UNIVERSITÀ DEGLI STUDI DI PADOVA

Dipartimento di Ingegneria Industriale DII

Corso di Laurea Magistrale in Ingegneria Aerospaziale

Development of an engineering algorithm for satellite collision risk assessment and classification

Relatore: Professor Alessandro Francesconi

Laureando: Federico Toson
1232107

Anno Accademico 2021/2022

Abstract

The frequency of space launches since the beginning of the space age has increased exponentially. The current number of orbital debris and hence orbital collisions is one of the most debated issues at present and for which various solutions are being sought. An inevitable need has arisen to regulate such launches and to determine the risk associated with space missions as effectively as possible. This need has been intensified by recent events that have shaken up the space market, leading to the growth of the private sector and the ambition to put not only military but also civilian astronauts into orbit. All this clearly defines the world's intentions, and in addition to sanctioning the start of space privatisation, it also imposes more stringent regulation and protection for stakeholders and space environment in general. This can be done mainly through an accurate study of space risk, which requires knowledge of possible single events, their probability of occurrence and their severity. Nowadays, several studies are known for the calculation of individual risk, but the scientific community and the space market are looking for a global and collective assessment of collision risk, i.e., the risk related to events that do not cause the failure of a single mission but may affect the whole orbital community. This thesis focuses on the development of a new engineering algorithm for the calculation of collision risk to provide a possible subsequent classification and interpretation of the hazards that a satellite and a space ecosystem may face.

Table of Contents

Abstract **3**

1 Introduction and Objectives **7**

2 State of Art **9**

2.1 Risk in Space **9**

2.1.1 General Definitions 9

2.1.2 Space Risk Assessment 10

2.2 Insurance Applications **13**

2.2.1 Preliminary space risk classification 13

2.2.2 More accurate classification 14

2.2.3 Main problems in space risk assessment 15

2.3 Collision Risk Assessment Introduction **16**

2.3.1 Space Debris Problem 16

2.3.2 Reliability 16

2.3.3 Factors influencing the risk of collision 16

3 Market Needs **18**

3.1 Collision Risk in Space Law **21**

3.2 Space Insurance Market **22**

3.2.1 The New Space Economy 23

3.3 The Need for Classification **24**

4 Space Collision Risk Assessment **25**

4.1 Current Methods and Indexes **25**

4.2 Inputs & Outputs **29**

4.2.1 Inputs 29

4.2.2 Outputs 31

4.3 Probability Introduction **31**

4.3.1 Population 31

4.3.2 Common Methods for Probability Computation 33

4.4 Severity Introduction **41**

4.4.1 Cost Analysis 42

4.5 Further Assessments **47**

4.5.1 Fragmentation Risk Evaluation 47

4.5.2 Survivability and Vulnerability of a Satellite 48

5 Proposed Formulation of Collision Risk **50**

5.1 Proposed Inputs & Outputs **50**

5.2 Collision Probability Computation **51**

5.3 Collision Severity Computation **54**

5.3.1 Fragmentation Consideration 54

5.4 Risk Formulation **55**

6 Index definition **56**

6.1 Proposed Classification Algorithm **57**

6.1.1 Collective Scenario 57

6.1.2 Individual Scenario 58
6.1.3 Mitigation Solutions 60
6.1.4 Final Definition 61

6.2 MATLAB® Development of the Algorithm 62
6.2.1 databasecreator.m 62
6.2.2 probability.m and severity.m 63
6.2.3 Other Functions 64

6.3 Examples of Application 65
6.3.1 ENVISAT 65
6.3.2 Sentinel-6 65
6.3.3 Starlink 66

7 Conclusions and Future Uses 67

7.1 Conclusions 67

7.2 Future Uses 69

References and Abbreviations 70

References 70

Abbreviations 74

Appendix 75

Acknowledgements 79

1 Introduction and Objectives

In order to address the topic discussed in this thesis, it is appropriate to begin with a brief overview of the current treatment of the topic and the environment in which it is confined.

With the wide range of risks associated with space missions, it can be observed that, as with all the so-called *special risks*, the overall understanding of space risk has several points of indeterminacy. A major limitation of space risk assessment is the small number of repeated historical events that, in larger numbers, would not only provide a precedent for the assessment of future missions but also the input for advanced simulations. Reducing more the amount of data available is the secrecy associated with many past missions that conceal information for government or research purposes.
However, the New Space Economy (NSE) and standardisation strategies, such as ECSS [1], are helping to make the use of mission data increasingly regular.
In addition to this, more and more studies are being carried out in the field of space legislation, which is leading to greater awareness in the legal assessment of space missions.
At present, the satellite (SAT) risk calculation, the calculation of the pure premium and the subsequent mission insurance is carried out by consulting teams and agencies that can assess relatively accurately the individual risk associated with individual vehicles.
Given that individual assessment is feasible and will become increasingly so over the years, the market's request is to create a common scale on which to include the players in the space ecosystem to determine the reciprocal dangers between them.
Having denoted the need to determine the collective risk by classifying the individual risk, in the study, even superficial, of this field, the risk of collision is the most consistent both in terms of probability and in terms of severity.
This importance lies in the studies already known about the increase in orbital population, especially in Low Earth Orbit (LEO), and the consequent repercussions in the event of catastrophic events such as the Kessler syndrome [2] [3].

Before discussing the actual development of the calculation algorithm, the first chapters of this master thesis will define the state of art (SOA) of risk assessment in space, its applications in insurance and the methodologies used to date. The current needs of the market will be discussed, with more attention paid to the collision risk in the legislative framework, in the insurance requirements, and a possible classification will be described.
Subsequently, the current methods of calculating individual collision risk, the inputs and outputs will be defined and then we will move on to the definition of collective collision risk and the proposed calculation algorithm.
The algorithm devised is based on workflow described in Chapter 5 (Proposed Formulation of Collision Risk) and is then implemented using a MATLAB® code for a true description and simulation of what is discussed in this thesis work.

Ultimately, the main objective of this thesis is to respond to the current need for risk classification, both in terms of technical and mission design aspects, as well as insurance and legislative aspects.

Below is a logical scheme of the entire thesis which is useful to understand the key points and how they are related to each other (Figure 1).

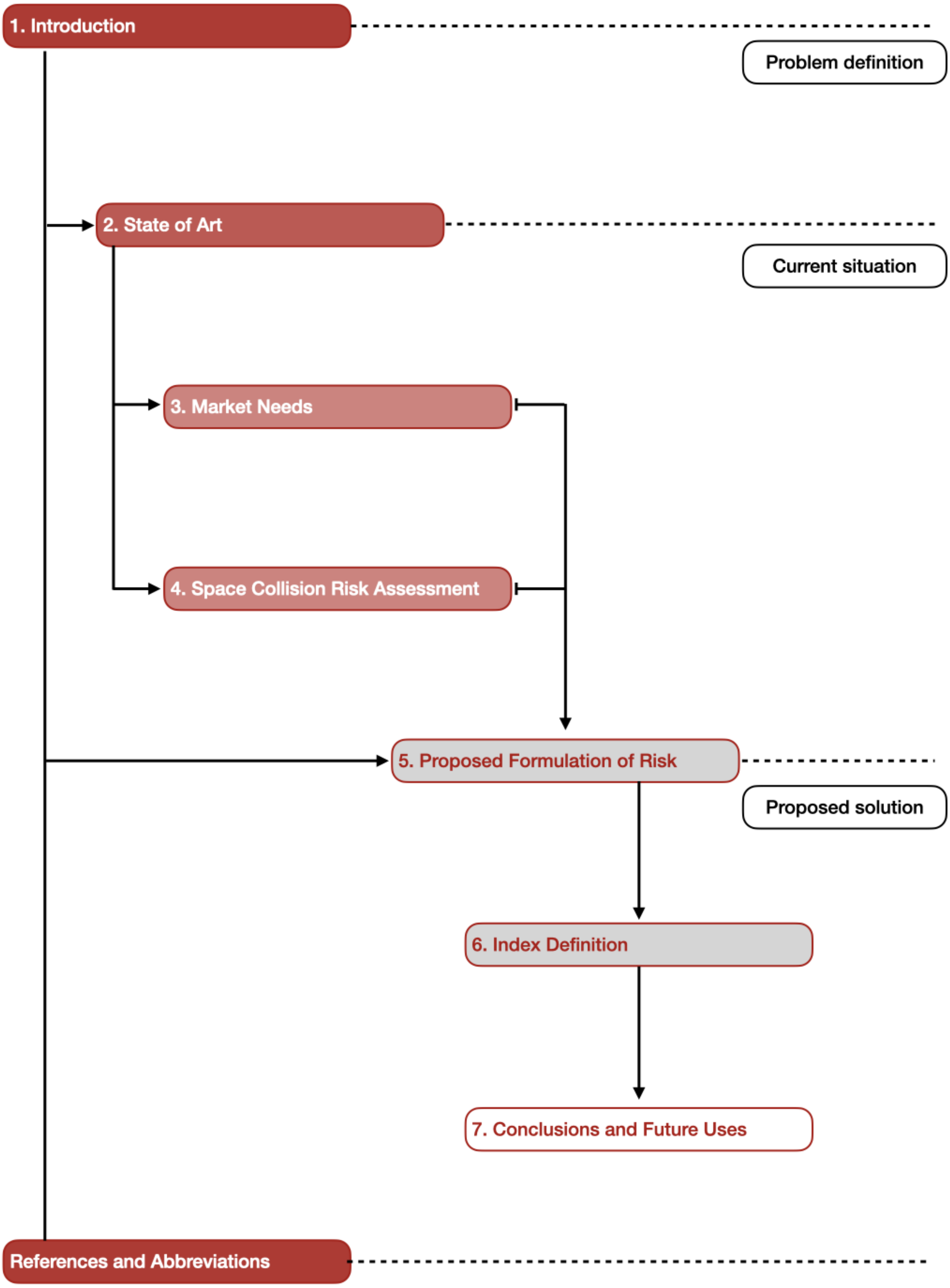


Figure 1: Thesis logic diagram.

2 State of Art

Starting from the SOA, it is inevitable to realise that, observing the introductory premises, this will have to be analysed on three different sides. Certainly, one aspect to be analysed, perhaps the most important, is the risk in space. Next, we see the implementation part of the same, which concerns insurance applications and, finally, entering the specifics of the topics covered, the applications in the field of collision through the definition of a preliminary collision risk classification.

2.1 Risk in Space

We therefore go on to define not only what is meant by risk but also how it is dealt with in the space environment.

2.1.1 General Definitions

According to the Cambridge Dictionary, the main meaning of the term risk is "*the possibility of something bad happening*" [4]; by defining the severity, that this event can cause (be it in economic, health or physical damage terms) and multiplying it by the probability of this event occurring, the risk is so defined as expressed in Formula 1 below.

$$(1)\quad R = P \times S$$

With R standing for Risk, P for Probability and S for Severity.

Risk, as well as having a wide applicability to various sectors, can be of different types, or rather it can have meanings that specify its meaning in relation to various contexts.
In fact, an important distinction that is made and that is fundamental for the appropriate analysis of the topics dealt with in this thesis, is the difference between individual risk and collective risk. These also have various applications and therefore, for an easier understanding, it is convenient to associate them first with familiar environments such as the road.
In the automotive scenario, collective risk is specified as the number of accidents that can occur on a given stretch of road in a year. While the individual risk refers to the single vehicle, in this case the car and the hypothetical accidents it may incur. Let's be clear that causes, now, are not distinguished from event to event, in fact, for the example we are giving, the accident is counted whether it is caused by a malfunction of the car, by atmospheric events, by the irregularity of the road, by driver error, and so on.
Individual and collective risk are, however, extremely closely related to each other; depending on the context, taking care not to make redundancies, one can move from individual hazard and frequency to collective risk and vice versa.
This correlation is fundamental not only for the best risk analysis but also for the specific case of this thesis, one of the objectives of which is to classify the various "protagonists" of a given scenario to understand their effects on the community.

Whether collective or individual, when an analysis is carried out in relation to a given event or series of events, related to a given activity or sector, we talk about risk assessment. This assessment is carried out according to strategies that may be uniform to corporate, national, or international regulations. Basically, when carrying out the risk assessment, an attempt is made to adhere to certain standards to allow an economic and financial quantification that gives an idea of the resources involved and a comparison with other similar scenarios.

2.1.2 Space Risk Assessment

In the space sector, the application modalities of risk assessment are very similar to other sectors but clearly adapted to the specific context. International entities have therefore defined guidelines to, as explained above, allow the analysis to be compared with previous events and/or similar missions.

In the European context, the regulations are expressed by the ECSS (European Cooperation for Space Standardization), specifically in the ECSS-M-ST-80C manual entitled "Space Project Management" in the "Risk Management" section [5].

The NTSS (NASA Technical Standards System) instead, does not provide precise directives for risk assessment, or rather, in the NTSS-8000 section (Safety, Quality, Reliability and Sustainability) [6] it provides directives for reliability assessment, but to find more specific standards, we rely on the manuals of the individual space bases, such as the GSFC-HDBK-8005 entitled "Guideline for performing risk assessment" [7], drawn up by the Goddard Space Flight Center documents.

Considering that the development environment of this research is located in Europe, both for regulatory correspondence and for a better applicability of the studied evidence, it was decided to progress keeping the previously described ECSS-M-ST-80C [5] model as a starting point. The European Cooperation for Space Standardization model not only assesses risk but also mitigates it as shown in Figure 2.

However, this cycle is only a part of the process, in fact, this loop of operations has to be carried out for the various phases of a space mission, which for the case of ECSS are described in the ECSS-M-ST-10 [1] handbook that always deals with the topic of "Space Project Management".

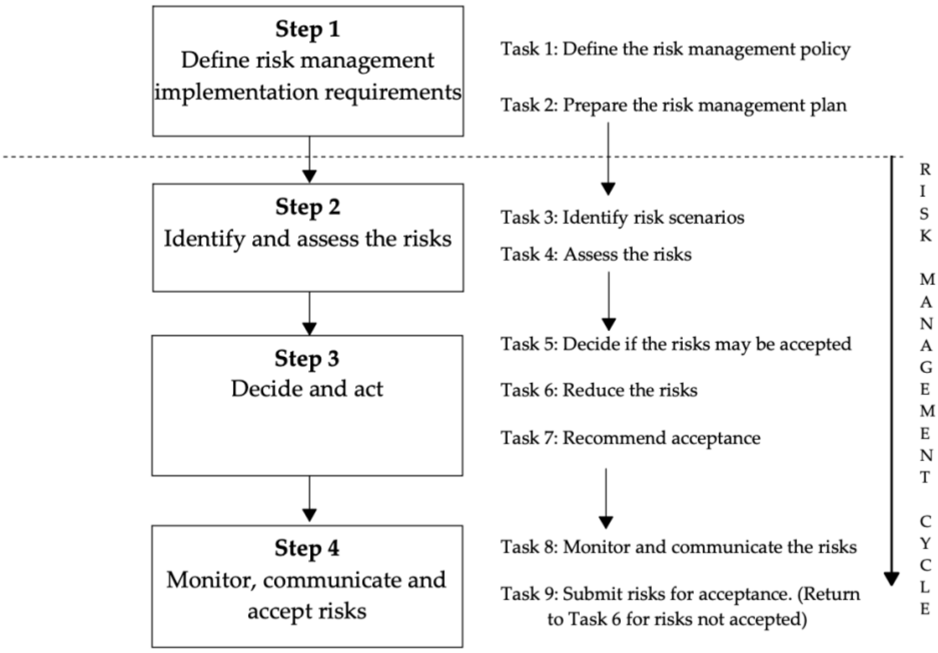


Figure 2: Steps in the risk management cycle from ECSS [5]

In the definition of the requirements and the risk management policy, the various degrees of severity are highlighted accordingly. As has already been specified severity and probability

are the two multiples of risk and need a calculation scale for the global assessment and, as usual, for an appropriate comparison.
In Table 1 and Table 2, again taken from the ECSS-M-ST-80C [5], it is possible to get a more descriptive overview of these classifications.

Table 1: example of a severity–of–consequence scoring scheme from ECSS [5].

Score	Severity	Severity of consequence: impact on (for example) cost
5	Catastrophic	Leads to termination of the project
4	Critical	Project cost increase > tbd %
3	Major	Project cost increase > tbd %
2	Significant	Project cost increase < tbd %
1	Negligible	Minimal or no impact

Table 2: example of a likelihood scheme from ECSS [5].

Score	Likelihood	Likelihood of occurrence
E	Maximum	Certain to occur, will occur one or more times per project
D	High	Will occur **frequently**, about 1 in 10 projects
C	Medium	Will occur **sometimes**, about 1 in 100 projects
B	Low	Will **seldom** occur, about 1 in 1000 projects
A	Minimum	Will **almost never** occur, 1 of 10 000 or more projects

Let us now suppose that we have an event whose risk we wish to calculate. Using the tables above, it is possible to define its severity and probability of occurrence in a simple way. The combination of the two terms will give us an immediate answer as to the extent of the risk. Obviously, however, in any space mission, it is undeniable that the risks involved can number in the hundreds. Therefore, a chromatic strategy is adopted to complete the simplification in the visualisation. In other words, the pair of scores obtained above is associated with shades of colour ranging from green to red.
In this way, if the risks of a mission were to be tabulated one after the other, it would be very easy to identify the most critical ones to carry out more in-depth evaluations.
This part of the method is also described in the ECSS handbook [5], but it is also a commonly used strategy in other sectors and in the insurance field in general. Table 3 below describes in full what is explained in words.

Table 3: example of risk index and magnitude scheme like the one from ECSS [5].

Likelihood						
E	Low	Medium	High	Very High	Very High	
D	Low	Low	Medium	High	Very High	
C	Very Low	Low	Low	Medium	High	
B	Very Low	Very Low	Low	Low	Medium	
A	Very Low	Very Low	Very Low	Very Low	Low	
	1	**2**	**3**	**4**	**5**	**Severity**

For the sake of completeness, it is worth mentioning that risk management reference manuals also include risk mitigation solutions. This is because, as also described in the cycle in Figure 2, the objective of a space agency or in general of a space mission manager is to carry out an iterative cycle leading to the minimisation of the identified risks. We clarify, however, that in the evaluation phase of the mission by external bodies, such as an insurance company, mitigation solutions are only useful for the economic quantification of the avoided damages and therefore remain an aspect related to the mission design.
Below (Table 4) is the relevant table that relates to the current ECSS standard [5] under review.

Table 4: example of risk magnitude designations and proposed actions for individual risks from ECSS [5].

Risk Index	Risk Magnitude	Proposed Action
E4, E5, D5	Very High Risk	Unacceptable risk: implement new team process or change baseline – seek project management attention at appropriate high management level as defined in the risk management plan.
E3, D4, C5	High Risk	
E2, D3, C4, B5	Medium Risk	Unacceptable risk: aggressively manage, consider alternative team process or baseline – seek attention at appropriate management level as defined in the risk management plan.
E1, D1, D2, C2, C3, B3, B4, A5	Low Risk	Acceptable risk: control, monitor – seek responsible work package management attention.
C1, B1, A1, B2, A2, A3, A4	Very Low Risk	Acceptable risk: see above.

After identifying all possible negative scenarios and related risks, an overall table summarising all these events is obtained. An example of such an overview is shown in Table 5.
In analysing the risks for a given mission, we must always bear in mind that the Severity of a given event can never be mitigated during the various iterations of risk assessment, while in the case of probability this can be done through appropriate actions that limit damage or make it much less probable. Such mitigation solutions should be reported in a table like the one below (Table 5), to highlight and justify low probabilities where severity is at critical levels, as in the example of the first risk (R1) in the same table.

Table 5: example of a summary table for space risk assessment.

ID	Scenario	L	S	Magnitude	Mitigation solution
R1	On-Board computer Failure	A	5	Low	Redundancy
R2	Active thermal control subsystem partial failure	B	2	Very Low	Passive thermal control
Rn	…	…	…	…	…

This table is therefore also a verification methodology to determine the reliability of a mission from the stakeholders and funders of the mission. However, it should be specified that the reliability of a SAT does not always coincide with its financial and economic repercussions, especially in the insurance field. In the summary table of all the risks, some involve repercussions linked to the compromise of the entire mission, others describe partial damage,

some present failures from the point of view of scientific research and others may involve damage to other payloads hosted on board the SAT or, worse, to other vehicles belonging to the same orbit.
In the unfortunate case that one of the events mentioned in the risk table occurs, the related damage should be quantified in advance, both to elaborate an accurate contributory negligence and to include a possible compensation by insurance agencies.

2.2 Insurance Applications

Given the most common method to carry out the space risk assessment, regardless of the type of mission, large sums of money are invested in launching a SAT into orbit, it is necessary to take out insurance with agencies specialising in the space sector. Given the many variables involved and the lack of data on past cases, the space insurer's job becomes a feasibility study with limited data, which therefore requires considerable effort.
A closer look at the insurance field reveals that space risk falls within the classification of special risks. Special risks are all risks that are different from those normally insured (cars, civil, etc.) and for which a specific feasibility study is carried out and there is no tendency to rely on automated mechanisms. One of the objectives of this thesis is precisely to try to develop an automated procedure for space risk, at least to have a preliminary result in the mission analysis phase.

2.2.1 Preliminary space risk classification

Like most special risks, the space risk needs to be split into several subgroups. This is because a SAT involved in each mission faces some life steps involving extremely variable environments, scenarios and accessibility with consequent risks and related damages that differ from one case to another. Therefore, the subdivision that the most quoted online insurance companies make for this type of coverage is as follows [8]:

- "*Pre-launch insurance provides coverage for loss or damage to the SAT or its components from the time they leave the manufacturer's premises, during the transit to the launch site, through testing, fuelling, and integration with the launcher up until the time the launcher's rocket engines are ignited for the purpose of the actual launch".*
- *"Launch insurance provides coverage for the period from the intentional ignition of the engines until the SAT separates from the final stage of the launch vehicle, or it may continue until completion of the testing phase in orbit. Coverage typically runs for a period of twelve months but is limited to 45–60 days in respect to the testing phase in orbit. Launch failure is the greatest probability of SAT loss and approximately 7% of SATs have failed on launch".*
- *"Coverage while in orbit provides for physical loss, damage, or even failure of the insured SAT while in orbit or during orbit placement. Elements of risk attached to SATs during orbit are damage caused by objects in the hostile space environment, extremes of temperature, and radiation. Because it is not typically possible to repair a SAT once it is physically placed in orbit, the coverage is basically granted as a product guarantee".*
- *"Third party liability is the final section of the policy and is a statutory requirement of the Government of the nation where the launch will take place, regardless of the nationality of the SAT owner. A special license must be provided to the regulating*

authorities before a launch can take place. Coverage usually runs up to 90 days following the actual launch. Loss of revenue coverage is also available but is not purchased often" [8].

Obviously, these also vary from case to case, i.e., the PL of a given mission can influence the value of the mission itself and the timescale of the activity also. To give an example, it is enough to think of a SAT belonging to a constellation of ten similar ones and compare it with an analogous one belonging to a constellation of only two; losing the vehicle in both cases leads to a failure of 10% and 50% of the mission respectively. It is therefore clear that, if we consider the two missions, if the expenditure to carry them out is the same, an insurer in charge of determining the respective coverage will calculate two different ones according to these details. However, as mentioned above, the various risks associated with a space mission are not of the same value, so, in addition to skimming off uninteresting technical features, insurance companies determine the pure premium.
The pure premium (*PP*) or net premium, is the one that is not affected by the management costs of the insurer, therefore it can be calculated, mathematically, as the product between a risk coefficient (ρ_R) and the total damages connected (*D*) to the event whose risk is discussed.

$$(2)\ PP = \rho_R \times D$$

The risk coefficient is mainly calculated on a probabilistic basis but also has policyholder-related influences. In the automobile insurance field, for example, a so-called bonus-malus is observed when taking out a policy, which changes the probability depending on the policyholder. In the spatial field, too, it is necessary to have guarantees from the agency being insured and to prove its reliability.

2.2.2 More accurate classification

However, by analysing the areas of economic coverage more carefully and taking the time scale of a mission as a basis, a more articulated subdivision into actual phases can be obtained.
For example, in the case of pre-launch coverage, one can distinguish between phases of long-time duration and which, in the hypothesis of the stipulation of a policy, should be highlighted.
A summary (Figure 3) of the scheme published by the Palgrave Macmillan Journals, in a paper dedicated precisely to Risk Management and insurance in the space field [9], is therefore reported. Some necessary comments on Figure 3, relate to the addition of phases that we have not mentioned so far. A glaring example is that, as anticipated, relating to the distinction between Manufacturing, Assembly, Integration, and Testing (MAIT), transport and pre-launch, which were previously combined. But another example that is of paramount importance is the addition of decommissioning. This phase, described as "Phase 5b" in Figure 3, tends to be included in the policy in the section that guarantees "in-orbit" coverage, but it is correct to highlight it as a parameter of great influence in the insurance context.
This is because the timing, mode, and reliability of End-Of-Life (EOL) disposal of a SAT are of paramount importance in determining the pure premium.
To be more precise, they provide information on liability towards third parties but also on risk assessment.

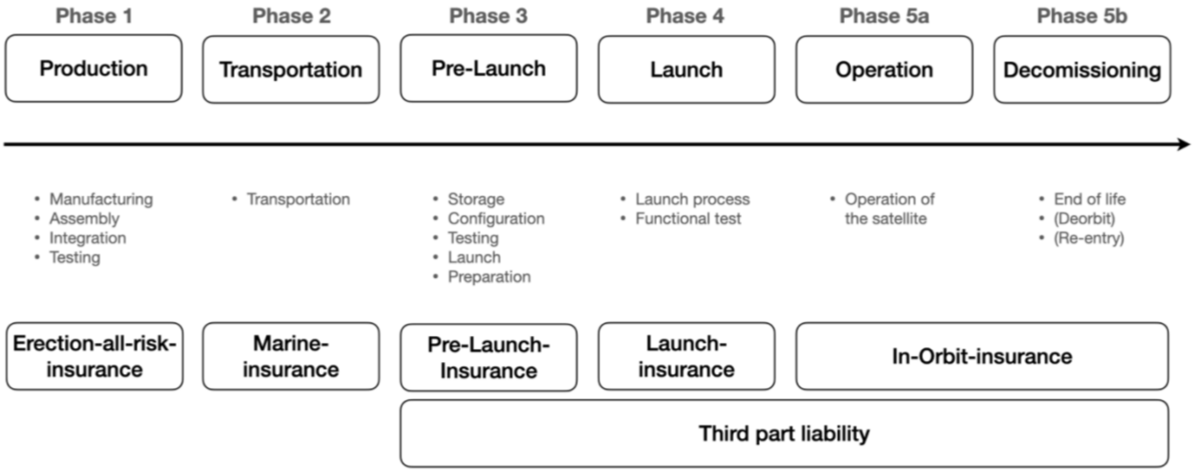


Figure 3: space mission life phases and insurances relations.

