UNIVERSITAS BERGENSIS

Space Debris as a Super-Wicked Problem: A System Dynamics Approach to Achieving Long-Term Sustainability in Low Earth Orbit

Master Thesis submitted in fulfilment of the requirements for the degree of

Master of Philosophy

System Dynamics

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“Science is the only true guide in life”.

Mustafa Kemal Ataturk

Bergen will always remain one of the cities I am in love with. Thanks to all the people made the last two years far more than worthwhile. I have my deepest gratitude to my dear friends Will, Noedine, and Min. They have been there all along the way. I would not be able to deliver this piece without their company and support. I want to thank my supervisor Lars-Kristian for his continues encouragement. I also would very much like to acknowledge my previous supervisor Elrena Van der Spuy at the University of Cape Town for her academic and personal support since my departure from UCT. I cannot forget mentioning Clifford Shearing also at UCT for giving me the inspiration to pursue an academic career in environmental sustainability and security. I must also express my gratitude to Birgit Kopainsky for her dynamism in the programme and never ending will to support all of us along the way. Many thanks to my family, my father, my mother, and my sisters. It is the home longing that makes me strive for my goals and aim for a better future, despite all. My dear girlfriend Ceylin, you have been here with me from the beginning to the very end. Thank you for making every single step much more meaningful.

It is to every single innocent individual who has been unlawfully deprived of his freedom for the last couple of years, that I dedicate this thesis. I would like to dedicate this work to the thousands of academicians, journalists, human rights advocates and activists, and members of parliament who share the same fate with tens of thousands of others, in Turkey’s prisons.

Abstract

The following study shows that a simplified orbital simulation model can generate prominent results from different scenarios in exploring the dynamics of the environment in low earth orbit and its ramifications. Concentrating on the long-term impact, satellite launches presented as an external agent to the system. The model behaviour suggests that a certain carrying capacity in the orbital medium exists. Once the threshold is surpassed, an environmental tragedy takes place in the form of cascading collisions and increased frequency of fragmentation first suggested by Donald Kessler (1978). The tragedy and the wickedness of this problem carry crucial implications not only for the long-term orbital sustainability and security but also for the satellite industry and the world economy that relies on the services provided by satellites. In the short term, the results suggest that the situation in low earth orbit is not close to a catastrophic chain reaction, yet. However, if the business-as-usual scenario persists, satellites, an important aspect of our modern civilisation, might as well become the very reason hindering space exploration.

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1. Introduction

1.1. Background

Since the first man-made object launched to outer space in 1957, human space exploration has produced extraordinary technological and scientific developments and inspired generations. Space technology has not only enhanced nations in achieving various technical advancements, but it also helped to reach improved welfare and a better understanding of our solar system and the universe. Satellite televisions spread information faster than ever before. Hubble telescope made it possible to detect planets in distant galaxies. Numerous academic, governmental, financial, and scientific institutions are now relying on satellite technologies to manage their daily operations. Today, the world economy is largely relying on the services provided by the ever-growing space industry. In short, the merits of the space industry are hard to comprehend and the absence of it would essentially create a financial and humanitarian crisis across the planet.

Ordinary citizens' dependence on satellite services has only begun recently. After the end of the Cold War commercial and private attention on space activities increased and diverse satellite services such as Global Positioning System (GPS) and many others, which were strictly used only by government and military officials, were made available for private use. With the advent of more sophisticated and efficient satellite manufacturing, even individuals are now capable of building satellites and sending them to outer space for relatively lower costs. Innovation and evolution in space technology are now at a point where satellites as small as laptops can have the same functionality as car-sized satellites used in the last few decades.

However, progress in the space industry has yielded a growing problem of space debris in the orbital environment. With every single launch, various mission-related objects are being released to the void of space to remain for decades. As time went on thousands of satellites started joining the debris population as they completed their lifespan. Today, there are more debris than operational satellites in orbit and this trend is expected to worsen in the next few decades. Orbital debris has no beneficial purpose and what generates concern about these objects is the fact that they threaten existing space infrastructure and human life in space. In some cases, debris also threatens humans and structures on Earth. The international community has acknowledged the growing threat of space debris (UNOOSA, 1999) and endorsed guidelines to limit the creation of further debris (UNOOSA, 2010; IADC, 2019). Despite the rising awareness and effort, there has not been any substantial effort in addressing the threat posed by orbital debris.

1.2. Problem Statement

Space debris is widely defined as any man-made object that has never served or no longer serves a useful purpose in orbit around the Earth. Such objects include non-operational satellites, spent rocket stages, and other mission-related objects such as decouplers, sensors, as well as fragmented debris (Garcia, 2013). A more detailed definition of the term space debris follows as below (UNOOSA, 1999):

> *"Space Debris are all man-made objects, including their fragments and parts, whether their owners can be identified or not, in Earth orbit or re-entering the dens layers of the atmosphere that are no non-functional with no reasonable expectation of their being able to assume or resume their intended functions or any other functions for which they are or can be authorised".*

Over the decades of intensive launches, the number of orbital debris has increased exponentially. As of April 2021, Space Surveillance Networks have approximately 34000 objects in their catalogue which are greater than 10 cm (ESA, 2021). There are an estimated 900,000 objects between 1 cm to 10 cm and over 120 million objects smaller than 1 cm. What makes these objects problematic is the fact that orbital velocities are extremely high. On average, an object in low earth orbit travels at a speed of 7-8 kilometres per second. At such a hypervelocity, a single collision can create an immense impact and fragmentation upon collision (Klinkrad, 1993). One of the first confirmed incidences of orbital collision happened during one of the Space Shuttle Orbiter Vehicle flights. In June 1992, a tiny piece of paint chip created a crater on the window of the Space Shuttle (Christiansen, et al., 2004). The impact was deep enough to require windows to be replaced after the mission.

