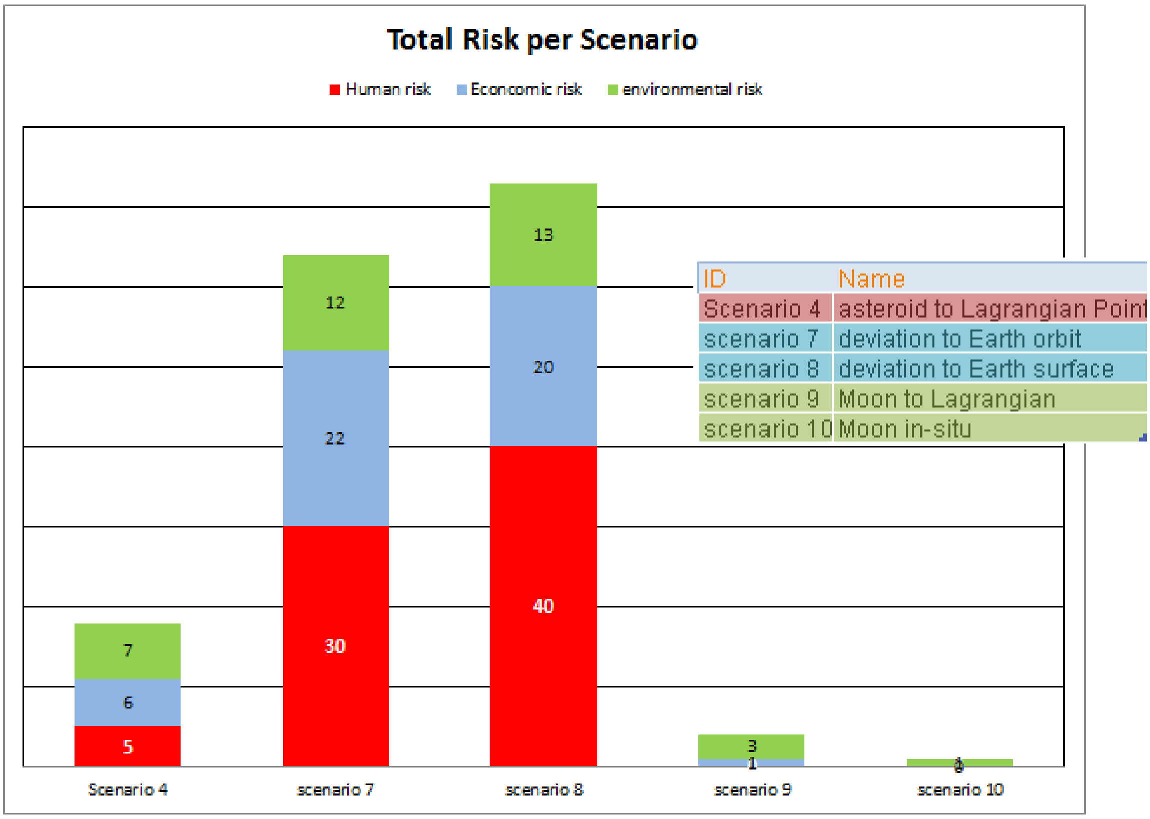


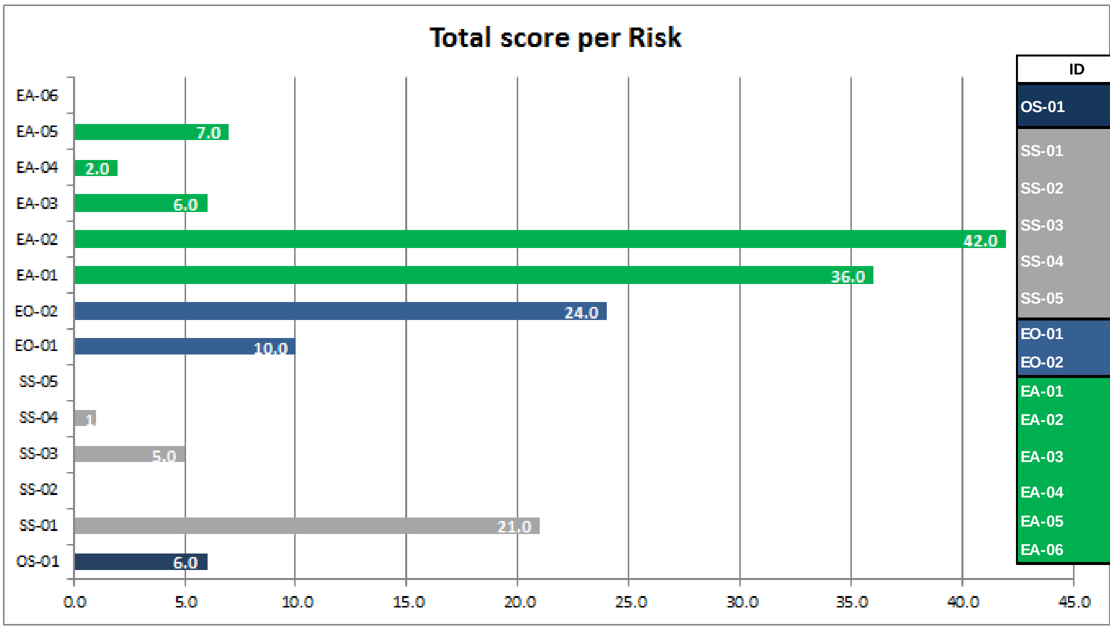
- Spacecraft
  - Chemical Propulsion
- Environment
  - Target Soil Composition
- Operations
  - Excavation
  - Earth-Moon Proximity Operation
  - Transportation (only for Scenario n. 9)