Let us therefore start from the outset by recognising the following points of influence as fundamental:

- Mission life duration.
- Mission PL, objective, and operation.
- Mechanisms for deorbiting and atmospheric re-entry.

In general, all the different operations and development phases of the SAT are to be recognised as necessary information for taking out a policy in the space field but remember that on the ground most damage is of a different nature and tends not to fall under special risks as, for example, in the case of transport, it is common practice to insure expensive loads for long journeys.
However, one of the riskiest moments and phases is the one called "Phase 3" in the Figure 3. This is because, even now, many insurance agencies do not take on the burden of insuring the entire SAT following events occurring during this phase. This is due to the high probability of failure in the moments immediately before launch and the high severity related.

2.2.3 Main problems in space risk assessment

To conclude then the insurance applications we can summarise the main problems related to insuring space travel, as described in the previously mentioned article "Risk Management and Insurance Solutions for Space and Satellite Projects" [9].
What makes this field of work problematic is therefore:

- The small number of insurable events leading to large variations in probability.
- The high rate of development which leads to uneven technological status.
- The high cost of missions, leading to high insurance risks.
- Accumulation of risk.
- Impossibility of acting on the vehicle during its operational life, which reduces the number of partial losses.
- High number of failures pre-launch or during launch.
- Diversity of the types of risks involved.

It is precisely this last characteristic that should be highlighted. As we have seen in paragraph 2.1.2, the variety and diversity of risks linked to the space field is very wide and, certainly, a

master's thesis cannot deal with this amount of information without incurring in simplifications or omissions.
Looking at the multitude of risks and searching for those that particularly affect not only the success of the mission but also the damage caused to third parties, the risk of collision inevitably stands out. For this reason, this thesis focuses primarily on the collision risk.

2.3 Collision Risk Assessment Introduction

Obviously, to conduct a consistent risk analysis, it is necessary to determine which factors influence the probability and severity of collisions. In addition, it is important to understand who the protagonists of an orbit are, both because they may have different types of responsibility and cause different types of damage and because they may be orbiting objects that are not the result of direct anthropogenic activity.

2.3.1 Space Debris Problem

As Kessler wrote in 1978 [2], the probability of space collisions is inextricably linked to the number of launches carried out and therefore of objects in orbit. Moreover, the effect of a single collision, following the fragmentation of larger debris, leads to a cascade phenomenon known as Kessler's syndrome [3]. Clearly, the fragmentation of SATs or other orbiting bodies in turn increases the number of debris, resulting in an exponential trend. According to Kessler's vision [2], which is not so pessimistic and in fact very accurate, the result is the impossibility of using entire orbits due to the unregulated launch of SATs without orbital retraction systems which would lead to orbiting *debris belts* [2].
Clearly, the resolution of this huge problem, which has received a great deal of attention in recent years, is not the subject of interest in this study, so these assessments will be used as a starting point for collision risk analysis.

2.3.2 Reliability

Having defined the scenario and its complexity it is fair to focus briefly on individual risk. In this case it is not quite correct to define the individual risk as an evaluative parameter; it makes sense however to refer to the reliability of a SAT and its subsystems and its propensity to be subject to collision for reasons related to its design, MAIT, and operation.
Therefore, the following reliability characteristics, useful for the study of the risk of collision, are highlighted:

- Collision avoidance systems and their reliability; thus, related to active risk mitigation.
- SAT operational life and choice of orbit.
- Re-entry prediction, related mechanisms, and their reliability.
- Propensity for fragmentation.
- Total and partial losses in case of collision.
- Mitigation systems such as redundancies.

2.3.3 Factors influencing the risk of collision

Therefore, by summarising what we have seen both from the point of view of environment and individual factors, we try to highlight the totality of mission characteristics related to space collision risk.

However, we consider at the outset that many of these factors are interrelated and therefore, for a better understanding a representative diagram of these characteristics is presented in Figure 4.

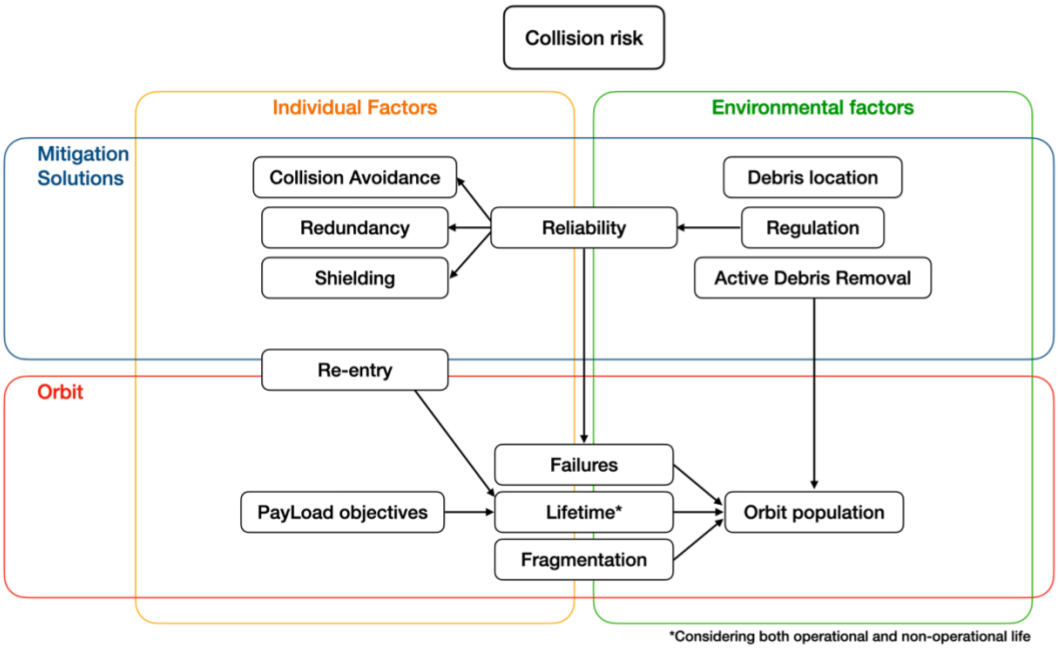


Figure 4: Factors influencing collision risk

It can be seen that many of these factors are mutually dependent, but only some of them directly influence the risk of collision. The most important factor is that of the orbital population, which is not surprising, since a high number of vehicles (operational and non-operational), debris and bodies, is decisive in risk assessment.

If we remain in Figure 4 for a few more moments, we can begin to understand the importance of the study proposed in this thesis, since, nowadays, the quantification of individual factors and the associated risk is commonplace. What is instead difficult to quantify is the collective risk linked to environmental factors. Certainly, also thanks to the studies of Kessler [2] and his successors, it is known that the increase in orbital populations is a considerable problem, but in order to carry out a regulation, quantification and classification is necessary.

But what is the motivation that makes this quantification essential? As is often the case with technological development, this is linked to economic and financial motivations.
Therefore, before analysing the facets that, to date, characterise individual risk and before proposing a possible classification and therefore interpretation of collective risk, we present a brief overview of what the space market currently is and the implicit demands it makes.

3 Market Needs

As mentioned above, the need to obtain a collective classification for the definition of collision risk stems from a market demand. The causes and repercussions are mainly of an economic nature; firstly, because the construction of a SAT and the development of a mission are services which have a considerable cost and secondly, because these capitals are made available by investors who perceive a potential return. We also must consider that these resources and related responsibilities are increasingly higher when, in some missions, human crews are involved, and therefore these are missions that require reliable safety and risk analysis. But how can we say that now more and more, and in the future increasingly, there will be a need to estimate the risk of collision?
If we consider that on July 20, 2021 the Blue Origin NS-16 mission was the first tourist flight into space [10] and that on August 25, 1919 the same happened for the first scheduled flight by the AT&T (Air Transport & Travel Ltd) company [11], and we also consider that the space field and the aviation field are two similar sectors with a comparable trend of technological development over time, we can guess that the fate of space tourism and in general of the space transport market may have a similar if not almost identical projection to that which happened for the aeronautical case. In Figure 5 we can observe the ICAO (International Civil Aviation Organization) [12] data concerning air traffic from the first commercial flights to the present day and in Figure 6 the data concerning the increase in space traffic in recent years.

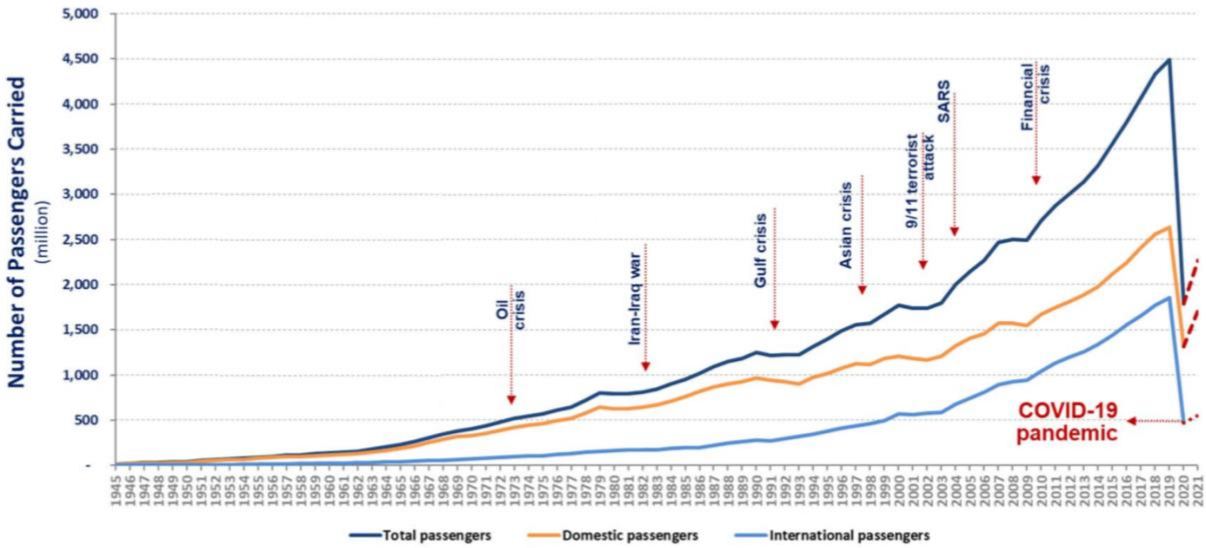
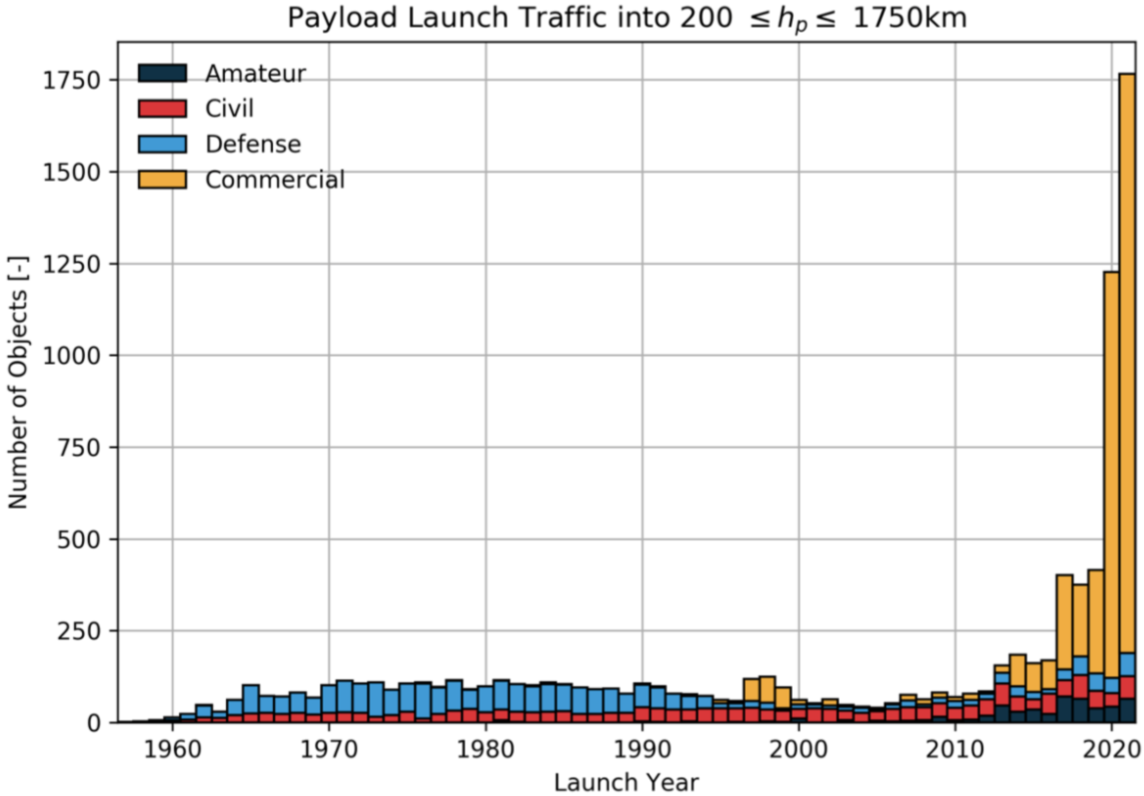


Figure 5: Air traffic data from 1945 to date (ICAO credits) [12]

Connecting the dots, we can assume that space flights are not only increasing, as predicted by Kessler [2], but are also becoming increasingly differentiated in mission types and objectives, leading to a demand for risk differentiation and classification. All this is combined with the need to express international regulations on third party liability since, again according to possible future forecasts, the era of space tourism is beginning in these years. To confirm this, just look at the graph in Figure 6, which clearly shows the sudden increase since Blue Origin together with Virgin Galactic and the first tourist on the ISS took to the skies, ushering in a new era [13].

To conclude this chapter, it is only fair to provide some data on the frequency of space travel, which inevitably results in the presence of debris and can therefore quantitatively describe what is explained in words. (Table 6) [14].



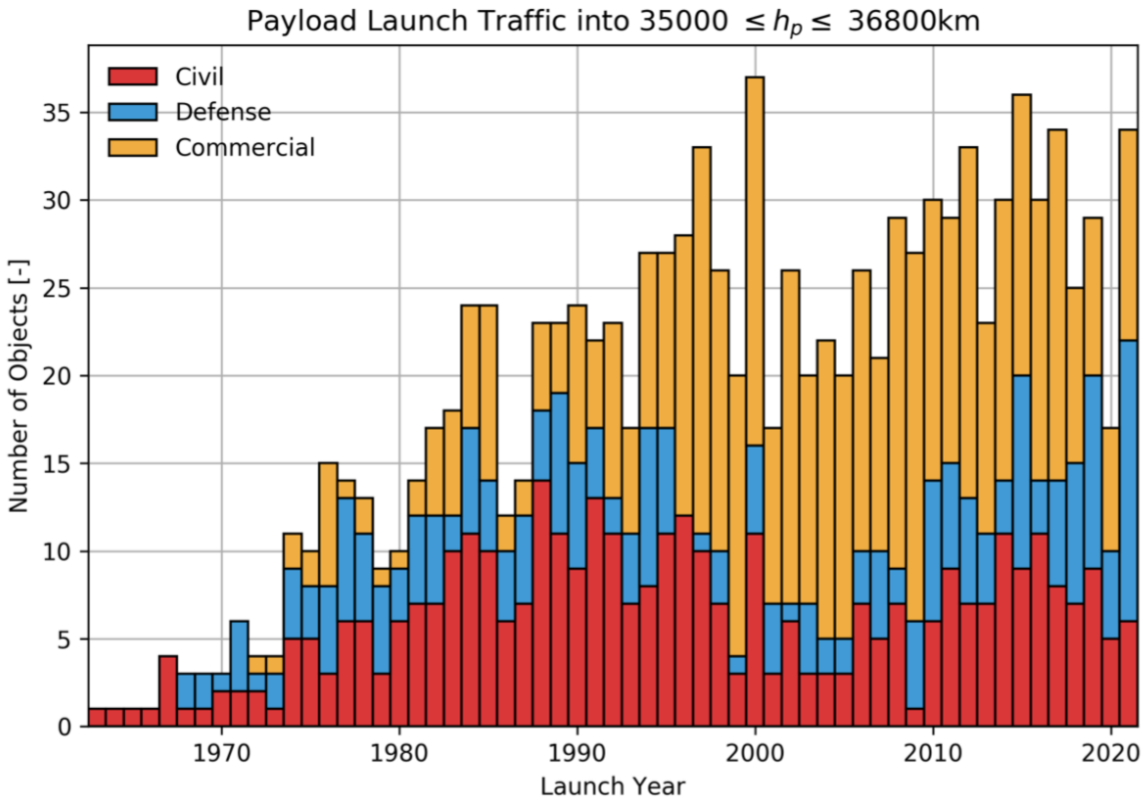


Figure 6: Payload Launch Traffic by ESA Space Environment Statistics [14]

Table 6: Space debris by the numbers [14]

Number of rocket launches since the start of the space age in 1957	About 6170 (Excluding failures)	
Number of satellites these rocket launches have placed into Earth orbit	About 12450	
Number of these still in space	About 7840	
Number of these still functioning	About 4900	
Number of debris objects regularly tracked by Space Surveillance Networks and maintained in their catalogue	About 30640	
Estimated number of break-ups, explosions, collisions, or anomalous events resulting in fragmentation	More than 640	
Total mass of all space objects in Earth orbit	More than 9800 tonnes	
Number of debris objects estimated by statistical models to be in orbit	36500	>10 cm
	1000000	1 ÷ 10 cm
	330 million	1mm ÷ 1 cm

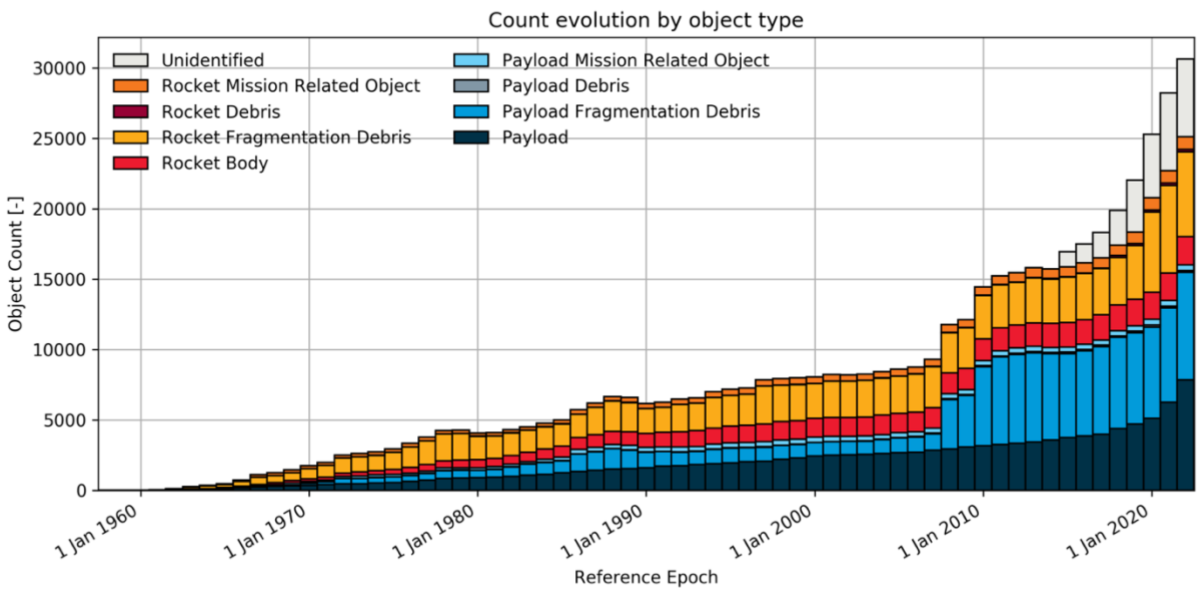


Figure 7: Space Debris count [15]

Therefore, an important detail to note in Figure 7 is the variety of space debris, especially unidentified space debris, which for this very reason requires the attention of international government agencies for global regulation.

3.1 Collision Risk in Space Law

So, when we talk about regulation, we are entering a very uncertain field, since, in the case of space, until a few years ago it was considered "no man's lan". In fact, the birth of atmospheric and space legislation dates to less than a century ago and, before the launch of Sputnik (1957), had never concerned orbital launches. However, at that time, organisations such as the IAF (International Astronautical Federation) were formed and began to hold the first discussions on principles of law applicable to space.

In those years, the United Nations [16] started to consider and negotiate the Liability Convention [17], and so from 1963 until 1972, this agreement was formed between many of the United Nations and adhered to by basically all the states that are today the main space launchers. In addition to government offices, non-governmental associations such as the IISL (International Institute of Space Law) [18] were created, which became the main protagonists in the field of Space Law.
But what makes the subject of space legislation so interesting or controversial? Certainly, among the reasons, there are the responsibilities, and, in case of failure, the consequences related to space missions.

Thinking about the possible scenarios in which an SAT can harm other vehicles or the community, uncontrolled crashes, fragmentation, and the consequent pollution of orbits with space debris and, above all, collisions, mainly come to mind.
Therefore, by analysing the Liability Convention [17] we understand what the basis for a possible classification in the event of a collision is. Article III of the Convention clearly states: "In the event that a space object of a launching State or persons or property on board such space object were caused elsewhere than on the surface of the earth by a space object of another launching State, the latter shall be liable only if the damage was due to its own fault or to the fault of persons for whom it is responsible" [17].

There is therefore a decisive methodology in the area of contributory negligence but no preventive methodology that would lead to useful guidelines for classification.
In other words, unless it defines the correct behaviour for SAT "coexistence" and unless it applies international law to the space field, the Liability Convention does not lay down numerical safety standards for positioning a SAT into orbit. Rightly, however, here the reverse process must take place, i.e., it must be the technical counterpart that defines a risk assessment scale to allow the legislative bodies to define ad hoc regulations to reduce the risk of collision.

Nevertheless, starting with this assumption of responsibility by the states involved in the convention, the space insurance market has emerged which, in addition to bringing us closer to the study conducted in this thesis, is the main player in manifesting the global need for risk classification.

3.2 Space Insurance Market

As in the case of legal aspects, insurance aspects have to wait for the first commercial launches before they can be applied in space. In the early days, in fact, launches were mainly related to experimental missions, military missions or in any case not reliable in any way.
However, the establishment of trade and related interests led production and launch companies and financiers to seek guarantees in case of failure.
Hence a first solution of interest is established but, as mentioned several times in the first chapters and reiterated by Piotr Manikowski in his article "Cyclicality or volatility? The satellite insurance market" [19], the space insurance market has some peculiarities: a very limited number of new insurance contracts per year, large potential single losses, and the participation of several insurers in a launch due to large potential losses and a limited number of insurers writing this one. All this has led the market to be volatile following bankruptcy events with associated sharp price changes and is shown in Figure 8 as a result of Manikowski's study [19].
At the same time, the space insurance market is cyclical, as it exhibits cyclicality in terms of profit and price, also shown in Manikowski's results (Figure 9) [19]. These two scenarios, cyclicality, and volatility, coexist and, considering the large amounts of capital involved, insurers require a better interpretation of SAT reliability to avoid such marked crises and booms.

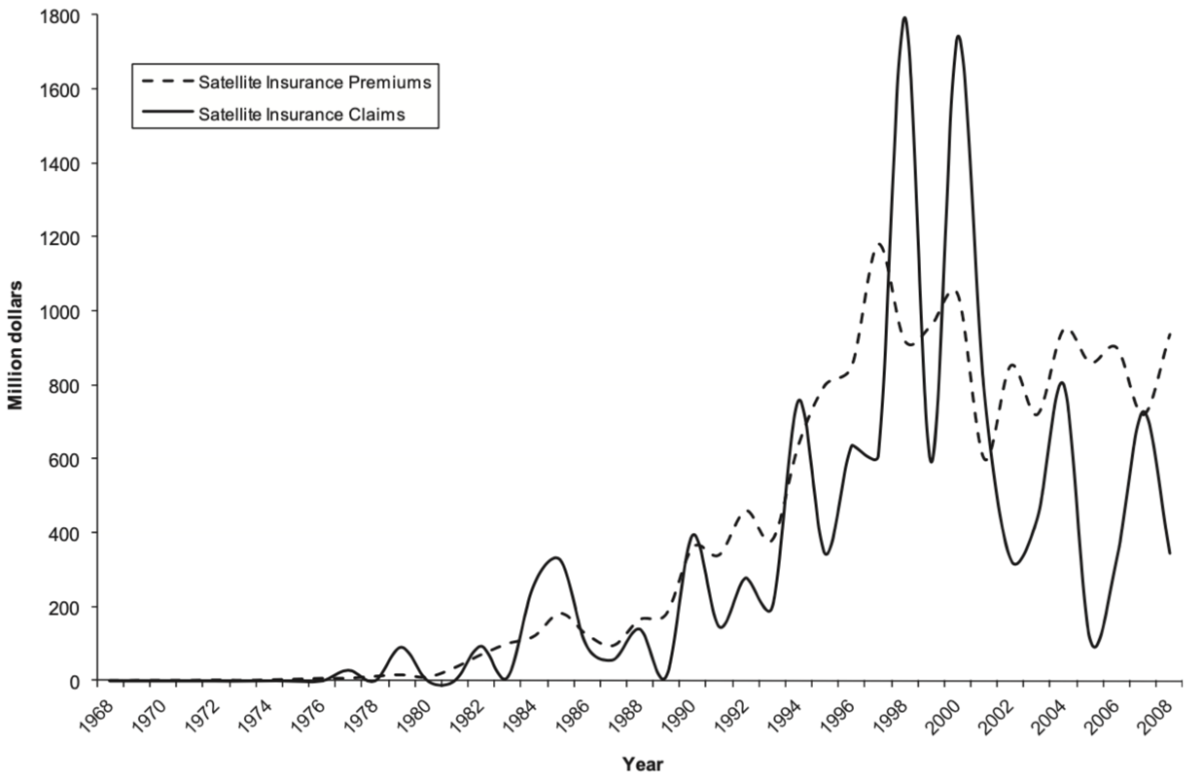


Figure 8: Satellite insurance premiums and claims: 1968-2008 [19]

In the quest for greater predictability of trends, insurers again encounter the limitations of determining the insurance premium associated with a SAT [20]:

- Large possible losses in every single event.
- Mainly total losses occur.