However, this demonstrates only the impact of a small paint chip that can generate. In case of a collision that involves relatively large objects, the results become far more catastrophic. The below image shows the potential impact of hypervelocity on even exceptionally well-protected space crafts. Even small particles as small as 1 cm is capable of generating extremely high impact upon collisions. This shows the severity of the problem.

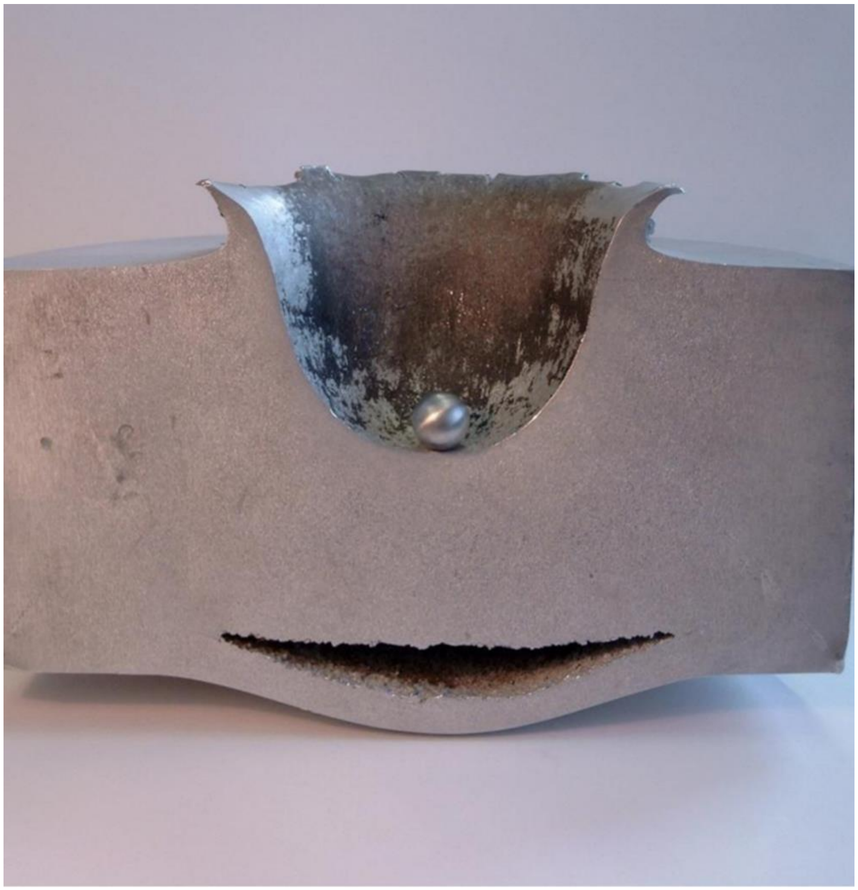
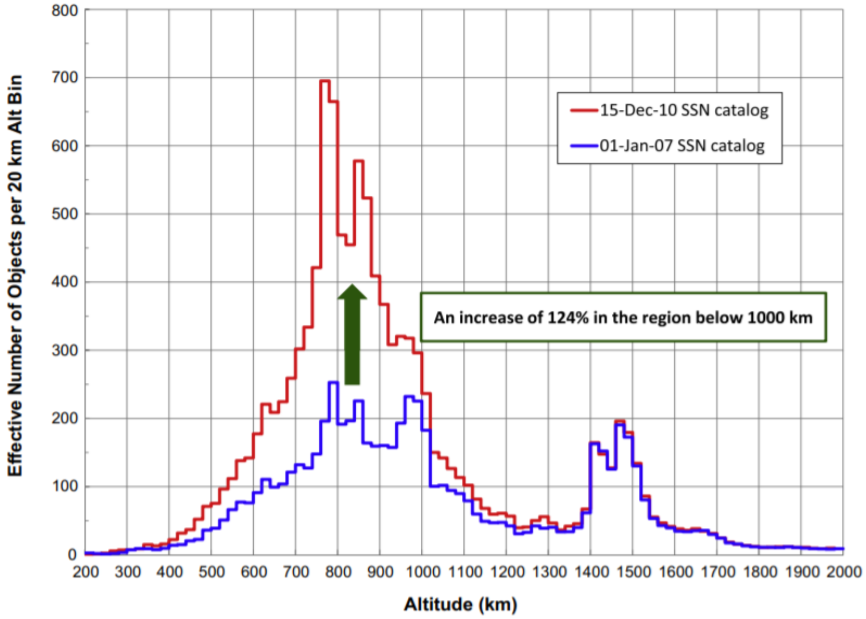