(**) as scenario 9 but modified

5.2.3. Total Risk per Scenario & Total Score per Risk

The total risk per scenario and the total score per risk are given in following figures.





ID	Risk
OS-01	Increase the MM background population
SS-01	Generation of fragments released in NEA orbit
SS-02	Forward planetary protection
SS-03	Release of toxic material or NPS on solar system bodies surface
SS-04	Pollution of Moon orbital space
SS-05	Catastrophic event on Solar System body
EO-01	Pollution of Earth orbit
EO-02	Crossing of Earth orbit
EA-01	Catastrophic event on Earth
EA-02	Re-entry of NEO fragments on Earth
EA-03	Re-entry of NEO and/or entry system on Earth
EA-04	Backward planetary protection
EA-05	Re-entry of toxic material
EA-06	Re-entry of NPS

Figure 5.2-2 Total risk per Scenario and Total score per Risk

In this second iteration, a similar exercise as in the first iteration has been carried out. Here, too, the same caution on the use of the numerical values shall apply; these amounts can be used to extract some trends but not to compare risks or missions. Bearing this in mind, the results are:

- Total Risk per Scenario
  1. Low value, for NEA Scenario (sc4) and Moon scenarios (sc8 & 9)
  2. High value, for NEA scenarios (sc7 & 8) where orbital redirection is foreseen
- Total score per Risk
  1. Minimum value, Increase of MM background population, Forward Planetary Protection, Pollution of Moon Orbital Space, Pollution of Earth Orbit, Re-entry of NEA and/or entry System on Earth, Backward planetary protection, Re-entry of toxic material and Re-entry of NPS (OS-01, SS-02, SS-04, EO-01, EA-03, EA-04, EA-05 and EA-06)
  2. Medium value, Generation of fragments released in NEA orbit, Release of Toxic material or NPS on solar system bodies surface, Catastrophic event on solar system body and Crossing of Earth orbit (SS-01, SS-03, SS-05, EO-02)
  3. High, Catastrophic event on Earth and Re-entry of NEA fragments on Earth (EA-01 and EA-02).

The “High” value for NEA scenarios (sc7 & 8) where orbital redirection is foreseen, together with the “High” value for risk “Catastrophic event on Earth (EA-01)”, is still mainly due to the high values assigned to Severity in the Human and Asset sub-categories i.e. 5. The value assigned to likelihood is high too (4) and is a function of the mitigation effect assigned to the use of electric propulsion in the Spacecraft category of EA01 Building Block. For example, changing the mitigation value from -1 to -3 leads to the Likelihood value of 3 and, hence, the Total score per Risk EA-01 changes from 104 to 78. It should be stressed however that the high values are still not associated to any numerical estimation of the factors based on physical models (e.g. for atmospheric entry and break-up of a small NEA or fragment); such models exist and can be incorporated in further and more detailed assessments.

The “Low” value for Moon scenarios (sc8 & 9) is due to its relatively high gravity field and escape velocity, sufficient to prevent the release of fragments to Moon and/or Earth orbit.

What is new in this second iteration with respect to the first one is that also the NEA Scenario (sc4) has a “Low” risk index value. In the first iteration (see 5.1.2) a “Medium” value was computed for the scenarios where no NEA re-direction was foreseen. The explanation is that a relatively big asteroid (Eros) has been chosen for this exercise (as data were already available, see 5.2.2); the larger mass of this asteroid results in a larger value of escape.
Hence, risk of increase the micrometeoroid (MM) background population is now lower because of the effect of a larger escape velocity and lower likelihood of surface material release into space. Also, because of the choice of mitigation options such as the encapsulation method for the asteroid (4660 Nereus) chosen for scenarios 7 & 8 with orbital redirection.

On the other hand the medium values for Generation of fragments released in NEA orbit, Release of Toxic material or NPS on solar system bodies surface, Catastrophic event on solar system body and Crossing of Earth orbit are driven from the choices done at Spacecraft and Operation categories level, coherently to the fact that a small NEA is redirected towards Earth.