- Difficulty in solving problems in outer space.
- Difficulty in determining causes of accidents.
- Small number of insured objects.
- Lack of homogeneity of risk.
- Possibility of large cumulative risk.
- Covered object (SAT) in an unfriendly space environment.
- Insuring against not only damages caused by outside forces, but also against damages which the SAT causes to itself (satellite/rocket breakdown).

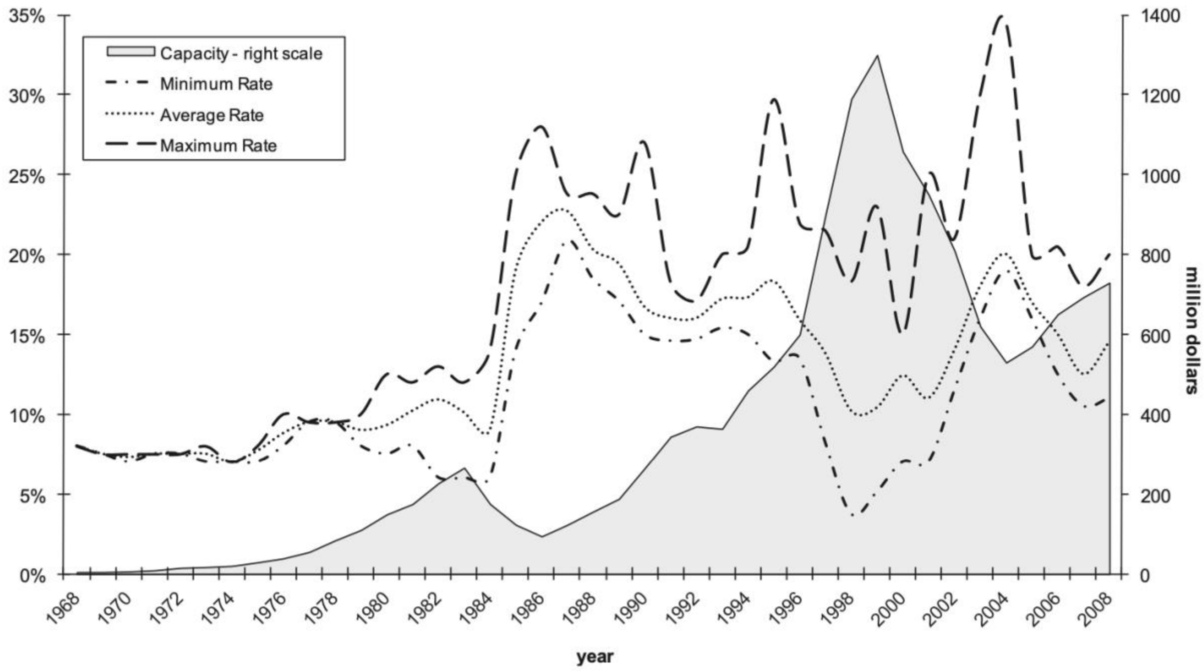


Figure 9: Capacity versus rates: 1968-2008 [19]

In order to mitigate the effect of these characteristics, the need to find an appropriate classification again arises.

3.2.1 The New Space Economy

One of the fundamental parameters that must be considered when analysing the space market is the accessibility of it and, clearly, the more parties are involved in the market, the more complex the insurance aspect becomes, and the more careful study is required to regulate complex processes.

As we will see in the chapter dedicated to the severity and therefore the costs connected to a space mission (4.4), there are various cost ranges for a SAT. Certainly, the scenario, as already mentioned and demonstrated in Figure 6, is more and more of a commercial nature. But what has brought about this sudden accessibility by private and non-governmental companies? Certainly, the factors are all intertwined and determining which one is the trigger is difficult but, to define this trend with the private space race as the main objective, the term "New Space Economy" is used.

The space business model thus becomes a real tool to create value and modernise almost obsolete sectors as described in the work of Parrella Rosa Maria [21]. Hence a way of doing space is evolving that is compatible with other types of business and that takes into account less costly production strategies.

With the aim of technological improvement and cost reduction, the NSE takes shape, and the direct consequence is the launch, sometimes uncontrolled, of SATs produced more quickly, with fewer restrictions given by the removal of non-institutional systems. Numerous spacecrafts (S/Cs), with a limited life span, in low orbit and launched by non-governmental entities thus enable the dream of thousands of investors to be fulfilled but define a space monitoring problem never seen before.

3.3 The Need for Classification

Summing up chapter three, we understand that the same motivations that express the need to classify the various players in risk assessment are the same limitations that make such work difficult.
However, this classification is perhaps more important than the Quantitative Risk Assessment (QRA) itself; this statement may seem almost absurd but several studies, including that of George E. Apostolakis [22], point out that QRA is not as important for the insurance market. Especially in the space environment case, where, as already said, the information and the basis for practicing QRA are few and fragmented, it is much more effective and valuable the trend that the market itself assumes, due to events that cyclically or randomly occur as seen discussed in the previous paragraph, when Manikowski's [19] was mentioned.

Having now noted the characteristics of space risk, how to carry out space risk assessment, the related regulations, and the implications for the insurance market, we return to the concept of individual collision risk. This time with a strong focus on the existing methodologies for calculating it, defining inputs and outputs, and briefly presenting the procedures implemented. From this we can then address the collective risk and then define the classification using the proposed algorithm.

4 Space Collision Risk Assessment

Let us then proceed with a Space risk analysis but starting with an individual one. Remembering what was said at the beginning, the individual risk is the one to which the SAT is subjected individually, certainly there will be factors that influence it linked to the environment but, for the modalities with which today the risk analysis is carried out, these are not referable to the collectivity.
In this chapter some of the current methods of estimation of the risk of collision to which a SAT is subjected will be presented; starting from the inputs and outputs, methods, such as ECOB (Environmental Consequences of Orbital Breakups) [23], will be explored to carry out the risk assessment. Then a cost analysis will be linked to these methods to underline not only a monetary quantification at damage level but also the savings that an accurate assessment can guarantee.

4.1 Current Methods and Indexes

As mentioned in the introduction to this chapter, one of the first examples of collision risk indices is the *ECOB* [23]. In the extension dealt with by Dr. Francesca Letizia [24] it can be seen that the calculation of the index is in itself sufficiently simplified but consistent to allow an effective analysis in the context of this thesis.
Being a risk index, the proposed calculation is given by a probability ($p_{c,j}$) (as mentioned above, this is also called likelihood) and a severity factor which, in this case, to give more relevance *"to targets representing orbital regions containing a high cumulative cross-sectional area"* [24], is a weighting factor (w_j).
The calculation is then as follows:

$$(3) \quad ECOB = \sum_{j=1}^{N_T} w_j \cdot p_{c,j}$$

As the name suggests, *"Environmental Consequences of Orbital Breakups"*, the analysis carried out is mainly aimed at SAT fragmentation for an observation of how this influences the probability of collision [24], and is therefore useful for the general purpose of collision risk calculation; ECOB, or indices with similar objectives, are the most important building blocks in the solution of a much larger problem.
In the extension of ECOB [24] a reformulation is introduced that considers the effects and thus the severity and there is a composition between probability and relative risk of collision and between probability and relative risk of fragmentation. In this way, the approach becomes even more consistent and is outlined as follows:

$$(4) \quad Index = p_e \cdot e_e + p_c \cdot e_c$$

Where '*p*' represents the probabilities and '*e*' the effects in the case of collision (*c*) and fragmentation or explosion (*e*).
ECOB, in this case represents the effects of the term 'e_c' but, clearly, the other terms remain to be analysed. In a subsequent study by the ECOB developers, a specific analysis of these three other contributions to the formula is encountered [25].

We understand, however, that in the collective study, and especially about insurance, third party liability and completeness aspects, a labelling such as the one proposed in the case just cited is perhaps inconvenient to use since it only concerns the debris aspect and does not consider the set of active SATs as a system of independent individuals who do, however, have a mutual responsibility for orbital safeguards.

While ECOB can provide a basis for calculating the risk of collision or explosion due to debris, it is necessary to extend this basis to include as many aspects of a mission as possible trying to cover all the sensitive and risky points and also to understand what is common between these formulations.

Shifting the focus to other work that allows us to look at all aspects of the problem, we introduce '*criticality*'; "*The criticality is an indicator that describes how harmful an object may be to its environment*" [26] instead "*The spacecraft environmental criticality is a term for the danger posed by any LEO or Geocentric Earth Orbit (GEO) object for other satellites to collide catastrophically*" [27]. In the works of Christopher Kebschull [26], Jonas Radtke [27] and others, a priority list based on environmental criticality (EC) is introduced and then a calculation method is proposed which leads to a first classification. At the expense of probability, it is identified how much an object is potentially dangerous for the environment (severity) and, based on this, the orbiting objects are ordered. The LUCA (Long-term Utility for Collision Analysis) software was used for the simulations [26] [27].
Criticality has two contributions, one relating to risk, 'c_{risk}' and one relating to impact 'c_{impact}', to be more specific, the cumulative formulation in a given time period can be obtained with 'c_{risk}' defined as the product of the collision flux 'Φ', the exposed surface of the object 'A' and the simulation time 't' [26].

$$(5) \quad C_{crit} = c_{risk} \cdot c_{impact}$$

$$(6) \quad C_{crit} = \sum_{t=t_{start}}^{t_{end}} \left[c_{risk,t} \cdot \sum_{\tau=t_{frag}}^{t_{end}} (\Delta p \cdot \Delta\tau) \right]$$

$$(7) \quad c_{risk,t} = \Phi \cdot A \cdot t$$

The term '$\Delta\tau$' is time elapsed after fragmentation has occurred and 'Δp' is described by considering the base scenario in which fragmentation occurs and the one in which fragmentation occurs:

$$(8) \quad \Delta p = p_{frag} - p_{no\,frag} = \left(\Phi_{frag} - \Phi_{no\,frag}\right) \cdot A \cdot t$$

"The EC respects the influence a fragmentation has on every orbit region. A target object is fragmented in every possible epoch and its influence is analysed by comparing the collision rate before and after the collision in every succeeding year (Δp). The risk of fragmentation is also part of the equation, determining the probability of the fragmentation just before it is triggered." [26]
Below is an image describing what has just been specified (Figure 10), also taken from Kebschull's work [26].

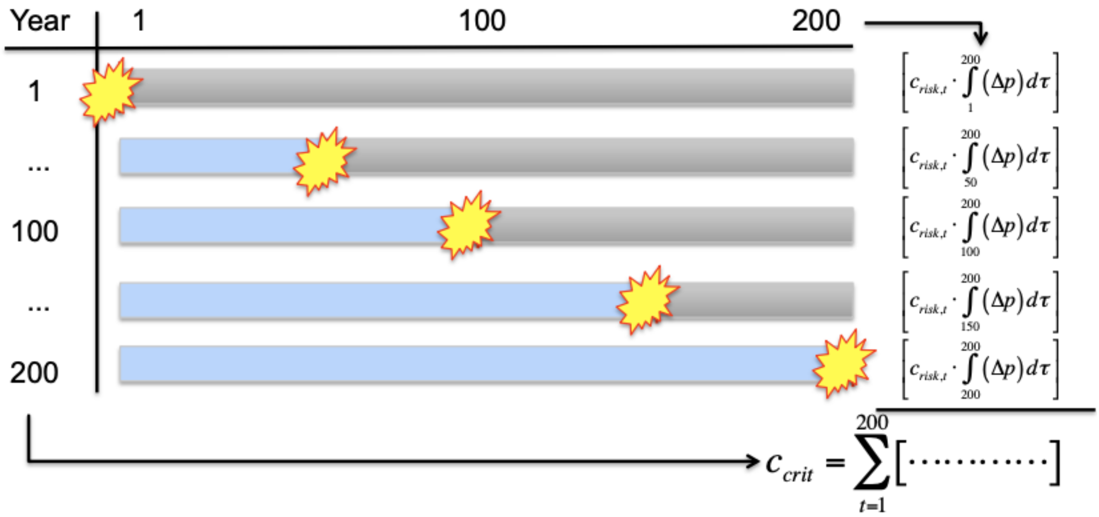


Figure 10: An example computation of the EC of an arbitrary target object that evaluates the influence of the object over a time span of 200 years [26].

Recall, that to define the collision flux we can make a parallel with the kinetic model of gases; thus *"Φ is defined as the number of molecules dN crossing a unit surface in one direction during a unit of time"* [28]:

$$(9)\quad \Phi = \frac{dN}{dAdt}$$

In order to better understand the usefulness of the two terms that make up criticality, let us give a definition: 'c_{risk}' is nothing other than the risk of the SAT under consideration colliding with another one in the population, while 'c_{impact}' represents the impact that the fragmentation of that SAT has on the population in question [27].
Calculating these two parameters at each time step of the simulation, in the case of LUCA one year, we note that they vary according to the orbit under examination and that the combinations of c_{risk} and c_{impact} are varied. From Radtke's work [27] we obtain an explanatory image that correlates time and altitude with evidence of the derivation of criticality (Figure 11).

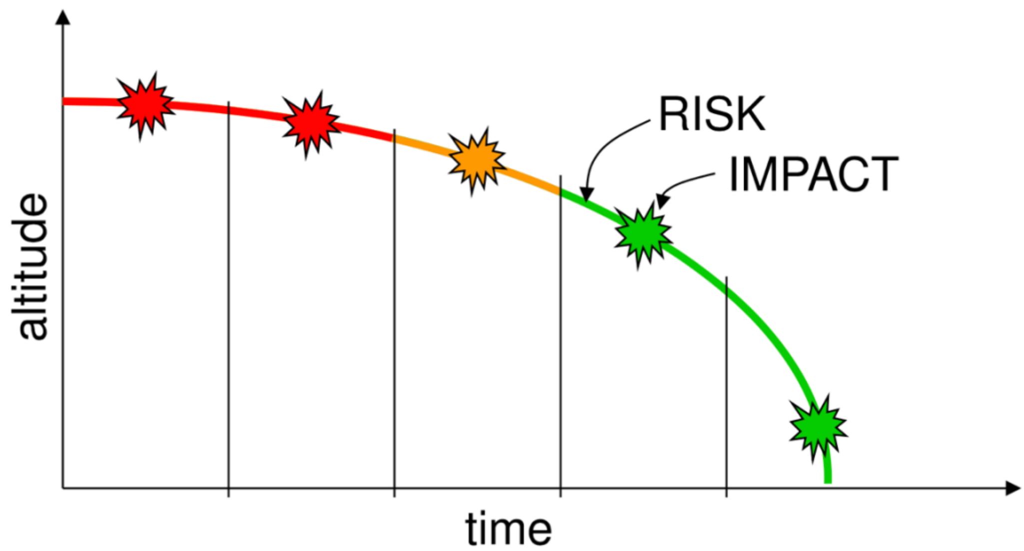


Figure 11: Schematic of criticality derivation [27].

Thus, we also have a focus on the effect that fragmentation has on the community and the population in general; however, we must remember that this effect will have to be correlated with the other risk factors and, above all, is not entirely sufficient to cover all the aspects that, as mentioned above, characterise the risk of collision.
Among the studies that attempt to touch on all aspects and that consider as input the physical characteristics of an object, the orbit in which it is located and the environment by which it is surrounded, the one by Rossi, Valsecchi and Alessi stands out [29]. An index called the CSI (Criticality of Spacecraft Index) is introduced [29], and, in this case too, the assessments made are used to determine the environmental criticality of abandoned objects. We are once again talking about space debris, although we are trying to go into the collective consequences with greater precision.

The limitations and strengths of this index are accurately described in the work just cited, in fact, CSI is more useful for large objects but at the same time has dependencies that other classifications do not have. The various dependencies can therefore be summarised as follows:

- Environment.
- Lifetime.
- Mass.
- Orbit inclination [29].

The CSI is then formulated [29]:

$$(10) \quad CSI = \frac{M(h)}{M_0}\frac{D(h)}{D_0}\frac{life(h)}{life(h_0)}\frac{1+k\Gamma(i)}{1+k}$$

$$(11) \quad \Gamma = \frac{1-\cos{(i)}}{2}$$

Where $\frac{M(h)}{M_0}$ is the mass dependence, $\frac{D(h)}{D_0}$ the contribution of spatial density and finally the last term in the equation is the dependence due to orbital inclination '*i*'; a term related to lifetime is also considered and, as for mass and density, a function of height '*h*'.

In the light of the Rossi et al. study [29], we understand that the need for the market to obtain a hazard classification is once again confirmed even for those bodies that are not abandoned or debris but could become so. It is all about quantifying this aptitude and, to do so, let us first try to clarify what the inputs are in the cases just studied; they will then be the same, perhaps with different weights, as in the case of the collective collision risk.
At this point we can consider what we have seen to be sufficient; the studies examined, as well as being very recent, show once again that market demand and the SOA point in this direction. Therefore, although they are not discussed in detail, also because this would be beyond the scope of the current master's thesis, they are a solid basis for reading and understanding the following chapters.

We conclude this paragraph by keeping in mind what has been described for ECOB [23], for criticality [26] and for CSI [29]. Therefore, in the following chapters we will list not only all those contributions that emerged but also the results they bring.

4.2 Inputs & Outputs

Let us therefore try to combine what has been seen in the previous chapters and what has been defined by the scientific community regarding the estimation of individual risk. In this section, we will see an extrapolation of what has been defined by the previous assumptions converted into a single list of inputs and outputs.

4.2.1 Inputs

We then define the following "categories" which branch off into other subcategories; they can be, from this moment, referred to as "inputs" in the field of individual collision risk analysis:

- S/C (Spacecraft) characteristics.
- Mission characteristics.
- Mitigation solutions.

Let us look in detail at each of these three macro-areas.

S/C characteristics

One of the most important inputs is certainly the set of physical characteristics that define the SAT. These are clearly also related to the mission objective and can be determined by design choices such as mitigation choices, however, as there is no direct correlation between these and having to decompose the wide range of possibilities that characterise a S/C, the common tendency is to approach the problem step by step and, rather than leaving out some details, a redundancy of results is preferred.

We then define the following factors as subcategories:

- S/C Size.
- S/C density.
- S/C geometry.

To define initial sub-indices, however, we need to relate them to mission characteristics and then add the influence of any active or passive mitigations.

Mission characteristics

Several points fall into this subset, including:

- The choice of orbit, which in turn influences:
    - Velocity.
    - Current and projected population.
    - Earth distance.
    - Number of debris.
- Mission lifetime.
- Other S/C involved in the mission:
    - ADR (active debris removal).
    - Constellation.
    - Approach to other S/Cs or stations.

Mitigation strategies remain to be analysed, a category that is sometimes excluded but which, in the context of SATs that have yet to be launched, is an important factor moving the needle of the balance.

Mitigation solutions

Mitigation is an important point that can lead to factors that improve or worsen the result, such as:

- Passive solutions:
    - Shielding.
    - Redundancies.
- Active solutions:
    - Collision Avoidance.
    - PMD (post mission disposal).

Finally, although not a purely mitigating factor, it is correct to include reliability in this section. With reliability, we then begin to address the first risk-related coefficients or contributes which, for example, in the case of ECOB [23] [24] and others [25] [26] [27] [29] are:

- Collision probability.
- Collision effect.
- Explosion Probability.
- Fragmentation index.
- Explosion effect.
- Survivability.
- Ballistic Parameter.
- Casualty.
- Criticality.

Summarising the inputs in a single diagram (Figure 12), we realise, once again, that the influence on the risk of collision is fundamental and that all the assumptions made so far always lead us to come up against the two main components of risk, namely probability and severity.

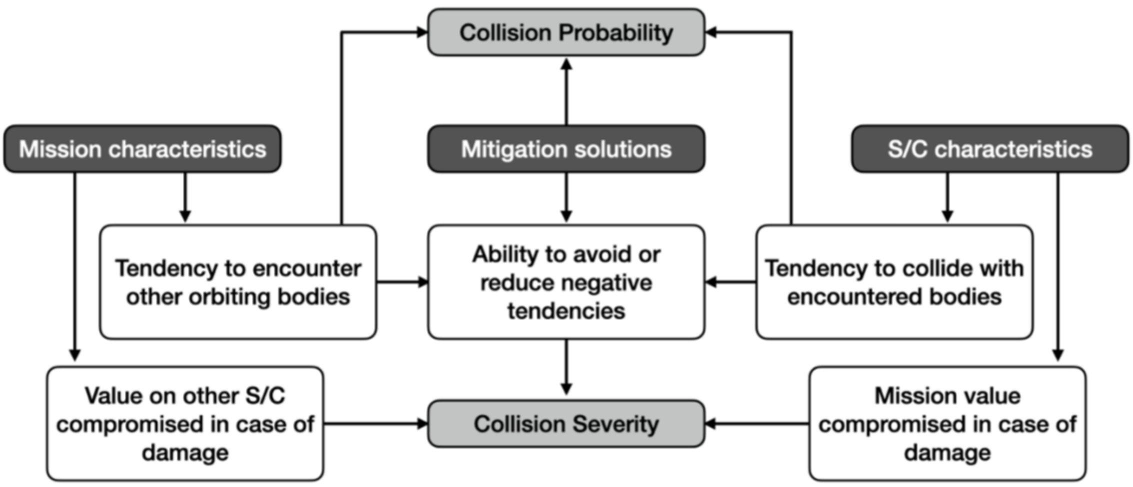


Figure 12: Overview of inputs and their effect on collision risk.

Confirmed then that the very essence of collision risk is the binomial of probability and truthfulness, we understand that these are the two main information that we will denoise in the next sections.

4.2.2 Outputs

However, the contributions we have just seen can also be considered as outputs or rather "hybrids", in fact in some cases these appear as inputs and in others as outputs. This is because not many people analyse the risk of collision as a whole and therefore some concentrate on calculating the probability, others on calculating the severity, and others, as in this case, use the formulations of others to rework them and define different methods of classification.

Let us therefore proceed to analyse these two outputs and try to observe what correlations they have with the factors seen above.

4.3 Probability Introduction

Let us therefore begin by analysing one of the most crucial elements for this thesis: probability. Recalling a specific definition (Cambridge Dictionary), it is defined as "the level of possibility that something will happen or be proved true" [4]. Obviously in this specific case the event in question is the collision. We will observe that there are several factors that influence it but, with ample evidence, these lead mainly to one prominent feature, which results as the main definition of interest, namely Population.

4.3.1 Population

This often orbit-dependent characteristic is a key parameter that needs careful explanation. In fact, it is an intermediate step that most QRA methods consider, as well as those addressed in the previous chapter. Just think of the concept of probability itself; the probability of colliding with someone in a crowded street is clearly proportional to the number of people you meet on your path. Similarly, the number of orbiting objects, which translates into the flux of SATs and debris, is proportional to the probability of one of them colliding with another.

Therefore, having to think on the spur of the moment about implementing QRA and, as described in Chapter 3, knowing the number of objects in orbit, everyone can understand the factual difficulty in determining concrete data.

Fortunately, strategies and systems for localising orbiting objects come to our aid. In the case of SATs, counting is simplified for two reasons: we know the history of launches and the objects in question are large enough to be easily identified. However, in the case of debris and smaller objects, the problem becomes much more complex. We must think, although we will see it better in the next chapters dealing with severity, that a pebble of a few centimetres at moderate speeds such as those we experience on earth will certainly not cause significant damage to a resistant object such as an SAT, made of materials specifically designed to protect it; the same is not true when speeds become orbital ones.

Therefore, even small objects must necessarily be counted as the damage caused can be of a similar nature to that caused by colliding objects larger than 10 centimetres.

Let us therefore list the structures, bodies, strategies, and methods for counting SATs and debris in space.

Among them is the Space Surveillance Network (SSN); "*The United States Space Surveillance Network detects, tracks, catalogues and identifies artificial objects orbiting Earth, e.g., active/inactive satellites, spent rocket bodies, or fragmentation debris. The system is the responsibility of United States Space Command and operated by the United States Space Force*." [30].

Debris tracking is currently only possible for objects as small as 5 centimetres, although the intention of the SSN is to go down to 4 centimetres and below; currently, for smaller debris, it is necessary to carry out simulations and estimates based on known fragmentation or collision events that may have generated such debris [31].
The reason for monitoring even smaller objects is, as mentioned before, related to the consequences that afflict a SAT after collision and will therefore be better addressed in the section on severity (Chapter 4.4).
Before concluding this excursus on the population, it is only fair to confirm that active SATs are also counted and monitored, and that in the event of a collision there are also direct legal and insurance aspects involved. Obviously, in this case, there are various databases such as 'Space-track.org' [32], a website where, by registering free of charge, it is possible to access up-to-date data on all orbiting objects, including active SATs. These databases remain updated with debris data, providing a useful resource to draw on.
At this point, however, it is fair to mention one of the most comprehensive and useful tools in the field of tracking: DISCOS (Database and Information System Characterizing Objects in Space) [33]. This is one of the most powerful tools that encompasses the analysis, forecasting and counting mentioned above and provides an effective overview of the problem. "*DISCOS serves as a single-source reference for launch information, object registration details, launch vehicle descriptions, as well as spacecraft information (e.g., size, mass, shape, mission objectives, owner) for all trackable, unclassified objects which sum up to more than 40000 objects*." [33] (Figure 13).