Image 1 – The impact of hypervelocity in space. The marble in the image is only 1.2 cm in diameter. The aluminium shield is 18 cm. The impact is measured at 6.8 km / s. (Credit: European Space Agency)

On the 10th of February 2009, Iridium and Cosmos communication satellites collided in low earth orbit at an altitude of around 800km (Pardini & Anselmo, 2017). This collision marks the first major coincidental accident which resulted in the creation of two debris clouds that have increased the total debris count drastically. The collision generated around 2000 pieces of debris and amplified the risk of further collisions at that altitude (Weeden, 2010). The below graph indicates the significance of such on-orbit collisions on the orbital population. The number of debris in the altitudes below 1000km increased more than 100% as a result of the Iridium / Cosmos and FY-1C Anti Satellite Test (ASAT).



Graph 1 – The number of objects in different altitudes. The number of objects before and after the on-orbit collisions in 2007 ASAT test and 2009 Iridium 33 / Cosmos 2251 (Credit: (Liou, 2011))

As Donald Kessler argues (Kessler & Cour-Palais, 1978), as the number of satellites and mission-related objects in earth orbit increases, the risk of collision between these objects also increases. Such collisions can generate a high number of fragments which in return would also increase the probability of even more collisions, leading to a cascading growth of debris in the orbital environment. This phenomenon is later called "Kessler Syndrome" where collisions lead to debris creation, to an extent where a cloud of debris becomes self-sustaining and making the use of orbital resources impractical and highly costly.

Different to other global commons, environmental degradation in outer space can happen relatively faster and the consequences are exceedingly irreversible. A single collision can create a financial loss of hundreds of millions of dollars. Although the tracking capabilities increased substantially for the last few years, most of the risk is posed by non-trackable debris. Therefore, the threat still exists and worsens with bad practices such as anti-satellite tests (Weeden, 2010). In short, space debris degrades the orbital environment and can cause great financial cost (Rouillon, 2020). It can ultimately hinder further space exploration, even for the ground-based sensors and telescopes as it increases the overall brightness in the night sky and interrupts vision (Kocifaj, et al., 2021). Debris creation is inevitable. However, the problems it poses to the long-term sustainability of orbital resources are potentially manageable. Formulation of this problem was made based on the principles presented by Astor et al. (2016).

1.3. Research Objective

The purpose of this research is to first identify the key aspects of the large and complex structure of the orbital environment including its internal and external agents. This involves defining the characteristics of the primary attributes of this ecosystem and demonstrating how they are inherently interconnected and how external factors are linked with this ecosystem. Based on this essential understanding, the study aims to design a system structure and a boundary that accommodates these key properties. It secondly inquires how these properties affect each other, how they function, and how they produce long and short-term impacts both on the low earth orbit environment and on the external drivers.

After defining the boundary and the magnitude of relations therein, the study thirdly aims to investigate the main feedback structures that create the observed increase in the population of debris in space over time, as well as the consequences it poses, and replicating the trend of this increase with the same reasoning and internal settings in a system dynamics model structure similar to the actual orbital ecosystem. Finally, it aims to incorporate robust policy proposals into the model structure in order to offer insights on future potential problems posed by environmental degradation in orbit and appropriate solutions to address them effectively.

To this end, this thesis grounds the problematic trend in low earth orbit to the context of “wicked problems” first offered by Rittel and Webber (1973). Based on this theoretical foundation the study is also aimed at offering insights from different problems taking place in different mediums. Because the proliferation of space debris, like other problems in global commons, lay beyond the jurisdictional and geopolitical boundaries and therefore requires a collected inter-agency action in order to tackle the root cause of the problem.

1.4. Research Questions

The trending nature of space debris has attracted large numbers of academics, politicians, and scientists, and a significant amount of literature enhanced our understanding of the dynamics of objects orbiting around the Earth. This study is not necessarily aimed at evaluating the analytical and numerical properties of the space debris problem. Instead, it investigates the issue from a more theory-oriented perspective and inquires policy effectiveness with a system dynamics perspective. Hence, the study attempts to answer the questions listed below:

→ What are the factors influencing the increase in the number of space debris in the low earth orbit?

→ What are the fundamental characteristics of orbital collisions and how they affect the debris population in the orbit?

→ What are the potential consequences of increased launch rates and excessive use of orbital resources on long-term environmental sustainability and space infrastructure?

→What are the potential robust policy interventions that could reduce the long-term impact of space debris and strengthen orbital sustainability?

1.5. Research Methodology: System Dynamics

In answering these questions, the study employs a system dynamics research methodology. First invented by Jay W. Forrester (1961), System Dynamics is a discipline of strategy and policy design founded on systems thinking and feedback systems theories (SDS, 2021). System dynamics has been widely used to investigate multiple global challenges such as climate change (Sterman & Sweeny, 2002; Naill, et al., 1991; Homer, 2021), pandemics (Struben, 2020; Ghaffarzadegan & Rahmandad, 2020), and many others. The systems dynamics modelling approach has also been previously used in exploring the space debris problem (Drmola & Hubik, 2018).