Last, it must be noticed that Forward planetary protection is 0 because it is not applicable to any of the chosen scenarios, Pollution of Moon orbital space is low because for scenario 4 the Earth-Moon proximity operation has a weighting factor of 1 and Backward planetary protection is low, too, because for scenario 8 the Earth-Moon proximity operation has a weighting factor of 1 and the Planetary protection Policy has a weighting factor of 1 (that is COSPAR standard).

6. CONCLUSIONS

In the study, the potential risks related to a SRU mission have been identified and classified according to threatened environment and affected entity. This classification provides the foundation for a methodology to evaluate the risk related to SRU missions. A risk index is calculated as a function of Severity and Likelihood. The Severity is estimated on the basis of severity drivers, while Likelihood is estimated based on the contributions of Mission Building Blocks.

The methodology was tested in two iterations on first ten, and then five mission scenarios. Each of the scenarios was defined using a pre-defined set of Mission Building Blocks. In principle, these should be relevant to the risk evaluation of any future mission concepts that apply for an authorization to operate by the certification authority.

There were also some lessons that resulted from the analysis carried out during the study. For instance, it was concluded that no accidental deviation of asteroids orbit is possible when considering a realistic SRU mission scenario. Intentional redirection however is a sensitive operation in case Earth’s orbital environment is affected, but risk of damage and liability due to an uncontrolled NEA re-entry is low due to the sizes of the objects, or fragments of objects, that can be considered in realistic mission scenarios.

Also, it seems unlikely that fragments and debris due to activity on Moon surface will pose a threat to the lunar orbital environment and to any assets on the Earth-Moon though some detailed analysis might be required to better assess the dynamics of surface ejecta and the long-term orbit stability around the Moon. Finally, the assessment concludes that forward planetary protection is not an issue for the targets considered in the analysis (moon and NEAs).

The study also included a revision of existing sets of norms that can be relevant to assess severity and/or likelihood. As a concrete tool for the use of the proposed methodology, a submission form was developed, with guidelines for the entities seeking certification.

Finally, a spreadsheet model has been developed to implement the methodology proposed in the study to support and test the risk analysis.

APPENDIX A : ANNEX 1

SS-05	Applicable				Spacecraft BB01	Spacecraft BB02	Spacecraft BB03	Spacecraft BB04	Spacecraft BB05	Environment BB01	Environment BB02	Environment BB03	Environment BB04	Environment BB05	Operations BB01	Operations BB02	Operations BB03	Operations BB04	Operations BB05	Likelihood driver
Catastrophic event on Solar System body					Reliability	Planetary Protection Policy	Propulsion Subsystem	Re-entry System	Toxic / Nuclear Material on board	Target Object Escape velocity	Target Earth Crossing distance (MOID)	Target Soil Particle Size	-	-	Surface Operation	Critical Operations	Asteroid Redirection	-	-	
Likelihood	3				Standard (TRL > 8, SFT)	COSPAR Standards	Electric Propulsion	Yes	Not Applicable	0.1<x<10 m/s	<0.05 Au	Compact soil	-	-	With debris mitigation	Earth-Moon Proximity operations	Yes, with encapsulation	-	-	
				weighting factor	0	0	-1	0	0	1	3	0	0	0	0	1	1	0	0	
Spacecraft	BB01	Reliability	Standard (TRL > 8, SFT)	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spacecraft	BB02	Planetary Protection Policy	COSPAR Standards	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spacecraft	BB03	Propulsion Subsystem	Electric Propulsion	-1	0	0		0	0	0.20	1.80	0	0	0	0	0.20	0.20	0	0	1
Spacecraft	BB04	Re-entry System	Yes	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0
Spacecraft	BB05	Toxic / Nuclear Material on board	Not Applicable	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0
Environment	BB01	Target Object Escape velocity	0.1<x<10 m/s	1	0	0	-0.20	0	0		1.80	0	0	0	0	0.20	0.20	0	0	3
Environment	BB02	Target Earth Crossing distance (MOID)	<0.05 Au	3	0	0	-0.07	0	0	0.07		0	0	0	0	0.07	0.07	0	0	3
Environment	BB03	Target Soil Particle Size	Compact soil	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0
Environment	BB04	-	-	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0
Environment	BB05	-	-	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
Operations	BB01	Surface Operation	With debris mitigation	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0
Operations	BB02	Critical Operations	Earth-Moon Proximity operations	1	0	0	-0.20	0	0	0.20	1.80	0	0	0	0		0.20	0	0	3
Operations	BB03	Asteroid Redirection	Yes, with encapsulation	1	0	0	-0.20	0	0	0.20	1.80	0	0	0	0	0.20		0	0	3
Operations	BB04	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
Operations	BB05	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0

Table 5.2-1 Likelihood calculation example

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