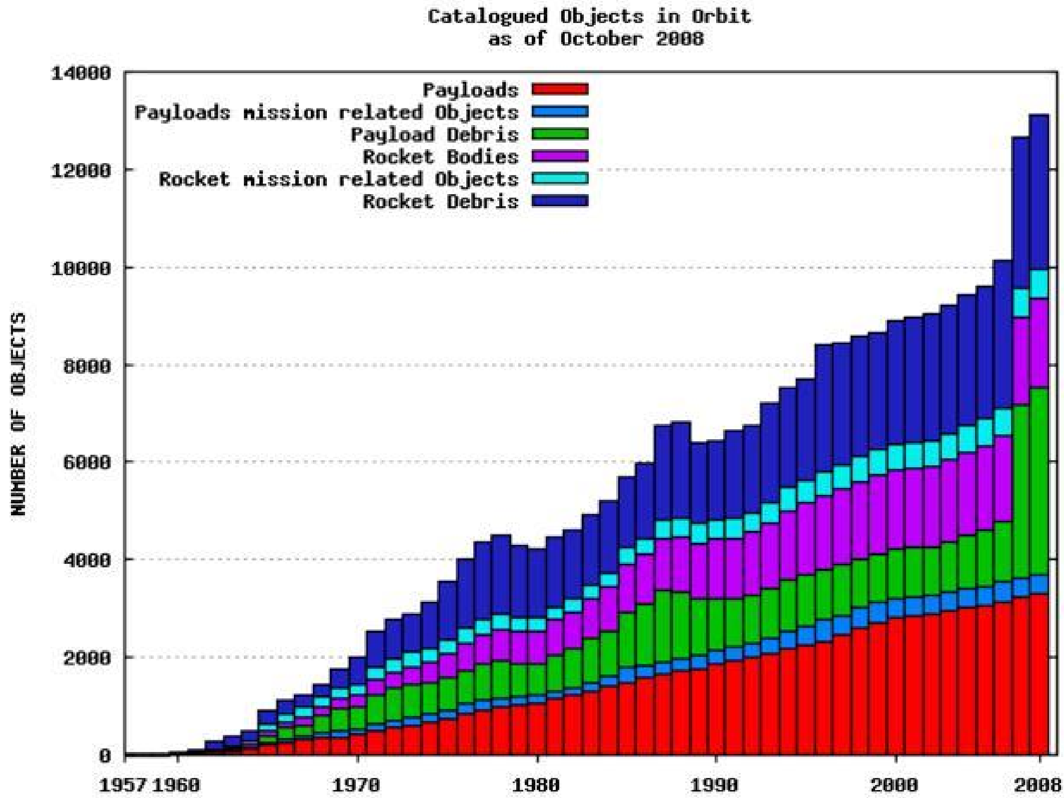


Figure 13: Representative image of DISCOS results [34].

DISCOS is therefore among the most popular systems for STM (Space Traffic Management) [35].
Having identified the tools for obtaining population estimates, we now turn to strategies for estimating the probability of space collision.

4.3.2 Common Methods for Probability Computation

We pass then to the calculation of probability; following the assumptions previously made, we understand how this branch pertains to the statistical side and that therefore, the mathematical models to be implemented are well clear. Obviously, in order to be applicable to the case under consideration (space collisions), it will be necessary to make simplifications or assumptions that do not make the computational cost too onerous and therefore move away from finding a rapid and effective result.

Volume model: A first model of probability calculation is the one that considers the SAT under consideration as a sphere, or rather an ellipsoid, of a certain volume and notify the danger when this "safety volume" is violated. A method was then defined which, following dedicated studies, took the space shuttle into account for a probability computation for potential collisions.
Summarizing the fundamental steps of this study carried out in 2002 [36], we observe that the starting point is the state vector of the shuttle, calculated from USSPACECOM (United States Space Command) data together with the relative covariance, with which the state and covariance vectors of a potential impacting object are also defined.
The analysis distance that was considered for possible future objects in conjunction with the space shuttle was 10 X 40 X 40 km in a 36-hour time range following the movement of the vehicle [36].

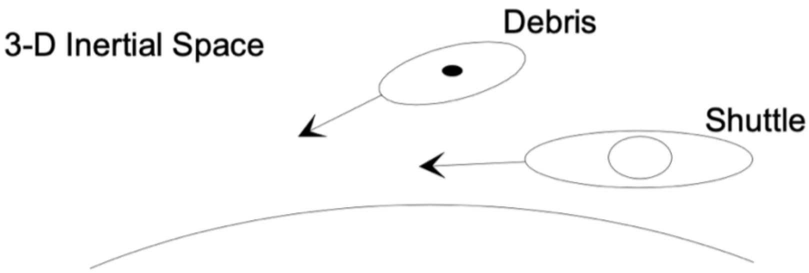


Figure 14: Depiction of conjunction scenario [36].

Given a possible conjunction event, as depicted in the image above (Figure 14), the distance between the two objects can be defined:

$$(11) \quad \vec{R}_{rel} = \vec{r}_{Debris} - \vec{r}_{Shuttle}$$

A common and therefore relative description frame is sought for the two objects, since they do not necessarily have the aligned directions of the surrounding ellipses, i.e., the graphical representation of the covariance matrix as this identifies the zone of uncertainty in which the object under examination could be. Let it be clear that the values for this method are clearly conditioned by a Safety Factor, both to avoid unwanted errors and because the mission for which the method was developed included crew and, as is known, in such types of missions very high safety factors are considered for obvious reasons.
A new reference system is then described (Figure 15): "*The axes of this conjunction frame are aligned with the relative velocity vector and the axes of the combined covariance ellipse at the predicted time of conjunction. The axes of the combined covariance ellipse (x and y) define the conjunction plane. This conjunction reference frame is unique to a particular conjunction event. In the conjunction frame the motion of the debris along with the combined covariance is seen relative to the vehicle (the vehicle is at the origin of the reference frame) and at the*

time of closest approach, the relative position vector ($\vec{R}_{rel}$), by definition, lies in the conjunction plane." [36].

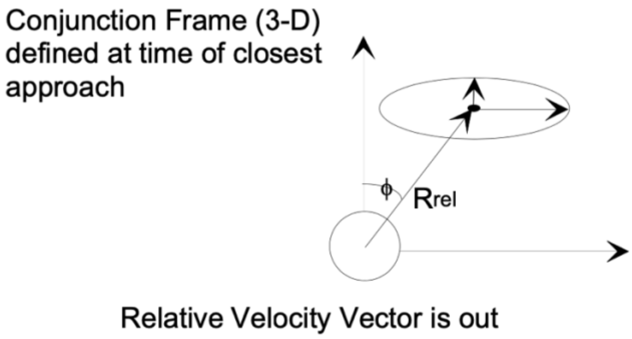


Figure 15: Conjunction reference frame [36].

It is also possible to perform a linear propagation and consider that in this system the two objects move parallel to the surface of the earth.
At this point we transform the three-dimensional problem into a two-dimensional problem as shown in Figure 16; this assumption, like the previous one, is possible thanks to the rapidity of the connected event, we are talking about times of less than a second, so it is acceptable to simplify the model as the committed error is minimal.

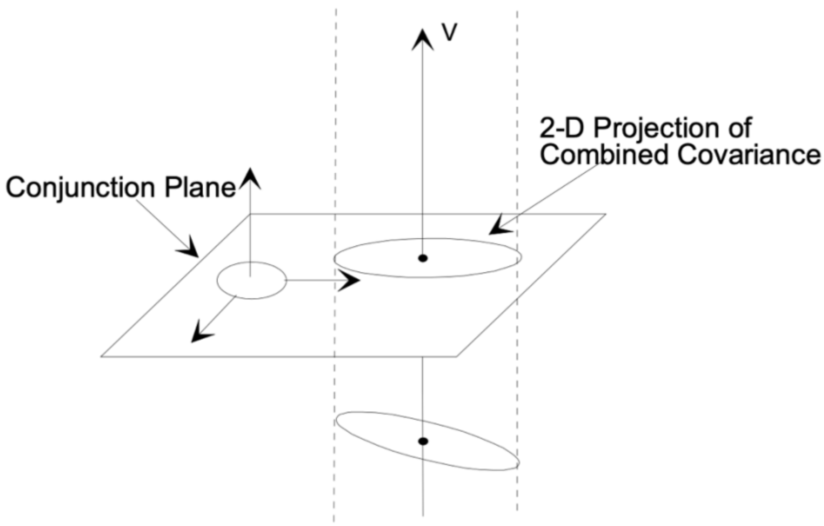


Figure 16: 3D to 2D conversion [36].

Continuity and two-dimensionality lead us to define the PDF (Probability Density Function) as a system dependent on the two (random) variables 'x_0' and 'y_0', which combined provide the following PDF on the conjunction plane.

$$(12) \quad f_{x,y}(x,y) = \frac{1}{2\pi\sigma_x\sigma_y} e^{\left\{-\frac{1}{2}\left[\frac{(x-x_0)^2}{\sigma_x^2}+\frac{(y-y_0)^2}{\sigma_y^2}\right]\right\}}$$

Where 'x' and 'y' are the orthogonal axes of the conjunction plane and the random variables 'x_0' and 'y_0' are defined as a function of the relative position magnitude 'R_0' and the angle of conjunction 'ϕ' visible in the Figure 15:

$$(13) \quad x_0 = R_0 cos\phi$$

$$(14) \quad y_0 = R_0 sen\phi$$

Making a further assumption that the radius *'R'* of the shuttle is that of a constant sphere; we can define the probability that the relative position vector '$\vec{R}_{rel}$' lies between 0 and R by integrating the PDF found above over the Area of the sphere of radius R.

$$(15) \quad \Pr(x^2 + y^2 \leq R^2) = \iint f_{x,y}(x, y)\, dA$$

Unfortunately, this definition has an intrinsic limitation, not due to the simplifications which, in fact, are not so absurd, but due to the operational methodology which works with an oversized safety.
If we were to consider this method, in fact, we would end up with a large number of "false alarms" that certainly do not help a clear classification of collision risk assessment.

Geometric model:
Another solution that can be thought of is to follow a geometric model that identifies the characteristics of the SAT and places it in a circular orbit close to the earth, differentiating between radial and transverse collision probability.
An accurate study that follows this strategy is that of Xu Xiao-Li and Xiong Yong-Qing [37], who formulated a probability calculation defined by the product of the two contributions just described, i.e., the one in the radial direction, connected to the altitude of the orbit, and the one in the transverse direction, caused by time differences.
In practice, the study under examination [37], introduces general methods for the calculation of the probability of collision, similar to the one described previously [36], highlights its characteristics and finally exalts its problems and potential.
The definition of probability can certainly be carried out keeping the relative distance as input and performing a calculation that passes from a three-dimensional PDF to a two-dimensional one, such a case however is not dropped in a clear definition of the necessity of collision avoidance manoeuvres and above all it is not aimed at determining a priori, with the aid of generic data the probability of collision of a given SAT.
"Since the sensitivity to probability of collision during the encounter is significant for devising strategies used in avoidance manoeuvres, an explicit expression of probability of collision in terms of relevant parameters is needed" [37].
From this statement, the methodology adopted is then reported: we assume that a collision in space occurs in the vicinity of the intersection of the orbital planes of two objects under consideration (Figure 17); from here we note that the incriminating events, i.e., collisions, are dependent on temporal conjunctions and differences in orbital altitude. These two characteristics are related to the velocity in the cross section (for time differences) and the radial direction (for altitude differences), respectively. These components can be decomposed if the studied motion has the cross and radial sections perpendicular to each other. This is the case for objects in a circular orbit and also for objects in a near-circular orbit; thus, consulting NORAD (North American Aerospace Defense Command) data, for more than 90% of the orbits that are identified among those with the greatest risk of collision (LEO and generally Near-Earth Orbit, NEO). Objects below the 2000 km orbital sphere are inevitably

characterised by an eccentricity equal to or less than 0.1, as can be seen in Figure 18, also the work of Xu Xiao-Li and Xiong Yong-Qing [37].

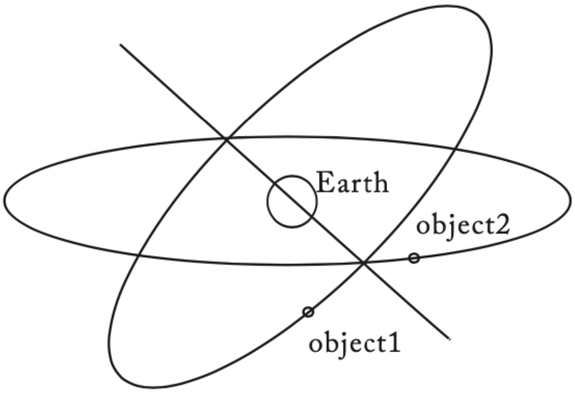


Figure 17: Zone of proximity to the orbital intersection [37].

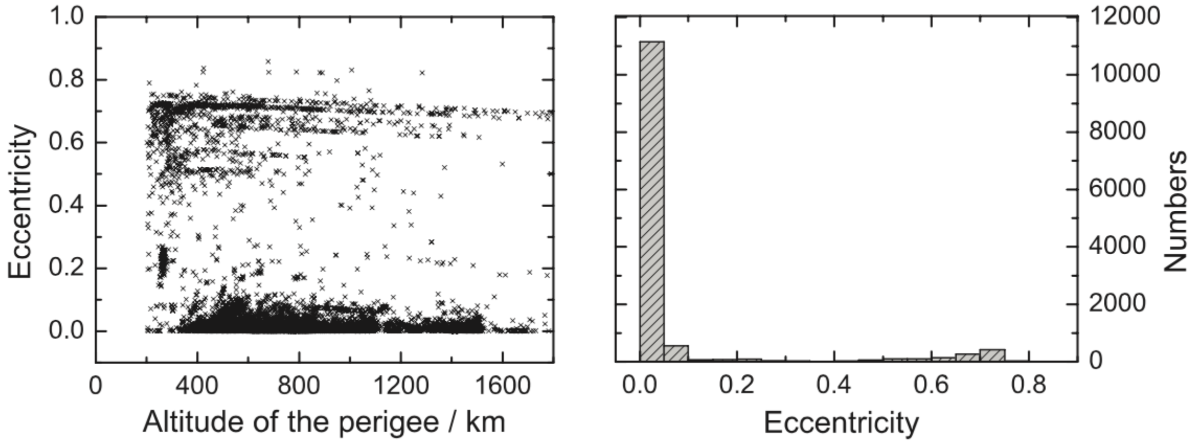


Figure 18: NEO population and their eccentricities [37].

From the above image (Figure 18) however, another factor can be noted, namely that the remaining orbits have very high eccentricities (0.7 - 0.8), this factor would therefore seem to be a weak point for the assumption necessary for our calculation. However, it must be remembered that, for orbits with high eccentricity (HEO), the time spent at perigee is very short, and this time window is also the one in which these objects are likely to encounter other possible bodies. In addition to considering this factor, which confirms the rarity of the event related to the collision of HEO objects and the validity of the initial assumption (which concerns circular orbits), we can also say that the probability related to encounter events between objects in HEOs and their potential colliders, is sufficiently simple [37].
By separating out encounters in NEO and encounters in HEO we validate the assumption that allows us to distinguish between radial and transverse collision probabilities; the calculation that then considers both characteristics will be a simple product of the two. Let us now distinguish between the radial and transverse cases and calculate them:

Probability in radial direction

Let us first define the radial position uncertainty by considering two objects that intersect their orbital planes simultaneously.

$$(16) \quad \rho(r) = \frac{1}{2\sqrt{\pi}\sigma_r} e^{\frac{-(r-\Delta h)^2}{2\sigma_r^2}}$$

With 'Δh' representing the altitude difference and 'σ_r' representing the relative position error and calculated as follows: $\sigma_r = \sqrt{{\sigma_{r1}}^2 + {\sigma_{r2}}^2}$ [37].
The radial collision PDF can then be described as:

$$(17) \quad F(r) = \frac{1}{2\sqrt{\pi}\sigma_r} \int_{-\propto}^{r} e^{\frac{-(r-\Delta h)^2}{2\sigma_r^2}} dr$$

And subsequently approximated like this:

$$(18) \quad F(r) = \frac{e^{a(r-\Delta h)}}{1+e^{a(r-\Delta h)}} \text{ with } a = \frac{4}{2\sqrt{\pi}\sigma_r}$$

Combining this result with the dimensions of the vehicle (r_a) or, in general, of the object under consideration results in:

$$(19) \quad P_R = F(x)|_{-\propto}^{r_a} - F(x)|_{-\propto}^{-r_a} = \frac{e^{\frac{4(r_a-\Delta h)}{\sqrt{2\pi}\sigma_r}}}{1 + e^{\frac{4(r_a-\Delta h)}{\sqrt{2\pi}\sigma_r}}} - \frac{e^{\frac{4(-r_a-\Delta h)}{\sqrt{2\pi}\sigma_r}}}{1 + e^{\frac{4(-r_a-\Delta h)}{\sqrt{2\pi}\sigma_r}}}$$

We then obtain a definition of Probability related to the difference in altitude, the error in determining it and the size of the object [37].

Probability in transversal direction
Let us first define the radial position uncertainty by considering two objects that intersect their orbital planes simultaneously. A scale factor $\beta = r_1/r_2$ is then considered to take into account the relative movement between the two objects and elide the altitude difference.
The Figure 19 below, also taken from the work under consideration [37], shows the reconstruction of the conjunction coordinate and the relative distance between the two vehicles is then calculated:

$$(20) \quad \rho(t) = (r_{20}\beta - r_{10}) + (v_{20}\beta - v_{10})t = \rho_0 + r_r t$$

Given the CPA (Closest Approach Point), such that $\frac{d}{dt}[\,\rho(t) \cdot \rho(t)]$ we also have the TCA (Closest Approach Time) given by: $t_{CPA} = -\frac{\rho_0 \cdot v_r}{v_r \cdot v_r}$

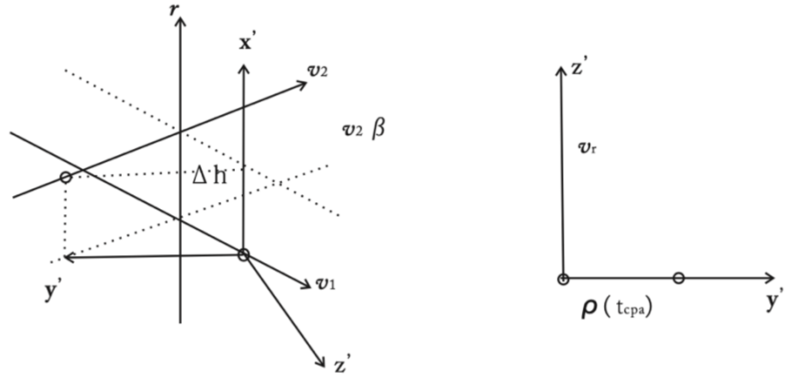


Figure 19: "The reconstructed encounter frame. The x' direction is normal to the cross section. The y' direction is defined as the position vector at CPA in the cross section. The z' vector completes the right-handed system". [37]

By reconstructing the data vectors from the PCA, '$\rho(PCA)$', and the unit vectors along the three axis directions we can, depending on the assumptions made earlier, move on to describe the probability of collision in the transverse direction given by the arrival time difference:

$$(21)\quad P_T = \frac{1}{2\sqrt{\pi}\sigma_t} \int_{-rt}^{rt} e^{\frac{-(y-\rho_{min})^2}{2\sigma_t^2}} dy$$

And, similarly to what we did before for the probability in the radial direction, we can, by considering the errors, obtain an analytical expression analogous to the other:

$$(22)\quad P_T = F(x)|_{-\propto}^{r_t} - F(x)|_{-\propto}^{-r_t} = \frac{e^{\frac{4(r_t-\rho_{min})}{\sqrt{2\pi}\sigma_t}}}{1+e^{\frac{4(r_t-\rho_{min})}{\sqrt{2\pi}\sigma_t}}} - \frac{e^{\frac{4(-r_t-\rho_{min})}{\sqrt{2\pi}\sigma_t}}}{1+e^{\frac{4(-r_a-\rho_{min})}{\sqrt{2\pi}\sigma_t}}}$$

Net Probability

So, we finish defining what we have obtained from Xu Xiao-Li and Xiong Yong-Qing's study, and we get a result produced from what we have calculated so far [37].

$$(23)\quad P_{tot} = \left\{\frac{e^{\frac{4(r_a-\Delta h)}{\sqrt{2\pi}\sigma_r}}}{1+e^{\frac{4(r_a-\Delta h)}{\sqrt{2\pi}\sigma_r}}} - \frac{e^{\frac{4(-r_a-\Delta h)}{\sqrt{2\pi}\sigma_r}}}{1+e^{\frac{4(-r_a-\Delta h)}{\sqrt{2\pi}\sigma_r}}}\right\}\left\{\frac{e^{\frac{4(r_t-\rho_{min})}{\sqrt{2\pi}\sigma_t}}}{1+e^{\frac{4(r_t-\rho_{min})}{\sqrt{2\pi}\sigma_t}}} - \frac{e^{\frac{4(-r_t-\rho_{min})}{\sqrt{2\pi}\sigma_t}}}{1+e^{\frac{4(-r_a-\rho_{min})}{\sqrt{2\pi}\sigma_t}}}\right\}$$

The numerical results obtained through this study are certainly interesting, but they distinguish methodologies that require high powers of calculation; however, from this study, one can retain the treatment of probability that will also consider the geometrical aspects or in any case the size of the objects involved.

Therefore, some of the assumptions made may, in the following chapters, be considered valid and combined with other methods analysed to provide an accurate overall picture.

Stochastic model:

This model uses a purely statistical distribution to determine the probability zones [38]. In fact, a PDF is identified somewhat like in the first case of the Volume but with a higher precision that does not lead to approximations made for the sake of safety. Furthermore, this method considers all three dimensions and finds a correlation between them, previous methods did not consider the link between the uncertainties and transformed the three-dimensional problem into a two-dimensional problem which was then, in some cases, decomposed [38].

Obviously, in the probability study, models of relative motion of proximity between the objects under consideration are exploited, but, generally, asymmetry and kurtosis (a measure of the heaviness of the distribution tails) are ignored. The trajectory is thus approximated in rectilinear form and the ellipsoid (considered in the first work presented [36]) remains constant in time. However, the observed behaviour, following the collected data, is not Gaussian-likely and the ellipsoid tendency is to flatten and deform assuming a "banana" shape.

Considering a n-dimensional Gaussian distribution, the model proposes the following PDF for the random vector [38]:

$$(24) \quad p(x, \mu, \Sigma) = \frac{1}{\sqrt{(2\pi)^n \cdot \det(\Sigma)}} \cdot e^{-\frac{1}{2}(x-\mu)^T \Sigma^{-1}(x-\mu)}$$

All three variables are n-dimensional and represent respectively: the state vector (x), the mean vector (μ) and the covariance matrix (Σ).
The relative uncertainty in three dimensions between two objects in space is then expressed in Gaussian form [38]:

$$(25) \quad p(x) = \frac{1}{\sqrt{(2\pi)^3}\sigma_x \sigma_y \sigma_z} \cdot e^{-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2}}$$

With $\sigma_x, \sigma_y, \sigma_z$ representing the uncertainties along *x, y,* and *z* (separation lengths in the approach zone).
Considering the area of intersection between the ellipsoids, integrating the PDF gives the probability of collision [38].
However, the proposed work is aimed at calculating probabilities for wire systems, so the order of magnitude of the probability is expected to be considerably higher than for systems without this technology as the volume occupied is totally different.

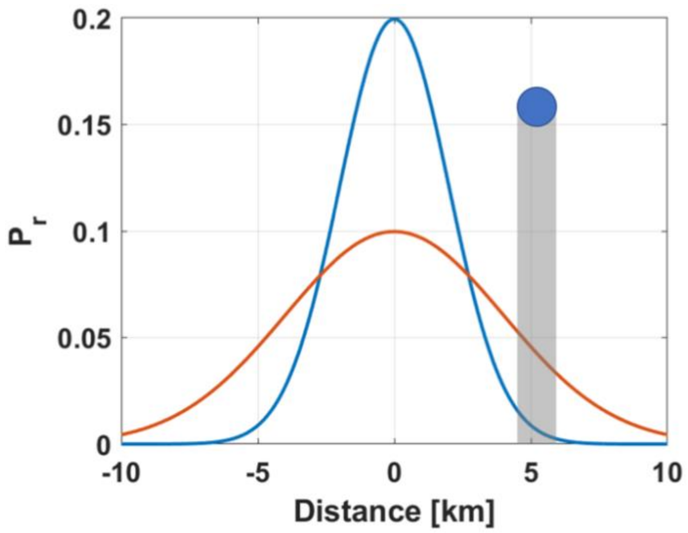


Figure 20: More accurate data (blue curve) appear less distributed than less accurate data (red curve), seeming to reduce the probability of collision due to lack of confidence: a phenomenon called probability dilution [38].

Although it may be of interest to quantify the probability of collision also for wire systems deployed in the re-entry phase, and although it may be of high utility to know the difference in risk between one re-entry system and another, the analysis carried out in this thesis work cannot consider complex treatments as it is a preliminary study and must lead to a simplification of existing methods.
However, this work is considered for a possible future analysis of the collision zone and the local probability of conjunction.

MOID model:

The models seen above refer to the single collision event. In other words, the works treated up to now identify collision possibilities assuming that one body is close to another and then, by means of relative motion equations or relative errors on the determination of the position of the bodies, the probability zone, represented by the PDF, was calculated.

However, in general, we can confirm the lack of applicability of methods such as those just described for the simple reason that they would require high computational masses to obtain data of little use either for the definition of a rapid classification or for definition using reliable data.

In the study of collision probability another model emerges called MOID [39]; this tool is, to be precise, used by astrodynamics scientists or astrophysicists and tends to deal with problems involving planets and large celestial bodies for the determination of risk windows. For example, it is used to classify dangerous asteroids and thus give a quick and concise classification of bodies that risk impacting our planet.

For a better understanding of a further methodology for calculating the probability of collision, we will now go on to describe the minimum orbit intersection distance (MOID).

The MOID method takes an object to be analysed, in the example seen above the Earth, and identifies all similar orbits and then separates the "riskier" trajectories from the less risky ones. Then, for each object, a comparison is made between its trajectory and that of the Earth. The MOID is nothing more than the absolute minimum of the Euclidean distance between a point on the orbit under consideration and a point on the Earth's orbit [40].

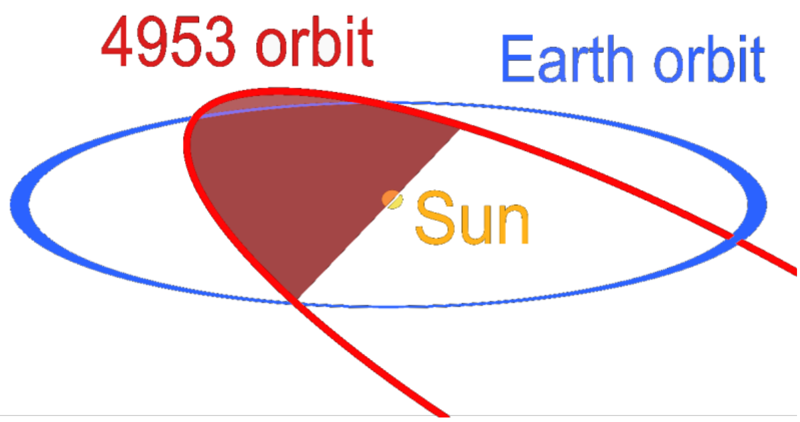


Figure 21: MOID representation; image credits to Wikipedia [39], modified by Federico Toson.

The image above is a simple representation of what the MOID is, but above all it allows us to visually understand the importance of the points of possible contact, which in fact, as mentioned above, are the points of intersection between the various orbits.