System thinking is considered a valuable approach in studying wicked problems as it endorses critical thinking and offers tools to define the boundaries of a system and identify interconnections between system agents (Cabrera & Cabrera, 2015). This study also applies the systems thinking and system dynamics methodology to provide an understanding of the issue and foundation for the policy design and implementation. This is achieved by identifying the essential casual relations in low earth orbit as to how long-term satellite deployment and the release of mission-related objects influence congestion in orbit and the usability of orbital resources. The study employed a stock and flow diagram structure on Stella Architect® software programme and various input scenarios, coherent and relevant to the current developments in the space industry. Furthermore, throughout the modelling of this project no data collection has been conducted. Thus, the ethics principles and regulations are not applicable in this research project.

2. Hypothesis

2.1. Theoretical Framework & Literature Review

2.1.1. Wicked Problems as Social & Environmental Issues

Historically, solutions to problems have been perceived and valued for their *efficiency* (Smeaton, 1791). Especially during the 18th-century classical economics, efficiency was considered as the condition in which a certain task could be achieved with minimal *inputs* of resources (Smeaton, 1791). This principle has guided most of the operations and developments in the following decades and even in some cases it still is one of the pervading factors of modern states and industries (Rittel & Webber, 1973). The recent developments in history have shifted this focus more towards the potential *outputs* of efficiencies and how they are involved and interconnected with other networks of systems. In other words, reasoning and doubt have become driving factors in determining and understanding how outputs become inputs for other systems and whether current strategies are right or wrong.

As Rittel and Webber emphasised (1973, p. 159), waves of repercussions produced by problem-solving actions created further awareness towards the nodes and the properties of the connections linking nodes to a wider system of internalities and externalities. According to the founders of the "Wicked Problems" concept, these recent shifts has evolved the prolonged perception of the definition of societal problems and how they should be confronted (Rittel & Webber, 1973). But what is a "wicked problem" and how could it be assessed in the context of space debris or any other environmental issues? To answer these questions, it is important to define what constitutes wickedness in a problem and what are the fundamental differences between a "tame" and a "wicked" problem.

Wicked problems characterised as multi-stakeholder decision and planning disputes that are highly complex and interconnected with other domains (Sydelko, et al., 2020). They involve a diverse set of stakeholder perspectives which means that sometimes an advantage for one can become an obstacle for another (Churchman, 1970). Therefore, the very nature of wicked problems creates controversy and conflict for optimal solutions. Checkland (1985, p. 766) further argues that there is not a possibility for a truly optimal solution as societal affairs present too many aspects which are not homogenous over time. Wicked problems different from "tame" problems because they encompass societal problems, and they cannot be merely approached by analytical methods. Tame problems are rather static and have clarifying traits with clear objectives and resolutions which allows their solutions to be exempted from societal affairs and makes their nature to be open to potential resolutions through application and the scientific method.

Although wicked problems are mostly public policy issues generated and/or affected by societal dynamics, some environmental issues are also widely considered as wicked problems as they have direct or indirect consequences for society (Ison, et al., 2015; Chester, 2010). Therefore, it is possible to argue that environmental problems are also concerning society, because they challenge the existing societal organisations and patterns of actions and thoughts. Climate change, for instance, has transformed the way people perceive fossil fuel extraction, processing, and consumption as well as the way they approach renewable energy resources (Hansen, et al., 2012; Luis, et al., 2018). Overfishing and disappearance of coral reefs have long been considered as examples of other environmental wicked problems with prominent social ramifications (Hughes, et al., 2012; Khan & Neis, 2010). Land degradation, because of excessive mining, also regarded as a wicked problem for ecological and social systems (Barkemeyer, et al., 2015). Whether it is regional or global, wicked problems present some of the most crucial challenges of modern history and this study argues that the issue of space debris is one of these environmental crises.

2.1.2. Space Debris as a "*Super-Wicked Problem*"

The concept of *super wicked problems* first introduced by Richard Lazarus in his paper drawing attention to the legislative vulnerability of climate change agreements (2009). He argues that global issues such as climate change require long-term visioned policies which are resistant to short-term political and economic pressures undermining the effectiveness and validity of climate legislations (Lazarus, 2009, p. 1232). Levin et al. (2012, p. 124) argue that super wicked problems have four fundamental attributes different from a regular wicked problem:

(1) Time is running out and there is a sense of urgency.

(2) Those who seek to provide solutions also cause the problem in the first place.
(3) The institutional strength and central authority needed to solve the problem are inadequate or non-existent.
(4) Irrational discounting worsens the situation and delays potential responses into the future.

When the issue of space debris evaluated from a wider public policy viewpoint, these properties become very apparent and relevant. Just like other global commons, issues encountered in the orbital environment can indeed be regarded as a Super Wicked problem. First of all, the hazard of space debris for space operators is increasing drastically and posing threat to international security. The number of studies suggesting immediate international action increased in parallel with on-orbit collisions in 2007 and 2009 causing sudden and massive addition of space debris. (Imburgia, 2011; McCormick, 2013; Skinner, 2017). Especially in the context of low earth orbit, time is indeed running out and "space situational awareness" increases the urgency for action as the debris population is threatening access to space and existing space infrastructure (R.Migaud, 2020).

Secondly, it is safe to argue that the space debris problem has been sparked by the major spacefaring countries. More than 75% of the debris in orbits generated by the two major participants of the Cold War era (RS, 2020). Today, the space agencies of these countries are actively involved in space debris mitigation activities (UNOOSA, 2018; ODMSP, 2019). As the number of spacefaring countries increases, the source of debris creation diversified over time (Anz-Meador & Shoots, 2019). Along with further debris creation, spacefaring countries started implementing space debris mitigation measures to explore the potential implications of increased orbital congestion and how to potentially address it through prevention, monitoring and removal (Adimurthy & Ganeshan, 2006; Ribeiro, et al., 2018).

Thirdly, the existing legislative framework for space governance was established during the Cold War (Gabrynowicz, 2004). However, none of the current five major space laws defines or mention the term space debris or create binding obligations for states in case of excessive debris creation (Haroun, et al., 2021). The existing instruments directly addressing the space debris issue are soft texts such as Space Debris Mitigation Guidelines from Inter-Agency Space Debris Coordination

Committee and United Nations (IADC, 2019; UNOOSA, 2010). Moreover, the current institutional authority predominantly states cantered and therefore it fails to consider the ever-increasing prominence of the commercial and private sector in space (Button, 2013). Listner (2012) argues that the issue of space debris presents various unconventional challenges to the legal and policy environment of space governance which are yet to be clearly defined and encountered.

Finally, past irrational practices such as Anti-Satellite Test missions (ASAT) (Weeden, 2010) have been worsening the orbital congestion and weakening the potential strength of policy responses. Overall, the tragedy taking place in low earth orbit demonstrates all four fundamental attributes of a “super wicked” problem. Levin and colleagues (2012) argue that, together, these properties illustrate the lack of effective policy formulation and implementation. In the context of outer space, a super wicked problem shows itself in the form of environmental degradation. Rittel and Webber (1973) suggest that the dynamic nature of wicked problems offer no possibility for solutions. Rather than “solving” the problems “managing” them is the way to deal with these problems.

Thus, as long as there is growth and demand for satellite services, there will be environmental consequences hindering the possibility of any permanent solutions. However, this does not necessarily mean that “managing” the problem cannot present any sustainable alternatives. The space debris problem, therefore, requires the development of a systemic intervention method capable of evolving and adapting to the developments in the space industry and ecological dynamics.

2.1.3. Space Debris as a Legal and Environmental Problem

In the recent years, the issue of space debris has been generating increasing levels of awareness and recognition not only amongst the scientist but also in public and commercial sectors (Lewis, 2015; Kharpal, 2020; BBC, 2021). The literature covering orbital debris has grown significantly and thousands of articles have been published on the economic, environmental, legal, technical, theoretical aspects of the problem. The issue of space debris has multiple impacts on every sphere of life. However, although the academic variety on the issue is proliferating, most of the focus is still predominantly aimed at addressing the legal and technical (environmental) aspects of the problem.

The majority of the public policy-related studies draw attention to the lack of effective legal and policy measures from the international community in handling the issue of space debris (Haroun, et al., 2021; Listner, 2012; Johnson, 2020; Dunk, 2001). Primary governance deficits are considered as the root cause of increases in the debris population in the orbits. Recently, however, this blame started to shift from public institutions to the privatisation of the space sector as the proposed satellite constellations are estimated to greatly increase the number of total objects in orbit (Venkatesan, et al., 2020). The technical dimension of the orbital congestion, collision, collision probability, fragmentation, and studies based on future scenario analysis are explored through various modelling methods (Rouillon, 2020; Celletti, et al., 2016; Pardini & Anselmo, 2017; Shelton & Junkins, 2019). There is currently only one system dynamics modelling study on the subject that explores the potential impact of cascading debris collision in low earth orbit (Drmola & Hubik, 2018).

Despite the ongoing legal and political discussion and the uncertainty in the international governance and management of orbital resources and environmental crises therein, the literature on the orbital mechanics and the dynamics of the debris problem is very well established and explored. At this juncture, reformulating the problem of orbital congestion with systems thinking approach can provide a redefined boundary in which various tools and existing knowledge from the literature can be utilised to explore the connections between the aspects of orbital debris and to observe the problematic behaviour generated therein. In the following section of this study, various findings from these studies will be reviewed in explaining the causality in low earth orbit.

2.2. Causality in Low Earth Orbit

2.2.1. Increased Demand for Satellite Services & Orbital Population

Historically, the primary driving motivation of launching objects to space was the Cold War, the struggle for space domination (Devezas, et al., 2012). However, with the advent of improved technology and the availability of existing space infrastructure, commercial activities in space gained momentum. Decreased cost of manufacturing and launching satellites enhanced the public and private use of satellite services in many sectors. Today, the data and imagery obtained from satellites are regularly being used in fields like urban planning and traffic management, agricultural settings, and even conflict management. Earth observation and remote sensing satellite services are highly (Donaldson & Stroeygard, 2016). According to the Space Economy Report by EuroConsult (2020), the space economy was valued at 385 billion dollars in 2020 and the industry has generated approximately 310 billion dollars of total revenue in the same year. Major financial institutions are expecting the space industry to exceed 1 trillion dollars by 2030 (Sheetz, 2020).