The calculation of the MOID is carried out in various ways and by various orbit mechanics experts [41] [42] [43] [44], however, mentioning some of these works would lead to losing the focus of the work of this thesis by entering into areas that have little to do with what is being discussed. Considering 'x_0' as the nodal distance and 'a', 'e', and 'I', the characteristic parameters of the asteroid orbit, a simplified formulation is described, which could be taken into consideration in the event of further study:

$$(26) \quad D_{min}^2 = \frac{x_0^2 a^2 (1-e^2) \cdot sin^2 i}{2a(1+x_0) - (1+x_0)^2 - a^2(1-e^2) \cdot cos^2 i}$$

We have therefore defined some of the potential methods of calculation but remember that only the MOID provides a classification model which, as the reader is reminded, is the objective of this thesis. Unfortunately, the MOID classification idea is not feasible in this context, but it can be the basis for defining a hierarchy in risk assessment. The other methods seen can also be a starting point for defining an unambiguous probability calculation method and a basis for further development.

Hence, in the following chapters, we will then define a dedicated mode for the calculation of probability which is partially outside what we have seen so far.
Let us then move on to the other contribution that characterises risk calculation: severity. In the next section we will have a brief insight into its determination.

4.4 Severity Introduction

Analysing the severity aspects and therefore the consequences related to space collision, we must remember that these work on several levels. Basically, making a parallel with what we read in the short paragraph dedicated to Space Law, the consequences are inevitably correlated to the different forms of legal repercussions since, on these, the cost analyses on the damages resulted are based.
From here we then go on to define the three categories of consequences to which the collision can lead:

- Individual damage and related to issues of the individual SAT.
- damage to third parties and related to the individual collision with another spacecraft with a defined PL.
- Large-scale damage to third parties related to catastrophic events.

Let us therefore analyse these situations one by one and determine possible calculation solutions.

Individual Damages

This kind of consequence might be misleading, as one might think that these repercussions are closely linked to the interests of the subject. This is certainly true, but in order to fully identify them one has to look at the funders and stakeholders of a mission.
Clearly, investors, collaborators, or any entity that benefits from the positioning of an SAT in a given orbit, are harmed by a possible failure. This fact is obvious but should not be underestimated, in fact just think of a telecommunication SAT placed in GEO that for some reason collides with a debris, in this case the risk assessment and the preventive insurance could save the huge amounts of money invested for the launch, the in-orbit insertion and, of course, the development and the MAIT of the SAT.

Damages to Third Parties

Keeping the focus on the example we have just seen, let us not forget that in the function of a collision against an inanimate body and without PL we can be "calm" since the repercussions are inevitably linked to the producer and, as said before, to the stakeholders. When the collision takes place between two active and PL vehicles the situation becomes enormously complicated. It must first be determined, as the Liability Convention [17] states, who is to blame. In most cases, this will result in both S/Cs being unable to prevent the collision and therefore being declared equally at fault. If, on the other hand, it was to be inferred that the fault is imputable to one of the two parties, well, this would certainly result in the guilty parties owing the injured party an obligation.

Catastrophic events

Events of a catastrophic nature are certainly not science fiction, and we can confirm this after the assumptions seen in the paragraphs dedicated to the SAT population referring to the Kessler syndrome [2]. Therefore, in this regard, as mentioned in chapter 3, concerning the needs of the market, we can see how a definition of risk by classification and above all one that includes large-scale phenomena in this classification is extremely necessary. Consequently, at the end of this chapter, a brief excursus will be made on fragmentation, survivability and vulnerability indices, inevitably necessary components to be introduced for the calculation of a risk coefficient taking into account the characteristics just listed.

4.4.1 Cost Analysis

Given the wide spectrum of possibilities for individual, third-party or worse, catastrophic events, it is understandable that the economic spectrum is even more varied and includes infinite types of situations. For this reason, large-scale quantification may be difficult. At the same time, there may be strategies that introduce simplifications, the result of which, however, is not so far removed from reality.

Before finding this issue and describing the simplifications adopted in this thesis work, we would like to propose a first general quantification for a definition of the costs related to the following areas:

- Design.
- Development.
- MAIT (Manufacturing Assembly Integration Testing).
- Launch.
- In-Orbit positioning.
- Supporting instrumentation (e.g., ground station).
- Management.
- Decommissioning.

From these, a value can then be decreed in the event of unfortunate events.

We begin by emphasising the fact that to sustain a space mission, in addition to the costs of its development, it is necessary to have, build or rely on ground facilities that allow not only house-keeping data to be monitored but also can communicate information. Communication that has a cost especially if these, as in most cases, are the primary source of revenue for the strategic positioning of the PL.

Based on this assumption, the quantification of the cost that we are making for this thesis is for reasons of risk related to the collision, so it will be necessary to exclude the non-injured components but, at the same time, to understand that even the investments made for a space mission that ends prematurely due to an unexpected event would often be considered as actual damage.

After this assessment, we are going to define, before describing quantification methods, the costs considered average for launching a vehicle into orbit.

What is usually done is to consider the cost per kilogram; in fact, this is the parameter of interest also for practical reasons. If we think about putting a S/C into orbit, the first action that must be performed after construction is the actual launch. Therefore, the quantification of the propulsive thrust is the first important cost that cannot be avoided and is independent of any mission. This thrust obviously has a cost, and this cost is proportional to the mass that must be transported. In addition, when sizing the launcher, we must not forget that there are no univocal solutions. In fact, manuals such as Ronald Humble's "Space Propulsion Analysis and Design" [45] can be used to clearly understand which is the most convenient solution in various launch situations. The solution will identify the propellant used, which, depending on the type of mission, will involve the size and thickness of the combustion chamber. For example, looking at the inheritance data described in Humble's handbook, one can see how the propellant fraction, defined by the formula below, where 'm_{INERT}' is the inert mass and 'm_{PROP}' is the propellant mass, varies according to the use of the SRM (solid rocket motor), e.g., boosters compared to launchers. A look at this inheritance can be seen in Figure 22, also extrapolated from Humble.

$$(27) \quad f_{PROP} = \frac{m_{PROP}}{m_{PROP} + m_{INERT}}$$

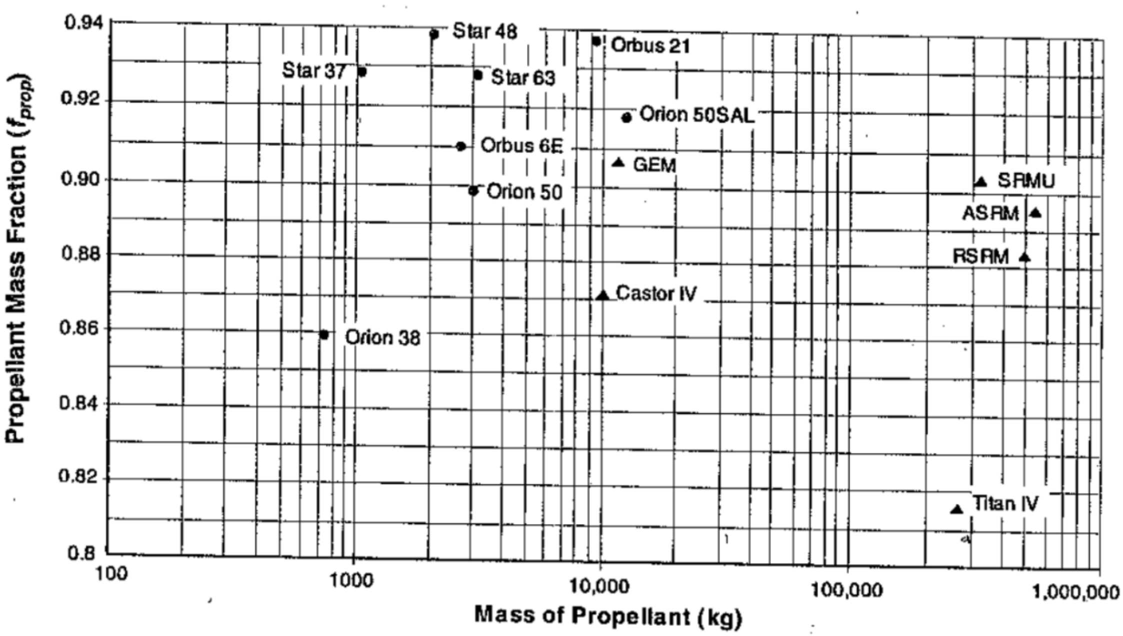


Figure 22: Humble heritage data about SRM [45].

Once the propellant fraction has been estimated, the mass must be calculated. This is where the design requirement that leads to cost comes in. In fact, to reach a certain orbit, a certain speed difference (ΔV) is defined. This is where the mass of the PL comes in, in fact, again referring to the Humble, we have the following formula [45], which is in fact the Tsiolkovsky rocket equation [46]:

$$(28) \quad \Delta V = g_0 \cdot I_{sp} \cdot ln\left(\frac{m_i}{m_f}\right)$$

Where 'g_0' is the gravitational acceleration, 'I_{sp} ·' the specific impulse (a fundamental parameter that distinguishes the performance of the selected propellant) and finally we can express with R the mass ratio 'm_i / m_f'. In 'm_f' is contained the mass of the PL and therefore the figure of interest which, after the choice of propellant, determines the cost, in fact we should also remember that:

$$(29) \quad m_f = m_i - m_{PROP} = m_{INERT} + m_{PL}$$

If we want to express the mass of propellant required, we can use the following formula:

$$(30) \quad m_{PROP} = m_{PL} \left(\frac{f_{PROP}(R-1)}{1 - R(1 - f_{PROP})} \right)$$

It should be noted that SRM has been presented here to describe one of the various sizing procedures, but the liquid engine could be considered. In fact, this excursus is not to be considered as a definition of technical dimensioning, for this there are special books such as the Humble [45], this paragraph is intended to be a way to describe the costs incurred during the launch phase and what they are divided into.
Basically, when dimensioning, you end up with the following chain (Figure 23) described on page 305 of the Humble [45].

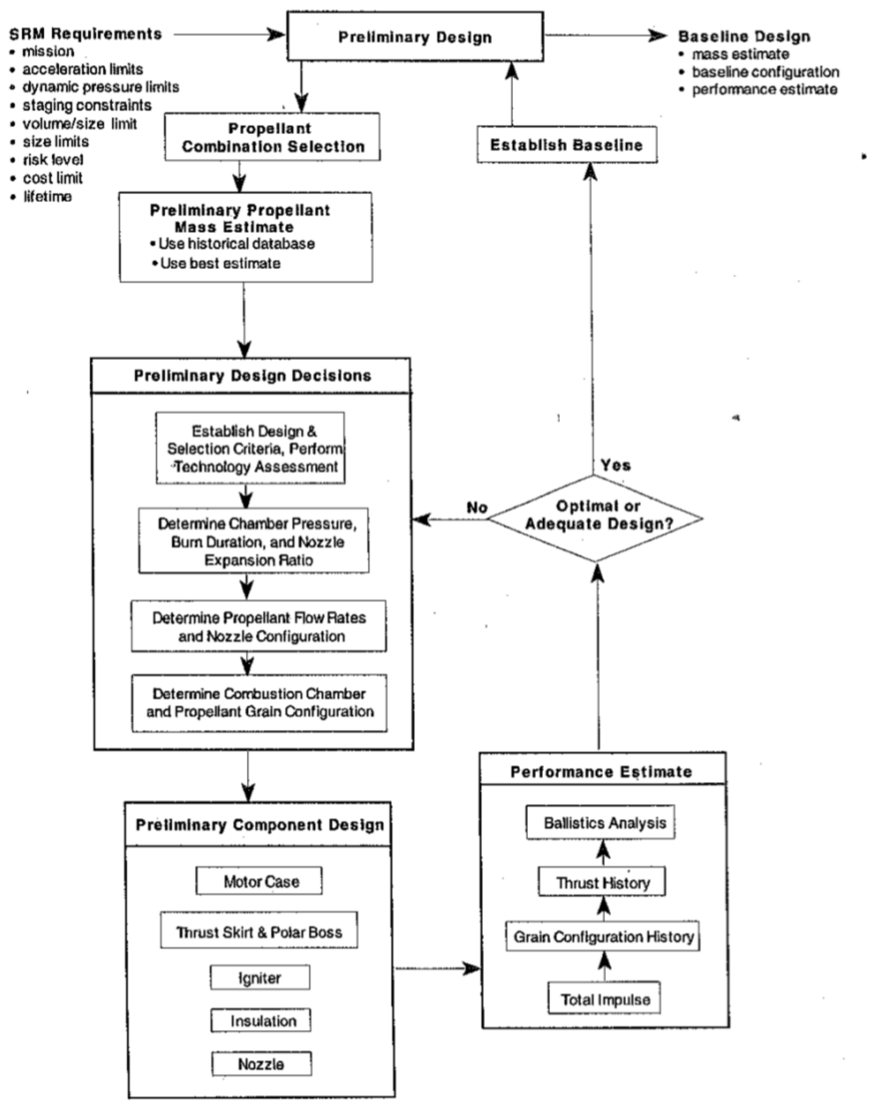


Figure 23: Humble design process for SRM [45].

Therefore, once the PL and its weight are understood and certain design choices are made, the following costs are incurred:

- Cost of the propellant (obviously proportional to the quantity and type)
- Cost of the case and support structures (this would be the inert mass as a whole)
- Cost of management and development (obviously, design, especially in an iterative manner, as in this case, can entail a large expenditure of effort or resources, whether the work is done in concurrent engineering).

Having defined this example of cost, it should be remembered that launch is something that no company can do without, and based on which the greatest speculation is made, including in risk assessment. In fact, more and more space logistics strategies are being undertaken that tend to reduce these costs to the point where some companies dream of assembling SATs directly in orbit. A classic example is the company SpaceX, which was the first to bring the option of reusing the launcher, leading to a significant reduction in costs (Figure 24).

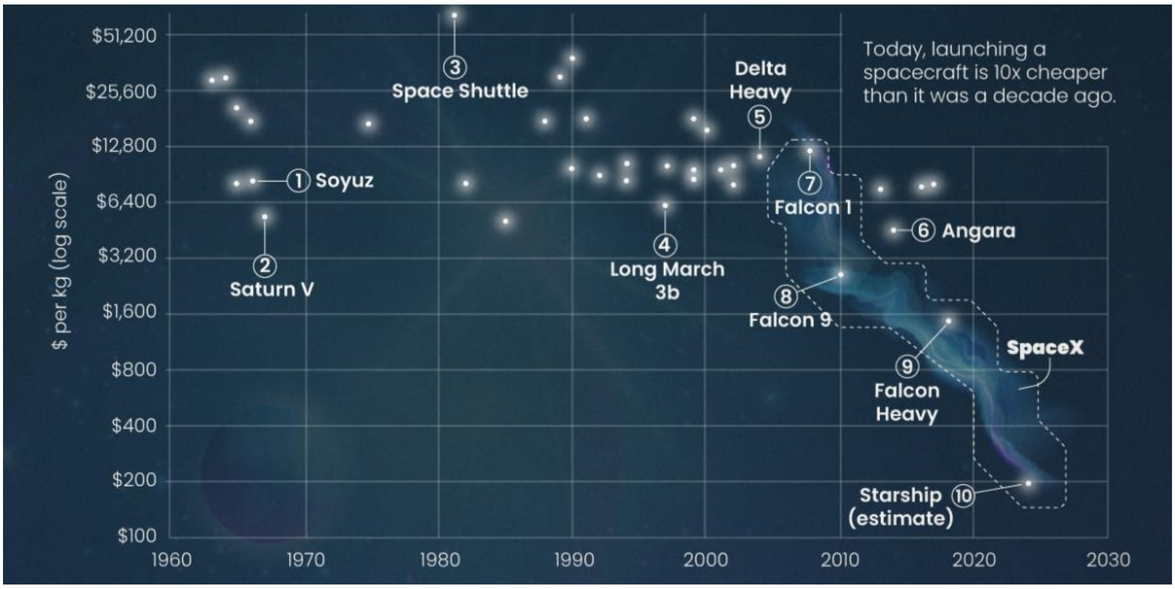


Figure 24: $/kg costs for different types of launchers [47].

In general, cost reduction in history has occurred to a constancy due to the inherent technological limitation of the launch. These are all signs that the NSE has a positive influence, described extensively in economic articles available online [47] [48].

The graph below (Figure 25), which is the result of the Aerospace Security Project [49] of the Center for Strategic and International Studies (CSIS), shows how the cost of the mission has been reduced, and this has been achieved with strategies that mitigate the cost of the launch. It should also be remembered that, to date, this cost is the one mainly covered by space insurers.

We identify, in all these cases, a way of calculating the cost of the mission given by a cost in $ per kg; this makes sense since it is also in agreement with the evaluation and sizing example given earlier, since the mass of the PL is the starting element and therefore, based on the solutions chosen, the determining character for understanding the cost of the mission.

It is pointed out that it is therefore all the result of a trade-off between performance and expenditure and that this leads to an increasingly differentiated distribution of the costs involved in putting a SAT into orbit.

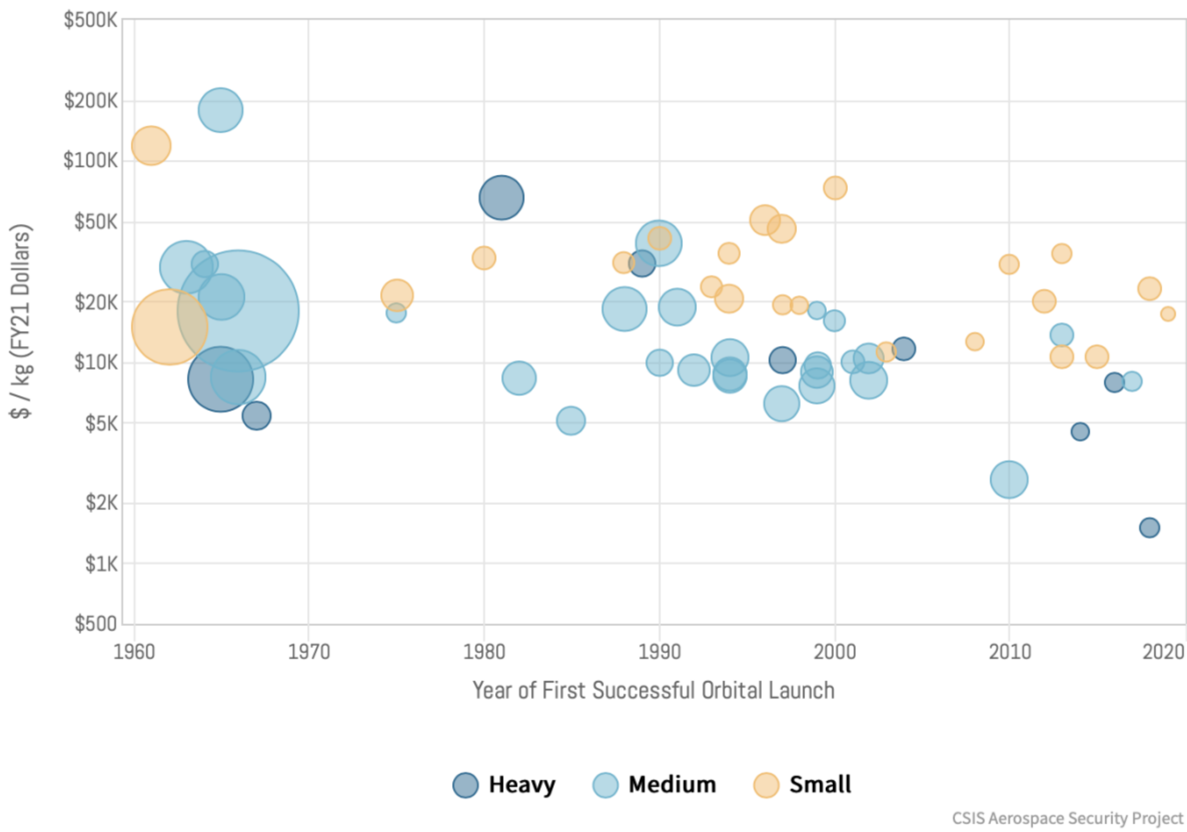


Figure 25: Breakdown of the cost of a launch according to the years and the various launchers [49].

From now on we introduce the γ_{kg} coefficient which describes the cost per kilogram, and which will then be used in the determination of severity in the following chapters.

In concluding this chapter, we can state that severity can be estimated in various ways, the most interesting and perhaps sensible being that of cost, but, of course, there are contributions and ways of expressing the severity of an incident that disregard the pure economic value which, in catastrophic eventualities often cannot even be determined. For this reason, a brief overview of the risk of fragmentation and its assessment is given in the next chapter.

4.5 Further Assessments

In addition to the methods of calculating probability and severity that can be found in the literature, there are other classification possibilities, closely linked to the field of collisions, which emphasise the risk associated with a given mission.
In this short paragraph, therefore, some assessments of fragmentation, survivability and vulnerability are given. Three indices that in a very thorough manner express key characteristics of a S/C and thus distinguish its interaction with the space environment.

4.5.1 Fragmentation Risk Evaluation

A topic that should certainly not be excluded in the analysis of collision risk is fragmentation. As was seen for ECOB [24] and other risk indices, it is inevitable that in considering the probability and consequences of an impact, the probability and subsequently the extent of the damage that such an impact may cause is calculated based on the intrinsic parameters of the vehicles involved.
In identifying the damage associated with the impact, the scenarios of explosion and subsequent fragmentation are highlighted. Consequently, these aspects need to be addressed when dealing with a risk index.
As far as adding this term to the overall balance sheet is concerned, it appears only as a de facto additive term. But, for the development of it, the questions and ways are varied.
So, to move to an index formulation that includes this term, what strategy should be adopted?
In the case of ECOB, especially in the extension that takes fragmentation into account [24], data from DISCOS [33] are used. However, it must be remembered that these data are in any case past statistics, so looking for other ways of dealing with them runs into another study by Rossi, Lewis et al. [50].
In essence, past data is always preserved but a prediction is created through it; given the non-linear nature of the spatial population and the variety of actors within it, it is undoubtedly useful to rely on accurate future assessments to predict, from assumed and future data as opposed to certain and past data, the evolution of satellite populations.
By means of Monte Carlo simulation, a fragmentation scenario is then assumed based on certain data and the criticality of this event is determined by means of an appropriate coefficient.
Consequently, considering the average number of objects in a reference scenario and calling this term N_r, considering also the number of objects in the case of fragmentation (term N_f) and the standard deviation (σ_r) due to the error of the Monte Carlo simulation, the following is obtained [50]:

$$(31)\ \ C_i = \frac{N_f(i) - N_r(i)}{\sigma_r(i)}$$

This is the population increase for each year (*i*), so if we want to express with a single number the criticality of the fragmentation scenario, we take the number of years (N) in which this occurred and get a single number as follows:

$$(32)\ \ C^* = \sum_{i=1}^{N} \frac{C_i}{N}$$

4.5.2 Survivability and Vulnerability of a Satellite

If we then want to move on to concepts, again of a quantifiable nature, useful for the study conducted for this thesis work, we focus on vulnerability and survivability.
An on-orbit SAT has some intrinsic individual reliability components, others certainly depend on external factors and together they allow us to indicate its reliability in the space environment.
Obviously, as already mentioned, in this thesis work it is not possible to analyse all the coefficients that identify the risk of collision, this because the focus is in any case to search for simplifications that maintain the consistency of more complex calculation methods and, at the same time, reduce the burden of calculation and the quantity of simulations.
It is still correct to assign ratings to leave room in the proposed code for possible implementation.
However, the main motivation that leads us to focus mainly on these two factors is related to the survival that the SAT shows in the space environment especially in the most critical phases, in essence, the time required for decommissioning. We are talking about a time when the SAT has completed its operation and which, by the main global standards (such as NASA's), must last 25 years at the most [51].

Therefore, we introduce two possible evaluation works in the indicated field [52] [53].
As far as survivability is concerned, the work conducted by Trisolini M. [52] is reported. This model "*analyses the satellite resistance against the impacts of untraceable space debris and meteoroids. Standard vulnerability analysis software relies on ray tracing method in order to predict the damage on spacecraft panels and internal components*".
The Figure 26 identifies the process implemented to determine survivability for the software proposed by Trisolini [52].
Finally, to provide a useful result for the work carried out, we consider that this effect can then define a percentage factor indicating how much such SAT has the aptitude to survive in the spatial environment.

Vulnerability, on the other hand, is an aspect addressed, for example, in a study conducted by Olivieri L. and Francesconi A., who developed *"a novel tool to associate the impact risk to the spacecraft ballistic response, evaluating the satellite protection configurations during the whole spacecraft life*". [53]
"The proposed procedure can be used both for the definition of a set of minimal required protections spacecraft shall implement to fulfil the constellation survivability to the debris environment and an independent evaluation of pre-defined configurations". [53]

These types of estimates are therefore kept in mind for the definition of a risk index complete with reliability coefficients covering aspects linked to moments of high-risk mission but also of considerable criticality for the space community.

Having identified a quantitative way of defining fragmentation, survivability, and vulnerability, we have touched on all the points for the formulation of a consistent index which not only considers the various factors associated with collision but also takes into account most of the variables involved.