As a result of the increased demand and advanced launching capabilities, one can expect a higher number of satellite launches. In fact, the number of satellites to be launched in the next decade is expressed in tens of thousands. Private companies such as Amazon, Google, OneWeb and SpaceX are planning to launch mega satellite constellations to low earth orbit (Bommakanti, 2021). To extrapolate on this expected figure; in the first half of this decade, the number of active satellites will be more doubled singlehandedly by SpaceX. Therefore, in addition to the existing objects, satellite constellations and other mission-related objects will drastically increase the orbital population and spatial density. By 2029, the total number of satellites is expected to reach 57,000 (Mosher, 2020).

2.2.2. Orbital Population & Risk of Collision

After the end of the Cold War, the space debris problem was becoming a major concern for spacefaring countries and space agencies (Shelton & Junkins, 2019). One of the earliest studies on the orbital population and the collision risk was conducted around that time by Foster (1992). His findings were indicating that the orbital collision risk is increasing over time. Furthermore, he argues that no matter how high the capability of debris avoidance manoeuvres, collision probability can never be eliminated (Foster, 1992, p. 1).

The founder of the so-called Kessler Syndrome (1978) Donald J, Kessler, in one of his early studies on the subject, argued that the altitudes between 800-1000 km of low earth orbit have become already unstable due to the accumulation of objects in this region. He estimated that the debris breakup rate will increase to one every two to five years (Kessler, 1991). In fact, by the year 2007, the fragmentation doubling rate has dropped to one to two years (Englert, et al., 2014). This is primarily because of the two catastrophic collisions that took place in 2007 and 2009 (Weeden, 2010; Weeden, 2010).

Over the years, many scientists and institutions have contributed to the understanding of collision risk in orbit (Rossi, et al., 1997; Anselmo & Pardini, 1999; Liou & Johnson, 2008) and the number of objects in orbit has tripled since (Englert, et al., 2014; ESA, 2021). The primary concern expressed within all these studies was that the increased launch rates and satellite populations will increase the probability of accidental collisions. Liou and Johnson (2008) studied the evolution of the effective number of objects in low earth orbit and predicted that the collision occurrence frequency will increase up to 60% in the regions between 900 and 1000 km altitude in the next two centuries. Along with the increased number of objects, they estimated the spatial density to intensify four times for objects larger than 10 cm in diameter. A similar study conducted by Matney and colleagues (2017) estimates that the growth in the effective number of objects will result in very high catastrophic collisions until the early 2200s.

Pardini and Anselmo (2014, p. 39) argued that the rate of fragmentation and debris creation was estimated to exceed the total loss of objects due to the natural decay effect. Their study suggests that the number of catastrophic collisions could have been much higher if not for the wide adaption of collision avoidance practices. The main concern of their study was the planned satellite constellations consisting of approximately 6000 new satellites. They estimated that the collision rate among catalogued objects can increase 20-30% in the coming decades. Since the time they have conducted this study, the number of proposed satellite constellations increased almost ten times. An updated study by May and colleagues (2018) confirms that this rate has increased significantly as there are now more companies planning to place more satellites in the most crowded sections of the low earth orbit. They estimated that during an operational phase of 5 years, the collision likelihood for the OneWeb constellation is approximately 5.0% and for SpaceX is around 45.8% (May, et al., 2018, p. 453).

As the orbital collisions increase the number of total objects, Kessler's proposition on the likelihood of cascading effect (1978) becomes ever more realistic. This has been expressed by many scientists as the severest threat to environmental sustainability in the orbital environment. At this juncture, as mentioned previously, the purpose of this thesis is to build upon this common understanding of orbital dynamics and to explore the potential impacts of such probability with a system thinking and modelling approach. The following section is aimed at indicating the threat of orbital congestion and its impact on the existing space infrastructure and the orbital resources.

2.3. Problem Structure

The issue of space debris can be assessed from many perspectives. As shown in the previous section, the literature focuses on various aspects of this wicked problem and its consequences for the modern world economy as well as for the space commons. This thesis approaches this problem from systems thinking perspective in which, the fundamental dynamics of this problem are explored in a system dynamics modelling approach in which stock and flow diagrams are employed to replicate the real-world structure and the behaviour it generates over time. This section starts with describing the causality of the space debris problem, including its key loops and interconnections. It continues by explaining various sectors and the mathematical interactions that are utilised in recreating the orbital congestion experienced over time. And finally, it analyses key properties of the space debris problem in low earth orbit based on the findings of the relevant literature.

2.3.1. Problem Structure – Causal Loop Diagram

The below diagram illustrates the relationships between the aspect of the space debris issue. It includes the fundamental reinforcing and balancing factors influenced by the economic and environmental nature of orbital resources.

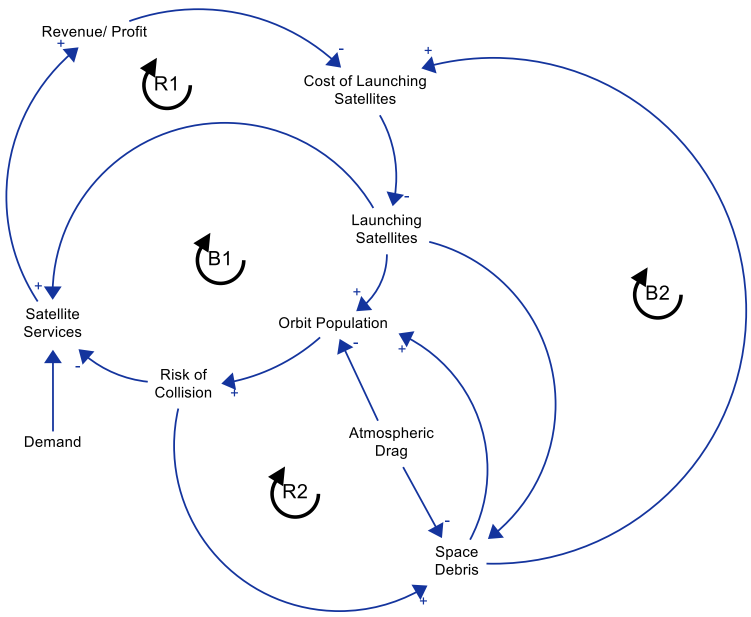


Figure 1 Causal Loop Diagram – Space Debris Problem

2.3.2. Growth in Satellite Industry

As explained previously, during the years of the Cold War, the demand for space infrastructure increased significantly. Today this force is predominantly driven by civil and commercial activities. Therefore, as a starting point, the demand for launching satellites, whether it is for military or commercial purposes, can be chosen as the initial entrance to this structure. Increased demand in various sectors results in launching more satellites. The satellites in return, provide services and revenue over time. It is also important to mention that commercial involvement in the satellite sector has amplified the revenue creation in the space industry for the last two decades. Furthermore, although it is not demonstrated in the diagram, just like in every other industry, a share of the revenue is assumed to be invested in research and development activities to increase the revenue from services as well as to decrease the cost of infrastructure and installation of these satellite services. Today, the cost of manufacturing and launching satellites are cheaper than ever before. This interaction between demand and revenue creates the first fundamental loop in this system. The reinforcing loop 1 (R1), starting with demand and continuing with launches, services revenue, and cost reduction can be regarded as the main reinforcing force that amplified the growth in the industry and the increased volume of satellite manufacturing specifically during the last decade.

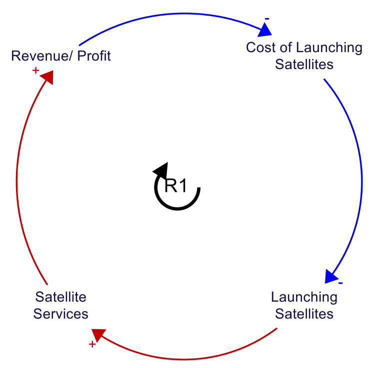


Figure 2 Causal Loop Diagram – Growth in the Satellite Industry

2.3.3. Population in Orbit and Collision

Following the intensified launch rates, the number of objects increases proportionally. Every launch results in satellites and other mission-related objects being placed in different altitudes of orbit. These objects are also subject to the atmospheric decay factor which also balances the growth shown in *figure 2.* However, the number of objects will always increase if the launch rate is higher than the decay rate and this will increase the likelihood of objects having close encounter in their trajectory. Closer encounters result in a higher risk of collision. For active satellites, collisions can be avoided. However, for the remaining catalogued objects, this risk is stable and increases in proportion to the number of objects in crowded altitudes. Although the risk of collision is extremely low as of today, with every single launch the risk increases. This interaction between orbit population and risk of collision establishes an important balancing factor, not as significant for the initial stages but very likely for the later future scenarios.

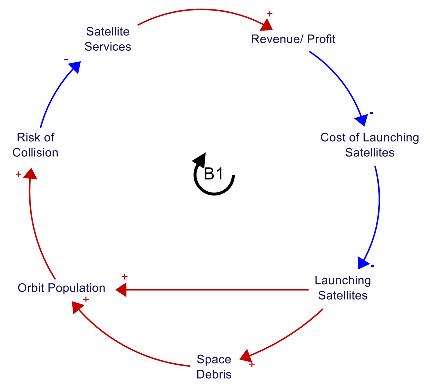


Figure 3 Causal Loop Diagram – Orbital Population

2.3.4. Kessler Syndrome – Cascading Collisions

This reinforcing loop identifies the risk that has long been considered the severest threat for the sustainability of the orbital resources. Assuming a stable increase in the number of satellites for the next few decades, the population in orbit increase drastically and this will result in higher risks of collisions between objects. Every collision has the potential of generating thousands of trackable and millions of non-trackable objects due to the hyper velocities in orbit. Past on-orbit collisions proved that high velocities could result in catastrophic outcomes and has the threat of turning into a self-sustaining debris cloud in the altitudes where the orbital decay effect is relatively slow. This risk regarded to be very low. However, the risk persists.