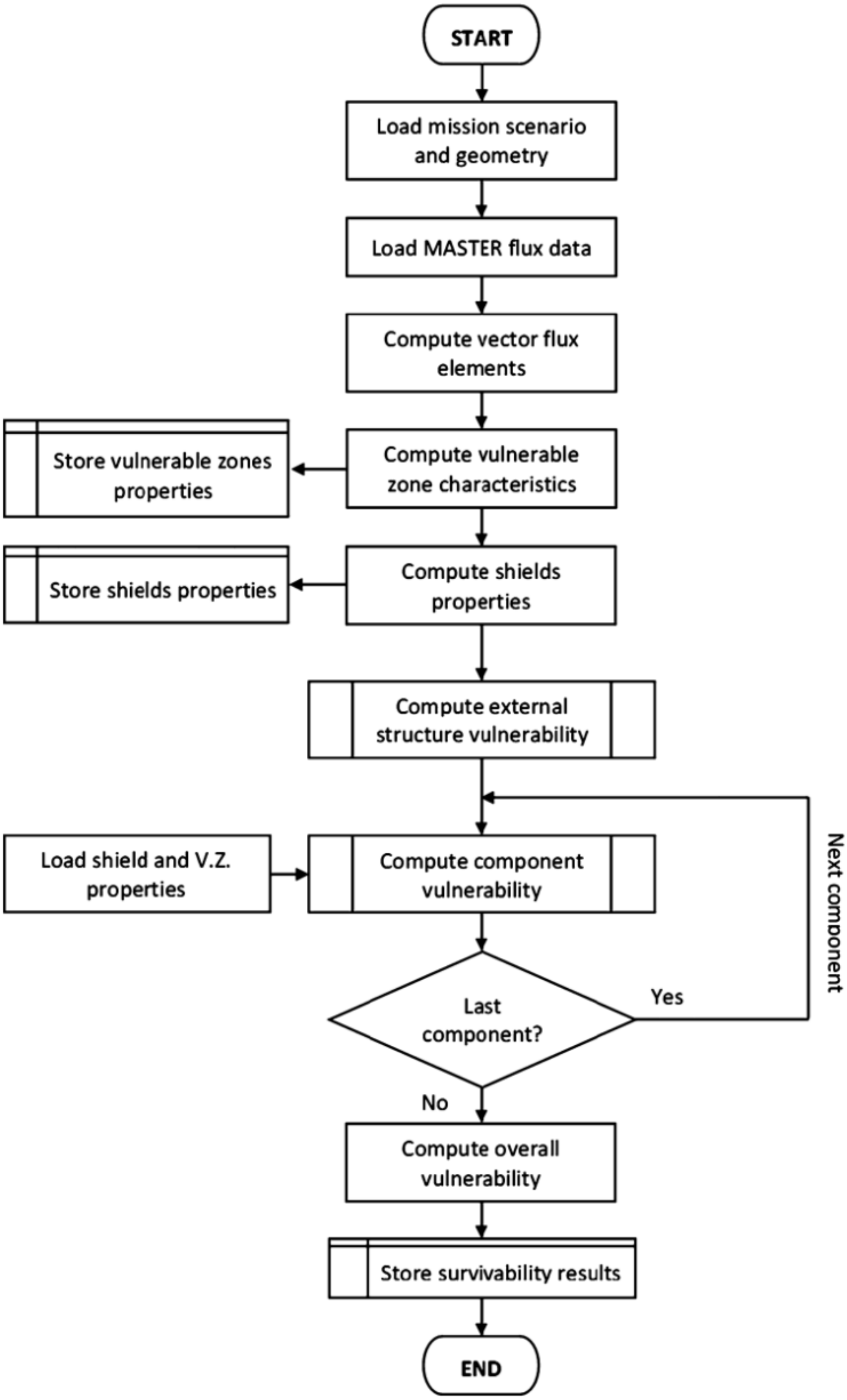


Figure 26: Flow diagram of the main structure of the survivability software [52].

We then move on to the actual risk formulation proposed in this thesis.

5 Proposed Formulation of Collision Risk

Given the main methodologies for carrying out collision risk assessment, we can easily understand how wide the spectrum of possibilities is.
It must be remembered, however, that the final objective is to carry out a hierarchical division of risk in order to classify the various orbiting space objects. Therefore, the definition of probability and severity must be at least simplified, rapid and subsequently easy to interpret. To do this, the essential inputs and outputs for an optimal probability and severity estimate are defined. In making this definition, we must not forget that some of the important aspects may be excluded, and therefore in order not to leave out any of the crucial areas, we referred to the diagram in Figure 4 (Chapter 2.3.3).

5.1 Proposed Inputs & Outputs

In the evaluation of inputs and outputs another important factor is their interest and value. Certainly, as already mentioned, in the field of individual risk assessment the variables considered are of a certain specific type. However, when looking at the collective environment, these inputs may change their value, some may disappear, and others may be introduced as new points of interest. To give an example it is clear that in the development phase the interest of a manufacturer and therefore of a company is to avoid the failure of most of the on-board instruments, especially those for which the SAT in question has been commissioned, but in the legal and insurance field some of these aspects may lose their importance; in essence, the failure to meet the PL objectives does not automatically imply a risk for the community. To describe this example even more accurately, a SAT for meteorological monitoring is not a potential hazard to others if it interrupts its monitoring due to a malfunction, it is if and only if this malfunction extends to other components and undermines possible collision avoidance, re-entry, orbital stability.
Following what has been mentioned, the decision in this case has been to consider three main branches of interest, the individual, the collective and the mitigation one. In Chapter 4.2 we talked about inputs and outputs; these inevitably translate into risk scenarios involving the satellite unambiguously and others where the satellite is a risk to the community. There are also factors that reduce these risks, mainly collective ones, so the aspect of mitigation strategies is introduced.
Consequently, in Chapter 6, this statement will be more precisely defined while in these pages we will focus on the solutions chosen for the risk assessment.
Consequently, the inputs defined for the risk characterisation in this thesis work are the following:

- Orbital parameters of the SAT whose collision risk is to be assessed.
- Orbital parameters of the objects present in the population.
- Physical characteristics of the SAT under consideration.
- Costs related to potentially colliding objects.
- Fragmentation index related to potentially colliding objects.

While the main contributions that appear as output and then define the actual risk are, as defined:

- Probability.
- Severity.

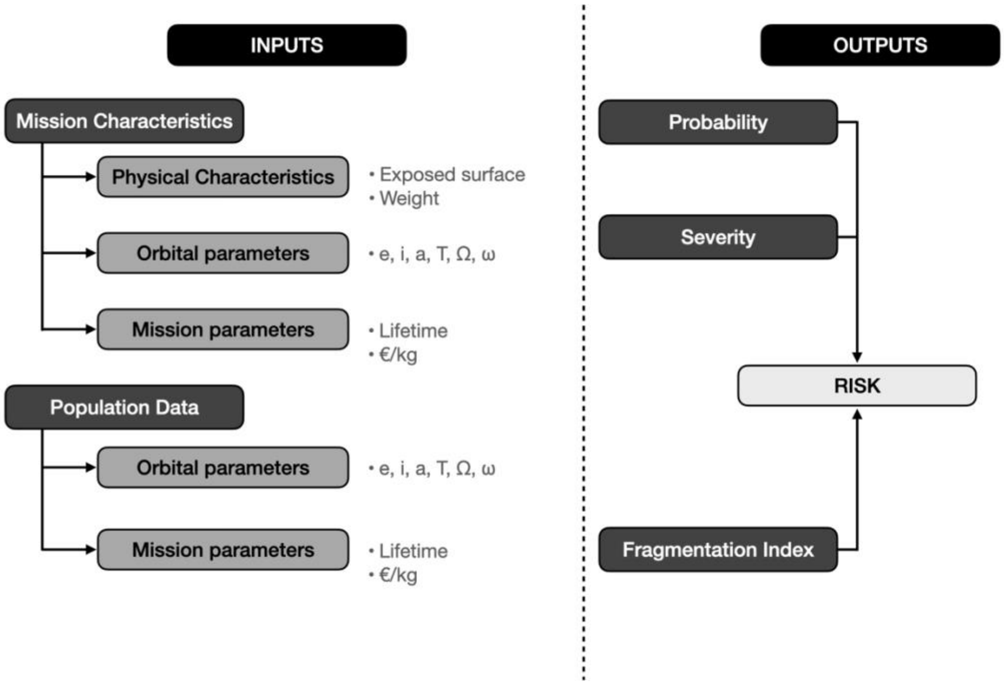


Figure 27: Selected inputs and consequent outputs.

The image above (Figure 27) accurately summarises what was anticipated.
So, based on what has been said, we move on to the calculation of probability and severity, which will then mainly serve to develop the collective scope.

5.2 Collision Probability Computation

Starting from the assumption that the methodology must be simple, easy to implement, therefore free of complex calculations and simulations but, at the same time, must provide a set of data that is almost immediate and easy to understand, the Probability calculation is researched by considering:

- All the objects involved.
- Simplified orbital propagations.
- Statistical methods with a large margin of error.

Furthermore, we must remember that this thesis is looking for a way of classification to be implemented on each SAT taken individually and therefore, the starting point is a hypothetical S/C with its mission characteristics well defined.
Basically, the simplest idea is to consider the SAT inserted in the orbital environment, which can be the result of true population data, but also simulated data. Clearly, the variability and presence of SATs and debris in the various orbits must have values that are traceable to the real ones, however, it is not necessary that these values are the real ones as this is a preliminary assessment. Subsequently, with creative information, it is possible to refine the calculation and obtain more truthful data that will not necessarily differ markedly.
Consequently, it is easy to construct a database with characteristics like the real ones, i.e., with a comparable number of SATs in GEO and LEO, equally variable orbits and true eccentricity distributions; all data that in the previous paragraphs proved to be easy to consult and find [14] [33] [33] [37].
Once the set of "protagonists" of the spatial environment has been defined, the S/C under examination is immersed in it, and the possible conjunctions with the other SATs are

identified, taking inspiration from the second model seen in the previous paragraph [37]. It is evident that the number of points found, realistically, considering a gap under the kilometre is equal to zero, but, obviously, the conjunction points can be defined as true if an error at least equal to three times the area covered in 1 second is considered. This is because it is correct to consider the previous instant, the instant of the potential collision and the following instant as a "safety" zone to be sure that no points of possible conjunction are missed.
By implementing this assumption, we are therefore creating potential collision zones that have a radius of about 10-20 kilometres and that represent with sufficient accuracy the fluctuations and orbital variations of objects around the Earth.
The actual probability calculation is introduced at this point; given the various assumptions and determined collision zones, still to be determined the small orbital portion swept by the SAT that is in the conjunction zone. To do this is sufficient to think about what is the probability that the S/C is located at a certain point of the orbit.
The definition that is given in this thesis work: The probability that a S/C is at an orbital point is defined as the time it takes the SAT to travel around the orbital point ‘dt’divided by the total time it takes to complete an entire orbit **‘T’.**

$$(33)\ \ P_{orbit} = \frac{dt}{T}$$

The evaluation of the orbital time or even of a section, knowing the true anomaly of the initial and final instants, is sufficiently obtainable by means of Kepler's equations [54].

$$(34)\ \ E = 2 \cdot tan^{-1}\left(\sqrt{\frac{1-e}{1+e}}tan\frac{\theta}{2}\right)$$

Where ‘E’ is called the eccentric anomaly, ‘e’ represents the eccentricity of the orbit and ‘θ’ is the true anomaly of the incriminating point.
The average motion (M_e) is then calculated, and the time fraction (t) of the entire orbit time (T) connected to the point of interest is identified:

$$(35)\ \ M_e = E - e \cdot sinE$$

$$(36)\ \ t = \frac{M_e}{2\pi}T$$

Consequently, if we wish to calculate the travel time between two instants, thus corresponding to two true anomaly values (θ_1 and θ_2), we simply repeat the above calculation and subtract the time obtained from the next instant from the previous one.
However, to define the travel space and thus the start and end points with their true anomalies, a strategy is sought that considers the characteristics of the S/C and then differentiates the calculation for the various situations. The solution is identified as a coefficient that considers the points before and after the motion in proportion to the exposed surface. Given that orbital discretisation is in the order of 20000 points per orbit, the following table (Table 7) defines the range of points before and after the point of impact as a function of surface area in square cm.

Table 7: points of the orbit discretisation before and after the collision taken into account in function of the satellite exposed surface.

Range (around the collision point)	Exposed surface of the satellite [cm^2]
± 1	S < 500
± 2	500 < S < 1500
± 3	1500 < S < 3000
± 4	3000 < S < 5000
± 5	5000 < S

Clearly, what we have come up with is very approximate and is for demonstration purposes only. A more accurate study of the exposed surface and its influence on the probability could make the data even more accurate. In fact, it is considered very useful to have a correlation between probability and exposed surface as it is already a way to distinguish hierarchically the collision risk for space objects.

At this point, given the calculated point ranges, we can estimate the probability that both objects involved in the potential collision are at the incriminated point. We then recall that what we have seen for the Formula 33 applies to both and then the probability of collision will be given by the product of the two 'P_{orbit}':

$$(37) \quad P_{collision} = P_{orbit,1} \cdot P_{orbit,2}$$

We must not forget, however, that the time factor has its influence, in fact, as described in Chapter 6, a time term representing the years in which both SATs coexist in the space environment is multiplied to the above formula; this is because for a correct calculation of probability it is necessary to consider all the orbits made and not just one.
Since, by definition, probability is always a number between 0 and 1, it makes sense that the probability of collision is a smaller number than the individual probabilities of the SATs being at the point of conjunction. From here, however, we try to estimate the total, hence cumulative, probability, which, by definition, is [55]:

$$(38) \quad \mathbb{P}(\mathrm{E}_1 \cup \mathrm{E}_2) = \mathbb{P}(\mathrm{E}_1) + \mathbb{P}(\mathrm{E}_2) - \mathbb{P}(\mathrm{E}_1 \cap \mathrm{E}_2)$$

That is, the total probability that two independent events occur is nothing else than the sum of the single probabilities of the two events minus the probability that they occur simultaneously. In the case under consideration, obviously, the last term disappears because there is no possibility that one of the two bodies in question is found either at one point or at another of the orbital intersection points (which we recall are two). So, the calculation of the total collision probability is reduced to a trivial sum of the collision probabilities related to all the conjunction points identified by the simulation.

$$(39) \quad P_{coll,tot} = \sum_{i=1}^{N} P_{collision,i}$$

With 'N' total number of conjunction points identified.

The probability calculation methodology developed in this thesis is thus defined, and it is made clear that this strategy is undoubtedly very simplified, but at the same time allows a hazard scale to be defined for the SATs involved.

5.3 Collision Severity Computation

Based on what was said in the Chapter 4.4, in this thesis it was decided to evaluate the severity of an event by correlating it mainly to the economic value of the bodies involved.

As previously mentioned, the coefficient 'γ_{kg}' is considered, which expresses the cost in dollars per kg. Obviously, this, multiplied by the vehicle mass, defines the actual cost of the mission considered. If we then add up all the incriminating conjunction events, we can then define the total severity resulting from the mission and the S/C under consideration (as expressed in the formula below).

$$(40) \qquad S = \sum \gamma_{kg} \cdot m$$

Of course, for many chain events it is difficult, maybe impossible, to estimate the actual severity involved. Therefore, in the present case the choice was to avoid making an economic assessment. The perfect example is the multi-cited Kessler syndrome [2], which is in fact a scenario with an unquantifiable amount of damage.

5.3.1 Fragmentation Consideration

We consider the possibility of introducing a coefficient expressing and quantifying, not so much the damage involved, but the ability of a SAT to fragment. As seen above this has already been done and can be exploited as an integration of the risk defined by probability and severity of collision.

As described for ECOB [24] with the extension of Letizia F. et al. and quoted in Formula 4 of this thesis, it is possible to add to the collision risk also the fragmentation risk in order to obtain a code that takes into account all scenarios triggered by the collision, even those of secondary nature.

Therefore, in this work, the basis is left for then defining a fragmentation coefficient, which, again by means of calculations (possibly simplified and with a low calculation burden), can enrich the application field of the classification code, thus making it more effective in the hierarchical distinction of the bodies involved.

A starting point can certainly be the estimate reported in chapter 4.5.1 and devised by Rossi et al. in the aforementioned paper "Analysis of the consequences of fragmentations in low and geostationary orbits" [50].

5.4 Risk Formulation

At this point we can close the circle; in the first chapters we defined what the risk was and, after a dedicated conceptual reworking we can return to the initial formulation involving probability and severity. We also add, for completeness, the fragmentation risk 'F'. Therefore:

$$(41) \quad R = P \times S + F$$

This formulation will then be the one used in the following chapters for the actual definition of the classification code.

6 Index definition

Whereas the formulation of the risk has been established, this chapter describes the actual formulation of the proposed index.
Considering the current methodologies for the risk assessment, we realise that not only are some of them lacking in practicality but also that they never lead to a true classification of risk.
Therefore, it is essential to find a way of presenting the data that allows the reader to interpret the risk situation associated with a SAT quickly and without misunderstanding. In the case of several SATs involved in the same orbit, it is necessary to determine for each of them a hierarchical position in terms of risk. This is useful for two reasons:

- Technical aspects.
- Legal-insurance aspects.

Both for the evaluation of a mission, e.g., within a company that intends to assess the compatibility of its product with the market, and by a third party, such as a consulting firm or an insurance company, that must assess the legal compatibility and estimate an insurable value of the vehicle.
It can be deduced that an internal and external valuation is easily associated with common standards for SAT assessment. Indeed, another of the merits of the risk classification in question is the possibility of constructing a kind of normative basis. A classification that can be easily interpreted even by "outsiders" to the aerospace engineering world, and with an all in all consistent technical value, is the precursor of a normative code which, if shared by all, would use the classification code under consideration as a development tool and also as a verification tool.

Based on the state of the art, the needs of the market and the current methodologies described in the previous pages, this chapter will deal with the specific formulation and the spectrum of solutions implemented for the formulation of a dedicated index.
It is premised from the outset that the following classification is in any case only a basic work, since the time and work done for the elaboration of a master's thesis would not have been compatible with an accurate study of the variables. However, we leave the skeleton for a future implementation that keeps the base described below and undertakes to expand each of the contents individually.

It should be remembered that the objective is to position a SAT or any orbiting object in a well-defined hierarchical scale. This is done, as already mentioned, not only with the aim of improving business productivity in design, but also, perhaps more importantly, to provide a reading tool for specialists and non-specialists in the aerospace world.
The image below describes and anticipates the structure of the chapter, faithfully reproducing the steps that even the MATLAB® code itself (Figure 28).
Starting with the orbital parameters and mission characteristics, the three main areas of interest will be outlined: probability, severity, reliability, and then translated into figures identifying the risk index developed, which includes:

- Collective scenario.
- Individual scenario.
- Mitigation strategies.

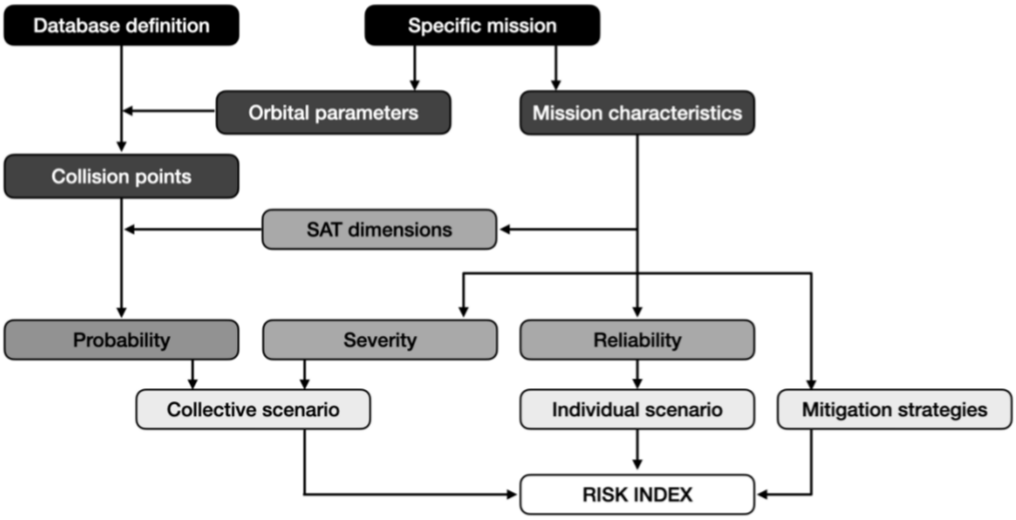


Figure 28: logical scheme of the algorithm.

6.1 Proposed Classification Algorithm

Starting with what has been described in the previous introductory paragraph, the formulation of the index foresees the distinction into three macro areas (Collective, Individual, Mitigative) and for each of these the definition of a risk classification. Therefore, the proposed classification will lead to the formulation of three distinct codes that, combined, define the unique risk index.
We then proceed to identify the three scenarios one after the other, starting with the collective one, moving on to the individual one and ending with the mitigating one.

6.1.1 Collective Scenario

This first section of the risk index is perhaps the most important one, as it clearly defines the aspects introduced in the previous chapters, manifests the considerations and design choices made earlier, and meets the market requirement described by the SOA.
It assumes that the collective view should best express the probabilities and consequences attributable to a given SAT among those involved in a precise orbital scenario. In this "ecosystem", which involves debris, active and inactive SATs, and any type of orbiting object, each of the "protagonists" must be studied to see if it could connect with the object under consideration.
In essence, all possible points of conjunction are determined, following the probabilistic model described in Chapter 5. Similarly, the severity is extrapolated and, as mentioned in Chapter 5.4, the risk associated with that SAT is estimated using Formula 41.
This formulation is as simple as it is effective and clearly expresses the result sought. However, it is necessary to introduce a simpler descriptive mode in order to make it easier to read for experts in the field and others.
The numbers obtained have orders of magnitude characterised by negative exponents and therefore can in some way identify the class to which the SAT belongs.
Consequently, it has been chosen to indicate, as shown in the example Formula 42, this part of the code called 'R_C' as a contraction of the result obtained. In practice, the rounded number is taken and the class to which it belongs, i.e., the order of magnitude to which it pertains, is added below. The class hierarchy is defined in the table below (Table 8) and was

produced by observing the results of the simulations, taking the letter F as the full scale (10^{-1}) and the letter A as the optimal result (10^{-6}). However, there is nothing to prevent results higher than 10^-6 as time progresses, so in these cases '+' is added according to the order of magnitude attributed.

Table 8: Classes definition for R_C part of the classification index.

Exponent	Classes
10^{-1}	F
10^{-2}	E
10^{-3}	D
10^{-4}	C
10^{-5}	B
10^{-6}	A
10^{-7}	A^{+}
10^{-8}	A^{++}
$< 10^{-9}$	A^{A}

Below is an example of 'R_C' code for a result obtained.

$$(42) \quad R_C = 2 \cdot 10^{-6} = A2$$

In this way the reading becomes sufficiently intuitive: low numbers and letters will inevitably correspond to low risks.

6.1.2 Individual Scenario

As far as the individual scenario is concerned, this is a second reading method referred to for the S/C or SAT under examination. In fact, this basically concerns reliability aspects and is therefore inherent in an analysis that is mainly made by the manufacturer, insurance expert or technical expert who must in some way give the mission under consideration a degree of risk.
To do this, fortunately, a manufacturer can exploit the work that European and international standards and risk assessors use, which in practice is the same described in the ECSS [5] and already quoted extensively in Paragraph 2.1.2.
Obviously, to go and set up a risk table for the whole mission, besides being burdensome, is certainly not so useful for a purpose of rapid interpretation. It was therefore decided to highlight the most significant elements of the individual scenario. These are divided into:

- Worst risk associated with the mission under consideration.
- Time required for decommissioning.

As regards the first of the two aspects, this operation is basically quite simple: one relies on Table 3 (as just mentioned) and determines the severity of the worst risk involved. The various combinations can be those expressed in Table 4 and so, in this case, there are as many classification solutions as possible.
Below is an explanatory table (Table 9), from this, the reader can begin to understand how the second part of the code will be outlined, which is given the name 'R_I'.

Table 9: Individual risk assessment result for the first R_I code part.

Worst risk result	Classes
Very Low	VL
Low	L
Medium	M
High	H
Very High	VH

Concerning the second aspect highlighted, the time for decommissioning, the matter is slightly more complex. Following guidelines such as the NTSS Standards [51], the maximum time for a SAT to be in orbit after the end of its activity is 25 years. It is clear, however, that during this time the reliability of the SAT and thus its tendency to survive in that environment must be assessed and that this attitude must have a bearing on the expected time for decommissioning. For this thesis work, a definition of the survival time (ΔT_{surv}) derived from the time required for decommissioning 'D_t' and a survival index 'σ_{surv}' was therefore formulated.
However, the definition and calculation of a dedicated survival index is burdensome and certainly cannot be approached with due care given the subject matter of the work in question. Therefore, the survivability coefficient 'σ_{surv}' under consideration was assumed during the simulations using realistic numbers, relying on the literature described in Chapter 4.5.2 and considering that it varied between 0 (guaranteed mortality) and 1 (guaranteed survival). The formula below describes how the ΔT_{surv} is calculated.

$$(43)\ \ \Delta T_{surv} = D_t \cdot (1 - \sigma_{surv})$$

Once this coefficient has been defined, it can be easily translated into risk classes which, if we consider the maximum time before re-entry to be 25 years and multiply it by an average survival coefficient, we obtain the bottom scale beyond which the class identified is the worst. From here the other classes are delineated which, exponentially in base 2, descend to a more than acceptable class, that is the first one (I).

Table 10: Survival classes for decommissioning time.

$\mathbf{\Delta T_{surv}}$	Classes
$\Delta T_{surv} < 2$	I
$2 \leq \Delta T_{surv} < 4$	II
$4 \leq \Delta T_{surv} < 8$	III
$8 \leq \Delta T_{surv} < 16$	IV
$16 \leq \Delta T_{surv}$	V

At this point, we have both reliability classifications that indicate individual risk 'R_I'.
Therefore, an example formulation could be the following shown in the formula below, where we consider a SAT, whose highest risk is in the "Low" category, with a decommissioning time of about 12 years and a survivability coefficient of 60%.

$$(44)\ \ R_I = L\ III$$

At the end of this section, we retrieved two risk estimates which intuitively express what has been calculated. It remains to compute the last of the contributions exposed by the code, defined by a mitigation coefficient called ‘M_S’.

6.1.3 Mitigation Solutions

Having analysed the risk aspects, it is correct to research the strategies assumed by a manufacturer that tries to reduce the tendency that the S/C designed may collide with other bodies in orbit. Indeed, it is also correct to take into account this type of manufacturer's commitment, which rightly puts on two different levels a SAT with a certain medium risk but with strategies to avoid collision and a SAT with a reduced risk of collision but which has no defensive methodologies and is uncontrolled.

For this reason, an attempt is made to summarise the mitigation solutions considering three main aspects:

- Active mitigation solutions.
- Passive mitigation solutions.
- Re-entry strategies envisaged by the manufacturer.

As in the previous cases, the definition must be intuitive and interpretable both by space "insiders" and “outsiders”; especially in this case, considering that the objective of this section of the code is to mitigate the risk, it is necessary that, for example, an insurer can easily understand the bonus-malus connected to the SAT under examination.

At this point a method is sought which with considerable simplicity puts together the three factors written above without going into excessive calculations; bear in mind that in this circumstance technicality is not necessary, as already mentioned above (Chapter 3.3) the insurance market is not interested in a purely quantitative analysis, but has a tendency to associate qualitative analyses and value classes.

Therefore, in this thesis work we have opted to proceed as follows: the presence of mitigating solutions is, for both passive and active cases, identified by a 0 (absence) and a 1 (presence).

The re-entry mode is, instead, the mitigation factor that most reduces the probability of collision since it not only allows the space environment to be freed from the now inactive S/C, but also can be done through various strategies that in turn identify the goodness or otherwise of the operation [56].

It was therefore decided to classify the re-entry strategies into four categories; these are set out in Table 11.

As anticipated the code for mitigation solutions is called ‘M_S’ and represents the three aspects listed above. Contrary to the case of ‘R_C’and ‘R_I’ this coefficient will have an "inverted" classification; this is because the construction goodness regarding the risk of a SAT will not be identified with the lowest possible classes and numbers, but, being a coefficient that opposes in a certain way to the previous ones, the higher it will be the better the mitigation effect will be.

Table 11: Classification of re-entry strategies.

Re-entry strategy	Exponent value
Controlled	4
Fast deorbiting (less than 1 year)	3
Slow deorbiting (more than 1 year)	2
Uncontrolled	1

Given the weight of the three areas, a three-digit code is then delineated which will respectively have:

- The number representing the return strategy obtained through Table 11.
- 1 or 0 depending on the presence or absence of active mitigation strategies.
- 1 or 0 depending on the presence or absence of passive mitigation strategies.

An example of such coding is described in the formula below for a SAT without collision avoidance (active solution), equipped with shields (passive solution) and for which a re-entry within one year of its activity has been foreseen.

$$(45) \quad M_S = 3, 0, 1 = 301$$

6.1.4 Final Definition

Taking up the examples just seen and wanting to describe the risk index in a comprehensive manner, we can observe the diagram below (Figure 29) which summarises the unique classification code for the examples under consideration.

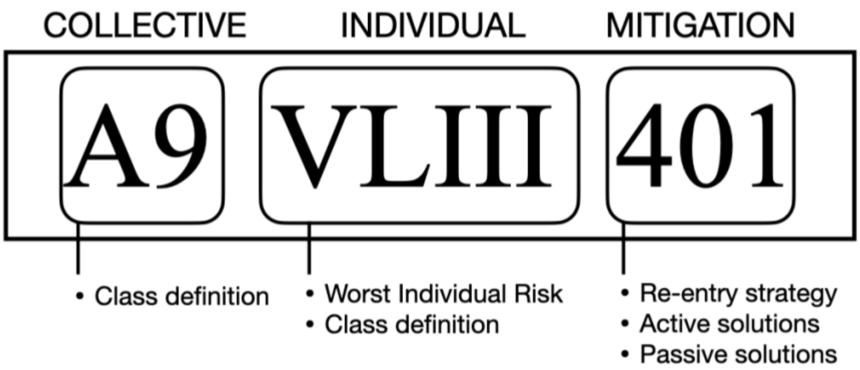


Figure 29: Summary of the designed index example.

The code, from left to right, thus includes, in an easy-to-understand format, the most important information for risk determination.
By assigning a value, also economic, to the various classes for the three scenarios (collective, individual, and mitigating) it is possible for a technician to understand the hierarchical risk placement of the SAT in question and for an insurer to estimate the total pure premium related to the mission coverage. A name devised for this classification code is NACRAC, which expresses its purpose: New Algorithm for Collision Risk Assessment and Classification.

6.2 MATLAB® Development of the Algorithm

The development of the algorithm, called NACRAC, relied on the use of MATLAB® calculation software. As a tool, it proved to be excellent for both orbital propagation and for carrying out simulations in a short space of time.
The code is structured with a main script which calls the various functions and finally returns the value of the risk code. These functions follow the steps of the algorithm, summarised in Figure 28, and are described in detail in this section of the thesis.

6.2.1 databasecreator.m

The first function is the one that constructs the realistic database and thus defines the environment in which the mission to be classified will be immersed. Considering that, as expressed in Chapter 4.3.1, completely obtaining data on all orbital bodies around the earth is possible but very expensive, it was decided to define a database of SAT, debris and other objects with realistic orbital distributions, mission parameters also with realistic distribution, but random. Consequently, this function was programmed to generate such a database, but, in order to be able to compare results from different missions in the same database, the possibility of making the random assignment of space objects repeatable was implemented. Below, in Figure 30 and in Figure 31 respectively the set of LEO and GEO orbits propagated by the database generator.
It is recalled, as specified in Chapter 4.3.1, that the starting data and the chosen orbital distributions are realistic and in agreement with DISCOS data [33].

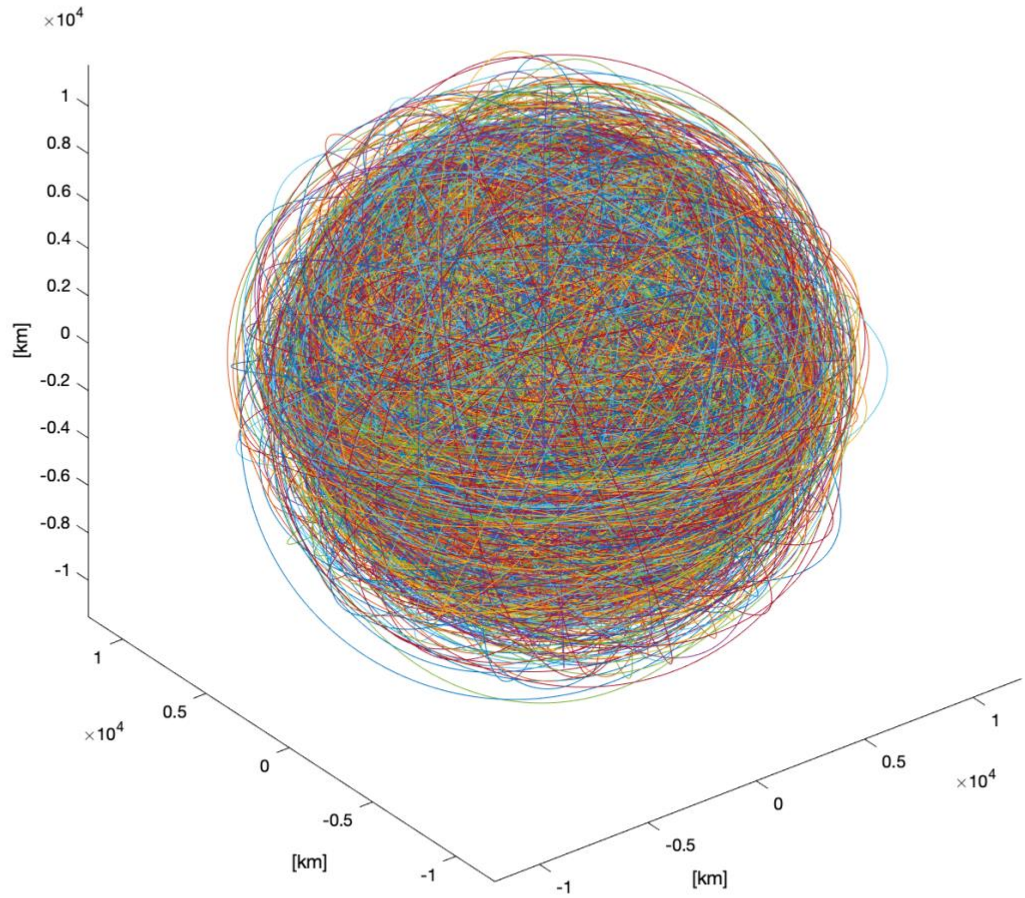


Figure 30: LEOs propagated in MATLAB® by the function databasecreator.m.

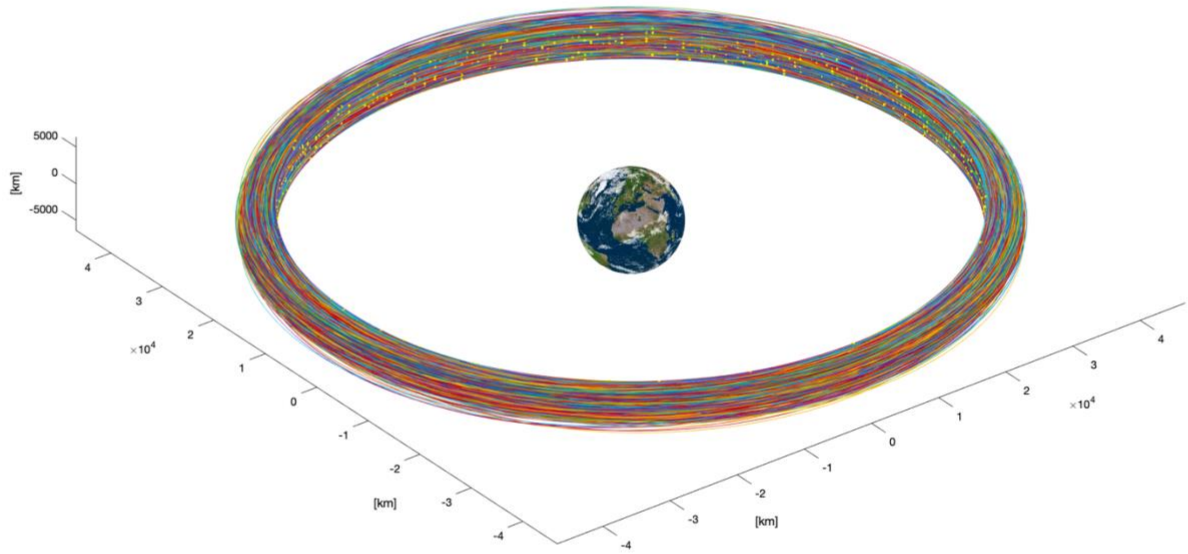


Figure 31: GEOs propagated in MATLAB® by the function databasecreator.m.

6.2.2 probability.m and severity.m

The functions calculating the probability and severity are among the most important to be described, as they faithfully follow what has been described in Chapter 5 and carry out the actual simulations of orbital collisions, searching for conjunction points and defining the first part of the NACRAC index developed in this thesis.

Below (Figure 32) is an example of a simulation highlighting the orbits detected as conjunction orbits and on which the risk estimate is made.

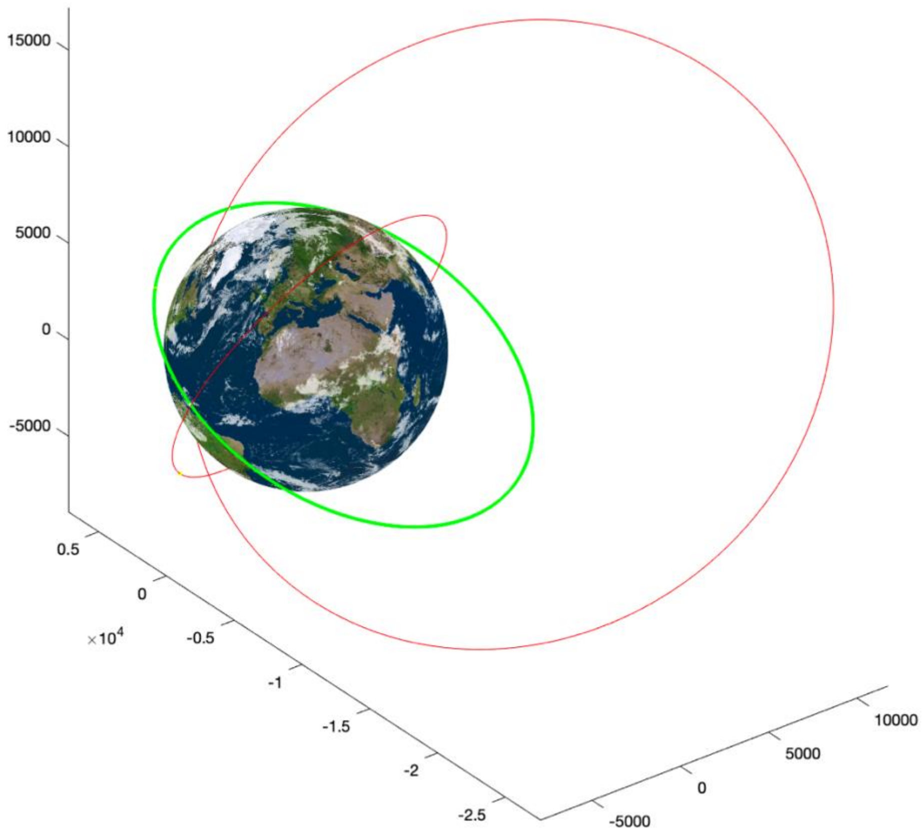


Figure 32: Conjunction orbits definition example from MATLAB® simulation.

As mentioned in Chapter 5.2, a clarification must be made in the calculation of the probability, since the simulation makes a calculation of the time in which the SATs in conjunction are simultaneously alive and then multiplies, by a time coefficient, the probability formula seen before (Formula 37).

6.2.3 Other Functions

The other functions called by the script are basically other random, but still realistic, parameter generators that describe characteristics of the SAT under examination and of the generated environment (e.g., survivability and fragmentation indices). Finally, the calculations made are converted into a string that provides the user interface with a comprehensible result representing the SAT under examination.

Further descriptive images of the code and simulations in the attached Appendix.
The image below (Figure 33) shows a flowchart of the software developed on MATLAB®.

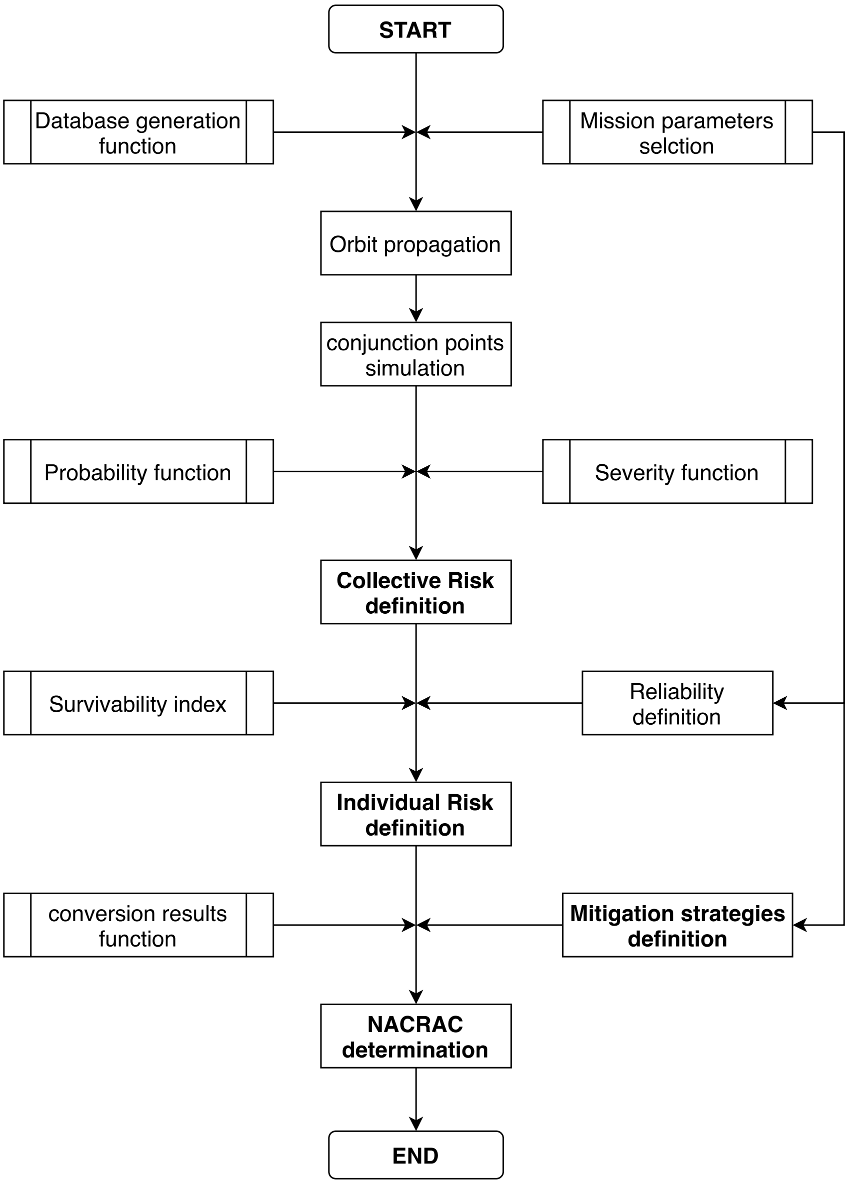


Figure 33: NACRAC software process flow.

6.3 Examples of Application

Following the development of the algorithm on MATLAB®, the algorithm was applied to different scenarios in order to observe the goodness of the results and to understand whether they are consistent with the objectives.
To do this, three SATs were taken whose hierarchical classification and definition of hazard is well known and therefore allows comparison with other calculation methods available in the literature.

6.3.1 ENVISAT

First, an inactive satellite was selected that is now defined by ESA as real space debris: ENVISAT [57] [58].
This object presents the following orbital data and mission characteristics, which are easily available and therefore useful for an immediate verification of the result produced by the algorithm. ENVISAT's orbital data are shown in the Table 12 below.

Table 12: ENVISAT data.

Launch Mass	8211 kg
Eccentricity	0.00042
Dimensions	26 × 10 × 5 m
Cost	2.9 billion
Perigee Altitude	772 km
Inclination	98.40°

The NACRAC result for ENVISAT is as follows:

$$(46) \quad NACRAC = F8 \sim V\ 101$$

The result obtained is well matched with the evaluations present in the literature, we observe that since the first term the class (F8) is very high, which confirms its already known dangerousness. Moreover, no risk sheet has been made public by the manufacturer therefore the reliability of the vehicle can only be determined by the survival class of the code which however, as for the collective part, leads the NACRAC code to fill the worst possible class (V). Finally, the result of the mitigation coefficient is very low, a symptom of the uncontrollability of the SAT.

6.3.2 Sentinel-6

A SAT of interest may be Sentinel-6 [59]; we are talking about a SAT that is also very large and in medium-low orbit, the cost and weight are certainly a limitation but from an individual point of view it is clearly better than ENVISAT [58], the risks involved are low (L) and the survivability is in class III. In addition, the mitigation strategies undertaken are optimal and show that the manufacturer is committed to ensuring that this satellite is controlled.
Below is the table (Table 13) with the characteristics for Sentinel-6 and the NACRAC classification code.

Table 13: Sentinel-6 Data.

Launch Mass	1192 kg
Eccentricity	0.000094
Dimensions	5.13 x 4.17 x 2.34 m
Cost	97 million
Perigee Altitude	1336 km
Inclination	66°
RAAN	36.41°
Argument of Perigee	90°

$$(47) \quad NACRAC = D7\ LIII\ 211$$

6.3.3 Starlink

To conclude this brief overview of case studies and application examples of the classification developed, let us turn to an SAT which should be of low risk from the point of view of collision risk and should therefore rank among the top spots in the classification.

A perfect example of this are the SATs of the Starlink constellation [60], which inhabit Very Low Earth Orbits (VLEO) and are therefore distant from high satellite densities and have a low mass and therefore exposed surface area [61]. The chosen altitude value is in the middle of the Starlink SATs range (between 340 and 550km).

The re-entry strategy of a Starlink S/C requires the SAT to burn through the atmosphere and therefore reduces unwanted events to zero and increases its re-entry coefficient to 3.

Some characteristics of Starlink's S/Cs are shown in Table 14.

Table 14: Starlink data.

Launch Mass	260 kg
Eccentricity	0.000001
Dimensions	1.1 × 0.7 × 0.7 m
Cost	1.1 million
Perigee Altitude	450 km
Inclination	53°

The NACRAC classification for this S/C is outlined accordingly.

$$(48) \quad NACRAC = B9\ LII\ 310$$

As expected, it is an optimal class and therefore confirms the validity of the code in assessing potential satellite collisions.

In Appendix, three descriptive photos of the satellites examined.

7 Conclusions and Future Uses

In this last chapter, a focus on the applicability of the algorithm devised is described.
Certainly, the most interesting aspect is to analyse to what extent the objectives presented in the initial introductory part have been achieved. Based on what has been defined as market demand and the current situation, the next few lines will summarise the situation and show to what extent the work of this thesis can be the basis for more in-depth studies.

7.1 Conclusions

Addressing, as a first point, the reported risk calculation methods, the emphasis is on the fact that these assessments do not consider a very detailed application of a single event but extend to many events to determine a general degree of risk associated with a single orbiting object.
Basically, if we wanted to define the strengths of this evaluation strategy, we would certainly have to consider the small amount of data to be processed and therefore the fast calculation speed. This, as a direct consequence, leads to a rapid implementability of the algorithm and therefore satisfies a large part of the requirements and objectives imposed at the beginning of the research.
The remaining market requirements are met by the structure of the code developed. In fact, in addition to the remarkable synthesis that it presents, the algorithm allows the hierarchical positioning of the different protagonists of the space scenario and the easy determination of which is the most dangerous in terms of collision risk.
Despite the speed and simplification of NACRAC, it still makes it possible to clarify the actual danger of a vehicle or debris in an effective and not inaccurate manner. Clearly this merit increases in value if we consider that an insurer or lawyer is interested in understanding, in the case of unfortunate events, whether the SAT is more or less likely to have generated them. In fact, the selected inputs are the key parameters from the point of view of collision risk sensitivity and therefore the outputs obtained from them are undoubtedly explanatory of the situation under examination.
What has just been described is obviously done to the detriment of a greater accuracy in the determination of the effective probability; it is a fact, that the distribution presented by other works cited in this thesis is more accurate with the regard to probability. As mentioned at the beginning of this section, however, the aim was not to determine precisely the single probability related to a particular conjunction, but to be able to quickly compute the total probability for all possible conjunctions. Indeed, a development such as those just mentioned, although useful it may be from a technical and scientific point of view, appears almost useless in terms of accurate classification.

Another point of interest is the evaluation of the three areas into which the algorithm is divided:

- Individual Scenario.
- Collective Scenario.
- Mitigation solutions.

Professional figures other than aerospace engineers or statisticians, but who nevertheless need an interpretation of space collision risk, have an interest in knowing:

- How a vehicle behaves in space.
- How reliable the vehicle is.
- Finally, what strategies are undertaken by the manufacturer to prevent unwanted events from occurring.

It is immediately clear that these three requirements are largely satisfied by the established division.
In fact, the first part of the code, the "collective" one, determines the risk of collision starting from the insertion of the object under examination in the chosen space ecosystem and therefore in a global context.
The second coefficient reveals information, which, following globally shared guidelines for the construction of S/Cs, determines the degree of reliability of the same and thus defines how far this may deviate from the assessment made previously.
The third and last part of the index, instead, concerns mitigation and therefore the solutions devised to avoid the conjunction event. Basically, this last coefficient defines the "bonus-malus" of the vehicle, it is therefore a part of high interest in assessing, by insurance agencies, any discounts, or surcharges and, in the event of a dispute, it can be easily associated with the contributory negligence described in the Liability Convention.
These three aspects together present a remarkably compact solution for collision risk classification.

The development of the algorithm using MATLAB® was remarkably simple; for high orbital discretisation's the calculation power must be high on average, but even for the most onerous simulations the result is obtainable in less than a minute. This fact also leads to the conclusion that a simple factual code can be an optimal starting point for easily obtainable classification.

Before ending this chapter, among the various observations concerning the thesis work, it is correct to include a comparison with other indices. Looking at the evidence in Chapter 6.3 it is possible to understand how the orders of magnitude of the risk for other classification algorithms are different from the designed one. In fact, from a numerical point of view, some discrepancy is observable, but the hazard hierarchy is preserved. If, with a considerably reduced calculation power, with a simple identification of the factors influencing the risk and with an intuitive reading of the results, the proposed NACRAC classification is still consistent, is preferable to other more cumbersome and less smooth methods.

In summary, it can be said that the risk assessment strategy is useful for a quick classification, and that it has several technical, insurance and legal fields of application. Therefore, in the next paragraph, possible future developments, and uses of what has been defined in this thesis are presented.

7.2 Future Uses

When studying algorithms such as the one described in this thesis or software derived from it, everyone can quickly understand the interest related to possible future uses. Certainly, tools of this type can be useful in the design phase to limit a priori possible errors of evaluation that do not consider parameters useful to the space market. To explain this concept more clearly, it is enough to think of a company that turns to an insurer for a guarantee on its SAT. In the design phase, the accent will be placed on parameters that concern the reliability of the SAT itself for PL complete functioning, but the subsystems that concern the community and the permanence of the S/C in orbit will not be considered as primary. These parameters of interest are those on which the insurance premium is designated and therefore the more they deviate from those initially considered, the more the cost for the launch agency will increase. On the contrary, if sensitive parameters for third parties were taken into account in the design phase, the acceptance of the S/C and the management and insurance costs associated with placing it in orbit would be much more cost-effective and secure.
Another fundamental step to be considered in the design are the potential litigations that, due to unpleasant events, may arise in space. If the SAT under examination is considered safe by the scientific community and respects various standards for what concerns the individual and collective risk assessment, certainly, in case of evaluation for "space accident", it is easier to consider it not guilty if it has collided with a vehicle that, through the above-mentioned classification, is considered not completely safe.
One aspect that should certainly not be overlooked is that of market need; as mentioned several times in Chapter 3, assessment agencies such as insurance companies or regulatory institutes such as IISL, need more and more means for rapid, first-approach assessment of space collision risk. Therefore, whether for the implementation of existing regulations, for increased space safety, or for foresight in the light of dire predictions regarding SAT population, tools such as the one proposed can be a bridge between technical quantifications and insurance or legislative assessments in the space domain.
Finally, from an engineering point of view, the main implementation for this type of code can be done in two ways:

- Through more data and correlations between them.
- By means of dedicated software.

Essentially, a future use for this algorithm could be the development of a software that looks at a variety of data and then analyses the risk of space collisions and correlated with economic classes, thus becoming a useful tool in the aerospace sector.

References and Abbreviations

References

[1] E. Secretariat, "ECSS-M-ST-10C Rev.1 – Project planning and implementation," ECSS, 2009. [Online]. Available: https://ecss.nl/standard/ecss-m-st-10c-rev-1-project-planning-and-implementation/.

[2] D. J. Kessler and B. G. Cour-Palais, "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt," *Journal of Geophysical Research,* vol. 83, 1978.

[3] I. Fino, "A Manifesto for cleaner Orbits," Space Legal Issues , 6 June 2021. [Online]. Available: https://www.spacelegalissues.com/a-manifesto-for-cleaner-orbits/.

[4] C. U. Press, "Cambridge Dictionary," 2022. [Online]. Available: https://dictionary.cambridge.org.

[5] E. Secretariat, "ECSS-M-ST-80C – Risk management," 2008. [Online]. Available: https://ecss.nl/standard/ecss-m-st-80c-risk-management/.

[6] NTSS, "8000 - Safety, Quality, Realiability, Maintainability," NASA, 2015. [Online]. Available: https://standards.nasa.gov/safety-quality-reliability-maintainability.

[7] NTSS-GSFC, "Guideline for Performing Risk Assessments," NASA - Goddard Space Flight Center, 2017. [Online]. Available: https://standards.nasa.gov/standard/gsfc/gsfc-hdbk-8005.

[8] Wikepedia, "Satellite insurance," 20 November 2019. [Online]. Available: https://en.wikipedia.org/wiki/Satellite_insurance.

[9] O. Schöffski and A. G. Wegener, "Risk Management and Insurance Solutions for Space and Satellite Projects," *Palgrave Macmillan Journals,* pp. 203-215, 199.

[10] B. Origin, "BLUE ORIGIN," 2021. [Online]. Available: https://www.blueorigin.com.

[11] F. Street, "100 years ago: The first scheduled international passenger flight departed," CNN, August 2019. [Online]. Available: https://edition.cnn.com/travel/article/first-scheduled-international-passenger-flight/index.html.

[12] ICAO, *Effects of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis,* Montréal, 2021.

[13] V. Stimac, "Space Tourism Took Off In 2021, Here's How It Happened," Forbes, 31 December 2021. [Online]. Available: https://www.forbes.com/sites/valeriestimac/2021/12/31/space-tourism-took-of-in-2021-heres-how-it-happened/?sh=12f3d4c74011.

[14] ESA, "Space Environment Statistics," ESA, 5 January 2022. [Online]. Available: https://sdup.esoc.esa.int/discosweb/statistics/.

[15] F. Letizia, "ESA'S ANNUAL SPACE ENVIRONMENT REPORT," ESA ESOC, Space Debris Office, Darmstadt, 2021.

[16] "Office for Outer Space Affairs," United Nations, [Online]. Available: https://www.unoosa.org/oosa/index.html.

[17] "Convention on International Liability for Damage Caused by Space Objects," United Nations, 29 November 1971. [Online]. Available:

https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introliability-convention.html.

[18] “International Insititute of Space Law,” IISL, [Online]. Available: https://iislweb.space.

[19] P. Manikowski and M. A. Weiss, “ Cyclicality or volatility? The satellite insurance market,” *Space Policy ,* vol. 28, pp. 192-198, 2012.

[20] P. Manikowski, “Satellite insurance market as a part of the insurance market,” *Argumenta OEconomica,* vol. 2, pp. 139-151, 2004.

[21] R. M. Parrella, G. Spirito, C. Cirina and M. C. Falvella, “The New Space Economy and New Business Models,” *New Space,* 2021.

[22] G. E. Apostolakis, “How Useful Is Quantitative Risk Assessment?,” *Risk Analysis,* vol. 24, no. 3, pp. 515-520, 2004.

[23] F. Letizia, C. Colombo, H. G. Lewis and H. Krag, “Assessment of breakup severity of operational satellites,” *Advances in Space Research,* vol. 58, no. 7, pp. 1255-1274, 2016.

[24] F. Letizia, C. Colombo, H. G. Lewis and H. Krag, “Extending the ECOB space debris index with fragmentation risk estimation,” in *7th European Conference on Space Debris*, 2017.

[25] F. Letizia, C. Colombo, H. G. Lewis and H. Krag, “Development of a debris index,” in *Stardust Final Conference on Asteroids and Space Debris*, 2016.

[26] C. Kebschull, J. Radtke and H. Krag, “Deriving a priority list based on the environmental criticality,” in *65th International Astronautical Congress*, Toronto, 2014.

[27] J. Radtke, S. K. Flegel, S. Roth and H. Krag, “Deriving the Spacecraft Criticality from Monte-Carlo simulations of the space debris environment,” in *65th International Astronautical Congress*, Toronto, 2014.

[28] D. Garanin, “Statistical Thermodynamics,” 1 March 2021. [Online]. Available: https://www.lehman.edu/faculty/dgaranin/Statistical_Thermodynamics/Molecular_theory.pdf.

[29] A. Rossi, G. B. Valsecchi and E. M. Alessi, “The Criticality of Spacecraft Index,” *Advances in Space Research ,* vol. 56, pp. 449-460, 2015.

[30] “United States Space Surveillance Network,” Wikipedia, 10 December 2021. [Online]. Available: https://en.wikipedia.org/wiki/United_States_Space_Surveillance_Network.

[31] M. Garcia, “Space Debris and Human Spacecraft,” NASA, 27 May 2021. [Online]. Available: https://www.nasa.gov/mission_pages/station/news/orbital_debris.html.

[32] “Space Track Login,” Space Track, [Online]. Available: https://www.space-track.org/.

[33] ESOC, “DISCOS web,” ESA, [Online]. Available: https://discosweb.esoc.esa.int.

[34] “ESA's DISCOS database: Composition of objects in space,” ESA, 20 February 2009. [Online]. Available: https://www.esa.int/ESA_Multimedia/Images/2009/02/ESA_s_DISCOS_database_Composition_of_objects_in_space_click_for_hi-res.

[35] “An EU Approach for Space Traffic Management,” European Union, [Online]. Available: https://ec.europa.eu/defence-industry-space/eu-space-policy/eu-space-programme/eu-approach-space-traffic-management_en.

[36] D. Leleux, R. Spencer, P. Zimmerman, C. Propst, W. Heilman, J. Frisbee and M. Wortham, "Probability-Based Space Shuttle Collision Avoidance," in *SPACE OPS 2002 CONFERENCE*, Houston, TX, 2002.

[37] X. Xiao-Li and X. Yong-Qing, "A method for calculating probability of collision between space objects," *Research in Astronomy and Astrophysics,* vol. 14, p. 601, 2014.

[38] G. Sarego, A. Valmorbida, L. Olivieri, A. Brunello, G. Colombatti, M. Salmaso and E. C. Lorenzini, "Collision Avoidance Maneuvers for space tether systems," in *3rd IAA Conference on Space Situational Awareness (ICSSA)*, Madrid, 2021.

[39] "Minimum orbit intersection distance," Wikipedia, 17 September 2021. [Online]. Available: https://en.wikipedia.org/wiki/Minimum_orbit_intersection_distance.

[40] G. F. Gronchi, "An algebric method to compute the critical points of the distance function between two Keplerian bodies," *Celestial Mechanics and Dynamical Astronomy,* vol. 93, pp. 295-329, 2005.

[41] G. Sitarski, "Approaches of the Parabolic Comets to the Outer Planets," *Acta Astronomica,* vol. 18, no. 2, pp. 171-195, 1968.

[42] R. Greenberg, "Orbital interactions: a new geometrical formalism," *The Astronomical Journal,* vol. 87, no. 1, pp. 184-195, 1982.

[43] C. Bonanno, "An analytical approximation for the MOID and its consequences," *Astronomy and Astrophysics,* vol. 360, no. 1, pp. 411-416, 2000.

[44] Y. JeongAhn and R. Malhotra, "Simplified Derivation of the Collision Probability of Two Objects in Independent Keplerian Orbits," *The Astronomical Journal,* vol. 153, no. 5, pp. 235-246, 2017.

[45] R. W. Humble, G. N. Henry and W. J. Larson, Space Propulsion Analysis and Design, New York: McGraw-Hill, 2007.

[46] "Konstantin E. Tsiolkovsky," NASA, 22 September 2010. [Online]. Available: https://www.nasa.gov/audience/foreducators/rocketry/home/konstantin-tsiolkovsky.html.

[47] B. Venditti, "The Cost of Space Flight Before and After SpaceX," Visual Capitalist, 27 Jan 2022. [Online]. Available: https://www.visualcapitalist.com/the-cost-of-space-flight/.

[48] L. Stein, "Launch Cost and Cadence Are Key Enablers for the New Space Economy," Medium, 29 Oct 2021. [Online]. Available: https://medium.com/prime-movers-lab/launch-cost-and-cadence-are-key-enablers-for-the-new-space-economy-510bf49c5dbb.

[49] T. G. Roberts, "Space Launch to Low Earth Orbit: How Much Does It Cost?," CSIS, 2 Sep 2020. [Online]. Available: https://aerospace.csis.org/data/space-launch-to-low-earth-orbit-how-much-does-it-cost/.

[50] A. Rossi, H. Lewis, A. White, L. Anselmo, C. Pardini, H. Krag and B. Bastida Virgili, "Analysis of the consequences of fragmentations in low and geostationary orbits," *Advances in Space Research,* vol. 57, pp. 1652-1663, 2016.

[51] NTSS, "Process for Limiting Orbital Debris," NASA, [Online]. Available: https://standards.nasa.gov/standard/nasa/nasa-std-871914.

[52] M. Trisolini, H. G. Lewis and C. Colombo, "Spacecraft design optimisation for demise and survivability," *Aerospace Science and Technology,* vol. 77, pp. 638-657, 2018.

[53] L. Olivieri and A. Francesconi, “Large constellations vulnerability assessment,” in *68th International Astronautical Congress (IAC)*, Adelaide, 2017.

[54] H. D. Curtis, Orbital Mechanics for Engineering Students, Elsevier, 2013.

[55] G. Carichino, “Probabilità Totale,” You Math, [Online]. Available: https://www.youmath.it/lezioni/probabilita/probabilita-discreta/5183-teorema-probabilita-totale.html.

[56] L. Anselmo and C. Pardini, “Computational methods for reentry trajectories and risk assessment,” *Advances in Space Research,* vol. 35, pp. 1343-1352, 2005.

[57] Wikipedia, “Envisat,” Wikipedia, 4 Feb 2022. [Online]. Available: https://en.wikipedia.org/wiki/Envisat.

[58] “EnviSat (Environmental Satellite),” ESA, 2022. [Online]. Available: https://earth.esa.int/web/eoportal/satellite-missions/e/envisat.

[59] “Sentinel-6 Michael Freilich,” ESA, 2022. [Online]. Available: https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/jason-cs.

[60] “Order Starlink,” SpaceX, 2022. [Online]. Available: https://www.starlink.com.

[61] “Starlink,” ESA, 2022. [Online]. Available: https://directory.eoportal.org/web/eoportal/satellite-missions/s/starlink.

[62] “Sentinel-6,” Wikipedia, 13 Nov 2021. [Online]. Available: https://it.wikipedia.org/wiki/Sentinel-6.

[63] D. Maloney, “HOW DOES STARLINK WORK ANYWAY?,” Hackday, 20 February 2020. [Online]. Available: https://hackaday.com/2020/02/20/how-does-starlink-work-anyway/.

Abbreviations

ADR	Active debris removal
AT&T	Air Transport & Travel Ltd
CNN	Cable News Network
CPA	Closest Approach Point
CSI	Criticality of Spacecraft Index
CSIS	Center for Strategic and International Studies
DISCOS	Database and Information System Characterizing Objects in Space
EC	Environmental Criticality
ECOB	Environmental Consequences of Orbital Breakups
ECSS	European Cooperation for Space Standardization
ENVISAT	Environmental Satellite
EOL	End Of Life
ESA	European Space Agency
GEO	Geocentric Earth Orbit
GSFC	Goddard Space Flight Center
HEO	High Eccentricity Orbit
IAF	International Astronautical Federation
ICAO	International Civil Aviation Organization
IISL	International Institute of Space Law
ISS	International Space Station
LEO	Low Earth Orbit
LUCA	Long-term Utility for Collision Analysis
MAIT	Manufacturing Assembly Integration Testing
MATLAB®	MATrix LABoratory
MOID	Minimum Orbit Intersection Distance
NACRAC	New Algorithm for Collision Risk Assessment and Classification.
NASA	National Aeronautics and Space Administration
NEO	Near Earth Orbit
NORAD	North American Aerospace Defense Command
NSE	New Space Economy
NTSS	NASA Technical Standards System
PL	Payload
PMD	Post mission disposal
QRA	Quantitative Risk Assessment
RAAN	Right Ascension of Ascending Node
S/C	Spacecraft
SAT	Satellite
SOA	State Of Art
SRM	Solid Rocket Motors
SSN	Space Surveillance Network
STM	Space Traffic Management
TCA	Closest Approach Time
USSPACECOM	United States Space Command
VLEO	Very Low Earth Orbit

Appendix

Figure 34: ENVISAT model picture from Wikipedia [57].

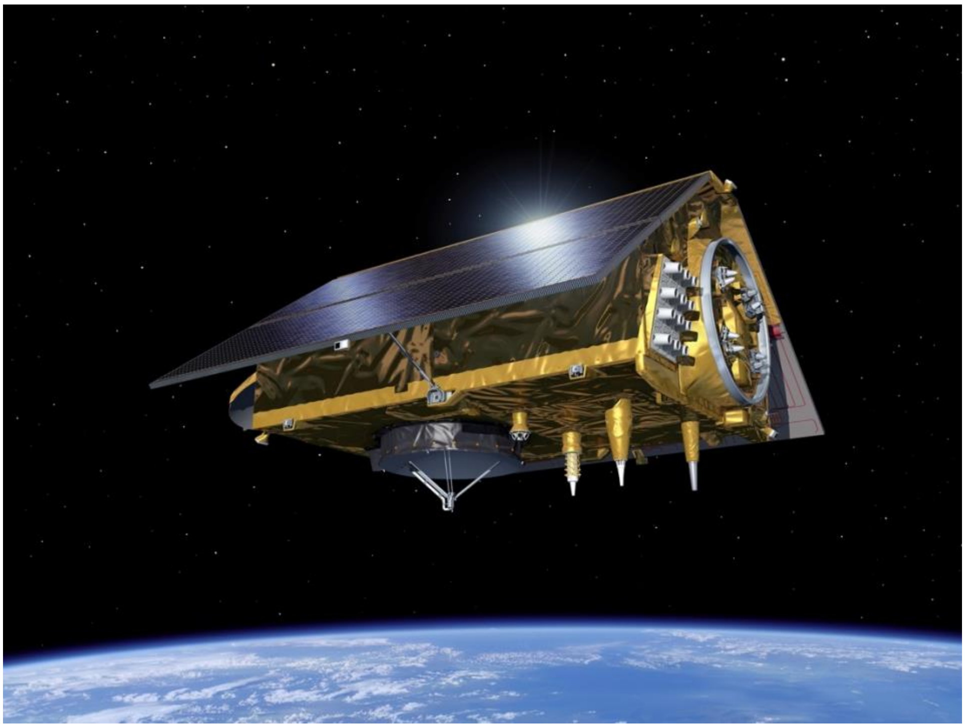


Figure 35: Sentinel-6 image from Wikipedia [62].

Figure 36: Starlink SAT image from web [63].

```
%%       ENGINEERING ALGORITHM FOR SPACE COLLISION RISK ASSESSMENT       %%
function [PopulationData]=databasecreator(repeatable,showLEO,showGEO,showOTHERS,showDEB)
% ----------------------------------------------------------------------- %
% Studente: Federico Toson                                  Mat: 1232107 %
% Relatore: Alessandro Francesconi                                        %
% ----------------------------------------------------------------------- %
% Data Base Creator                                                  2/10 %
% ----------------------------------------------------------------------- %
%{
  This function generate a random database of SAT with realistic
  distribution in space

INPUT: Decision in repeatability of random data and intention to show
orbits on the graph

Some DATA
  ecc < 0.2 90%
  ecc > 0.7 10%
  LEO 55% pop
  GEO 35% pop
  Others 10% pop

%}


if repeatable=="y"
rng(1);
end

N=7840;                        % In orbit SAT
ActSat=4900;                   % Active SAT
Deb=30640;                     % Detriti > 10 cm
Deb=N-4900+Deb;                % Detriti > 10 cm + non operative sat
LEOsat=ceil(ActSat*0.55);
GEOsat=ceil(ActSat*0.35);
OTHsat=ceil(ActSat*0.10);
DebLEO=ceil(Deb*0.55);
DebGEO=ceil(Deb*0.55);
DebOTH=ceil(Deb*0.55);

rearth=6378;
anu=0:pi/100:2*pi;
conv=pi/180;
```

Figure 37: Header of the Database development function, note the definition of repeatability to obtain consistent results in the various simulations.

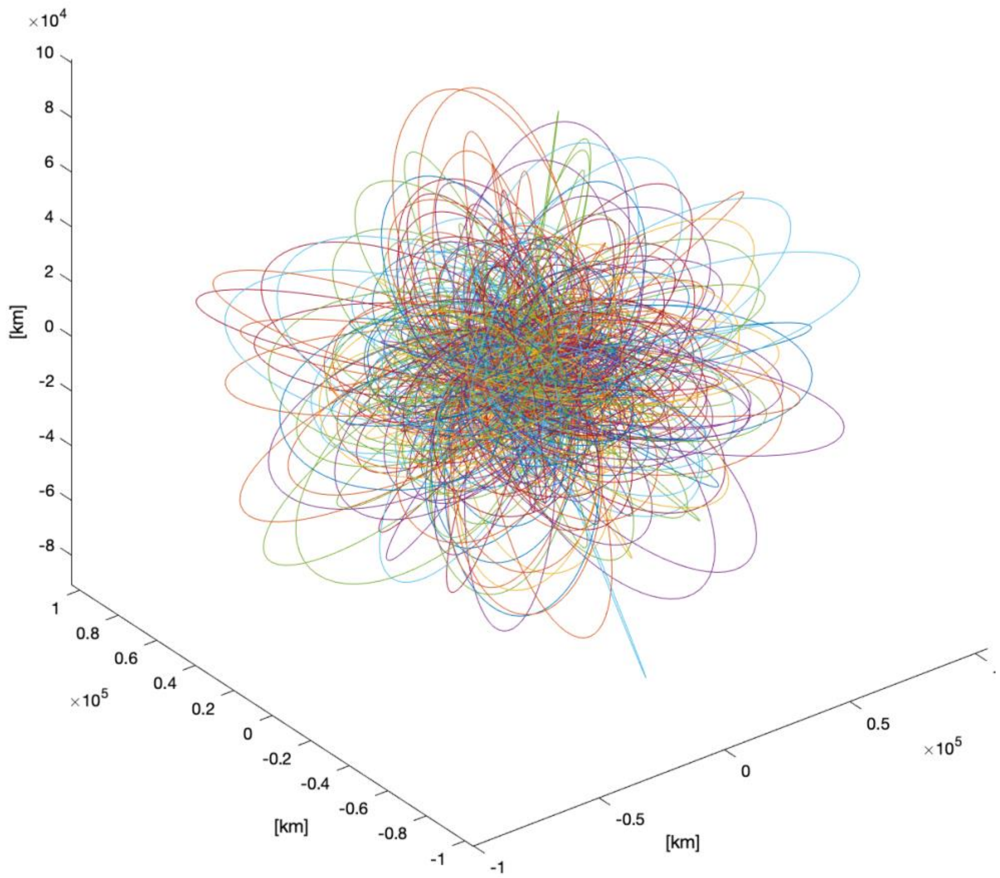


Figure 38: MEOs and other SATs propagation from databasecreator.m function.

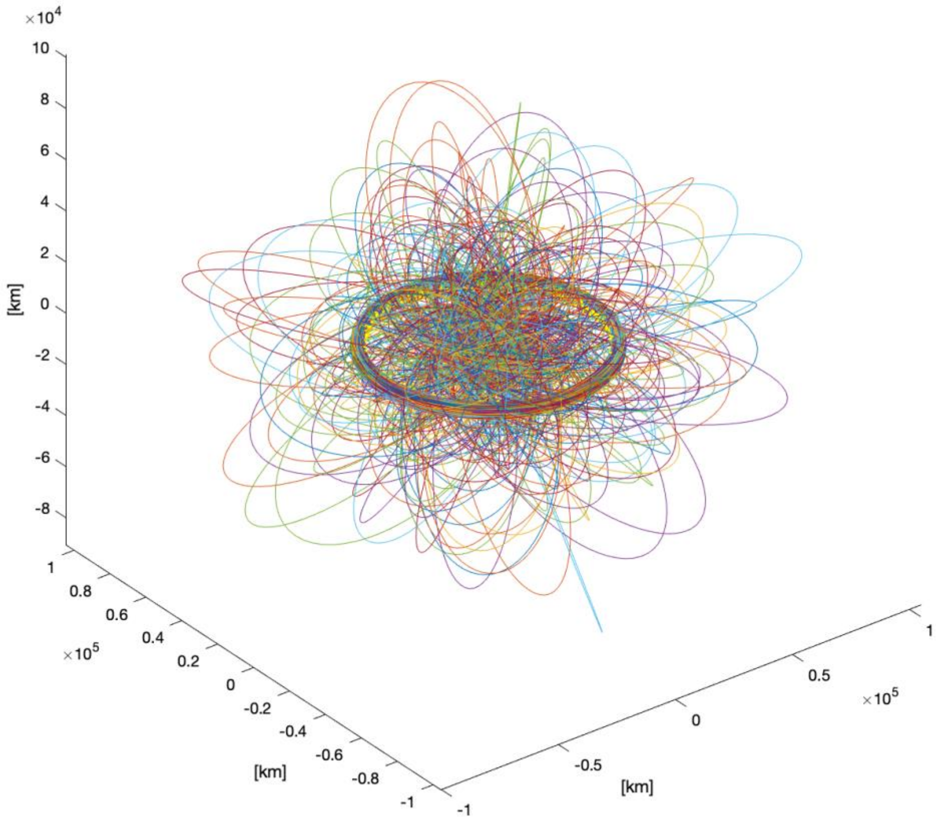


Figure 39: Total population representation example.

Acknowledgements

To begin, I would like to express my gratitude to the people who gave me life, my parents Elisabetta and Luigi. They have never repressed my curiosity and my way of thinking, sometimes outside the box, but always respected. Thank you also for not making it easy for me... people often think that support comes from the constant justification of their child's actions, but I know for sure that the discussions, the anger, and the moments of quarrelling led to my even greater commitment to show you that my path, although not planned, had proved to be the right one. Six years ago, you would never have thought I would get this far, you hoped, you did not stop me and that was the important thing. You were proud of me at every step and even more so because it was unexpected. Thank you, this degree is mainly dedicated to you who have never let me lack anything morally or financially.
Then I want to thank my sister Linda, who has been a constant presence and who, although I was difficult to deal with, never stopped trying to break through my impetuousness and impulsiveness and teach me a way of seeing life that was different from my own.
Thanks also to all my family: because in each of you I have always seen a part of me, and you have loved me despite my difficult character. From Grandma Carla, a support without whom I would not be the way you are now, to Grandma Tosca, who has always won my heart with her simplicity. To my two grandparents: Paolo, and Mario, I would really like to have you with me right now. Thank you for always being with me, at least in the genetic makeup that I display every day, but also, by all accounts, in their way of doing and being.
Thanks also to all the other family members who love me and have wanted and still want the best for me, Vanna, Dino, Roberta, Enrico, Matteo, Tiziana, Roberto, Anna, Francesco, Alberto and the whole Piovan family.

Thanks also to all the people I have met and who have stayed until now, making me grow and helping me to sculpt my person. Starting from Filippo, my Confirmation godfather, to Don Carlo, for having, with great charisma, conquered my spirit and my friendship trough parish groups, summer camps and lots of laughs. Thanks also to all the people who live the parish community and from whom I have only to learn. Thanks also to Iccio, Leopoldo, Mirko, who are a reference point in Scout life, but obviously also in life.
Thanks to Abu and Cli, who initiated me into the world of music, which I will never leave, and which gives me so much joy. Thanks also to those who, in this world, have found in me a friend, the Mods, the 7clips and the whole association Tempi e Ritmi and MeS.
To Sensei Gianfranco, who with his charisma and great experience brought me to the 2nd dan and still renews my spirit in karate, a martial art without which I would not be who I am now.
Thanks to those in the sporting sphere who have represented positive turning points, from Nakayama to CUS rugby to the RugbyTots staff.

Thanks to all the people who have accompanied me throughout my schooling, first my teachers Fiorenza and Lidia who, with their inclusive ways, have sown in me the acceptance of others so that my stubbornness would not get the better of me. To Professor Sarasin, teacher of music and life to whom I have already given, by his will, an autograph for when I become famous. To Headmaster Pavanini, Professor Colombo, Professor Maimone, the other professors of the 5I class and the entire teaching staff of the Pietro Scalcerle school in Padua, who with immense passion have accompanied me and other students in the pursuit of their

dreams and given me indelible memories in my life. Thanks also to the robotics teammates and the representative committee with whom we did great things.
Thanks also to the lecturers at the University of Padova who awakened my curiosity and who, contrary to what some say, proved to be humanly rich. From the mathematic exam passed only thanks to the patience of Professor Bertelle, the exchanges with Professor Simi, the passion for research and projects of Professor Bettanini, the great growth brought by Professor Francesconi, the comparisons with Professor Debei, Professor Navarro, Professor Brunello and Professor Picano, personalities who fascinated me. Finally, I would like to thank Professor Fava and the Cultural Anthropology course from the bottom of my heart, a surprise, and a moment of unparalleled growth.
Thanks also to the support figures for teaching and, in my case, for my path as a student, in particular the engineer, PhD, Doctor (and many other titles) Lorenzo Olivieri, a friend and a person who has held my hand in very difficult moments.
Thanks also to all my classmates, especially those with whom I shared study rooms, coffee and even a few spritzes, especially Anto, Emiliano, Baghe, Ciano, Paolì, Borto, Emil, Leo, Dumi and all my friends from the study room Gali and Tito, among whom we must mention "Il Dottore" (AG) and Sofia.
Thanks also to the guys I met during the innovative projects, the AVERLA team and the O-ZONE team, a group of friends that I claim credit for having built but who gave me much more than I would have thought. Thanks also to everyone I met during my travels for the project especially the friends from ESA, among whom I remember the best mentor ever (Koen DB) and the guys from REXUS/BEXUS.
To close the university side thank you to the Goliards and to the F.O.L.P.O., which besides having my certificate of ownership, explained to me that Goliardia is Culture and Intelligence, love for freedom and that the University of Padova embodies these values.

Thanks to Martina, my love, a person without whom I cannot imagine my life, a woman with I share interests and heart, thanks for being there and for the patience with which you support me every day. Thank you also for involving me in everything you live, in your family, in your interests and in your way of being.

And finally, thanks to the best part of me: my friends.
Thanks to "I Ragazzi", after 20 years of knowing each other, I know you are my second family, I carry you all in my heart and I hope it will always remain so despite the distance; Metez, Nicio, Luci, Dani, Lollo, Simo, Bede and Matte. Thank you for being so close to me but above all, with great sincerity, for helping me to grow with constructive comments that only true friends can make.

Thanks also to all those I have not named but who, together with all those I have mentioned, allow me every day to dream of space but understand that going to the Moon is useless if you are alone.