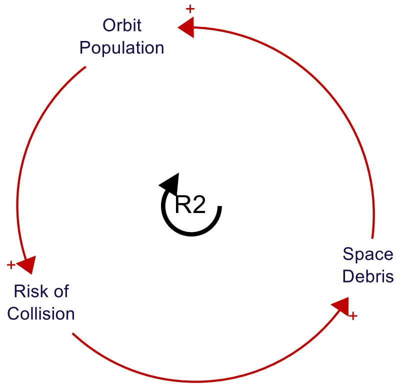


Figure 4 Causal Loop Diagram – Kessler Syndrome

2.3.5. Threat to Space Infrastructure

The final fundamental loop describes environmental degradation and its impact on the satellite industry. Further congestion created by the reinforcing “Kessler” loop increases the cost of launching satellites. The cost here can be divided into two categories: cost of launching and cost of operating. Firstly, the cost of launch would correspondingly increase because the launch missions would be highly exposed to debris travelling at hyper velocities. Therefore, there is a possibility of collision during the allocation phase of the mission. Secondly, after successful placement of satellite, satellites would spend extra fuel in case of close encounters, this would increase the cost of launch and operation as the satellite would require additional structures and fuel to successfully execute manoeuvres on orbit. Moreover, the relevant cost could also increase primarily because of the persisting threat of debris and its impact on the overall lifetime of satellites and the potential revenue generation.

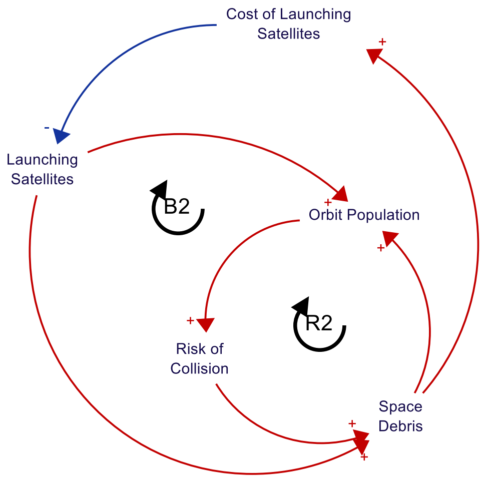


Figure 5 Causal Loop Diagram – Space Debris effect on Cost of Launch

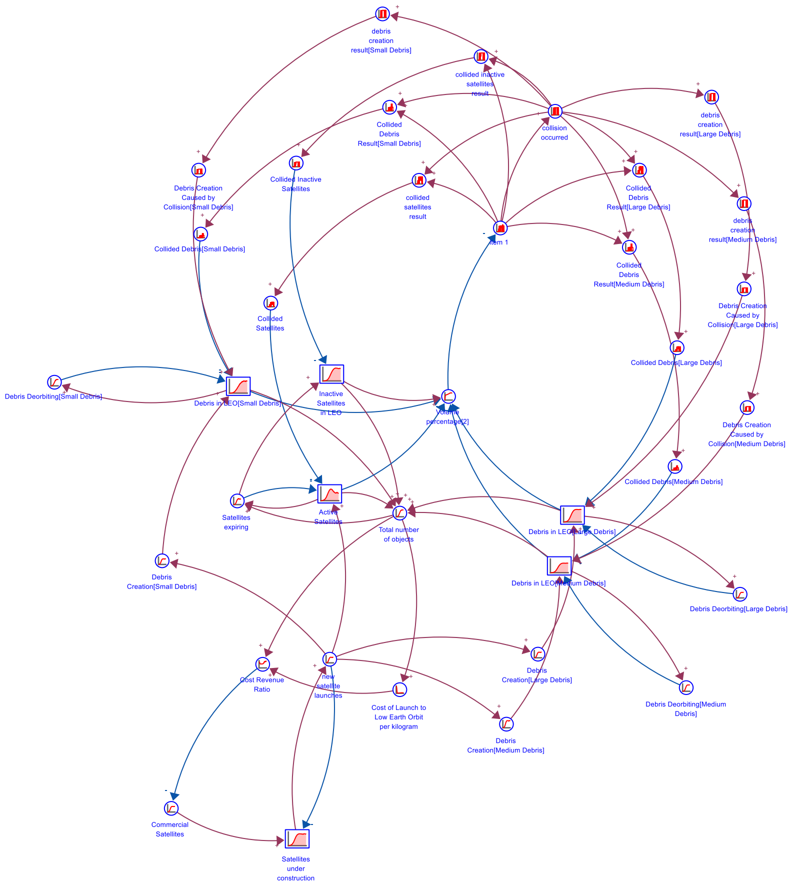


Figure 6 Causal Loop Diagram – Entire Model Structure

The fundamental problem structure is comprised of these fundamental loops. The entire model structure, as seen above, on the other hand, consists of multiple other loops that connect objects in different subcategories, and dynamic relations in between. Fundamentally, the problem structure is constructed based on the existing knowledge provided in the literature. The next section introduces the system dynamics model structure used in exploring the super wicked problem in the space medium.

2.4. Model Structure

The explanatory model structure is comprised of 3 sectors: Satellite Sector, Debris Sector, and the Collision Sector. The model structure represents a system dynamics perspective in creating an operational version of the existing work conducted by many researchers over the decades. The model structure and the sectors therein are designed in pre-defined boundaries to better explore the interconnections and interactions between the essential attributes within and across different sectors.

2.4.1. Satellite Sector

The Satellite sector demonstrates the development of different categories of satellites and how the sector components interact internally and externally.

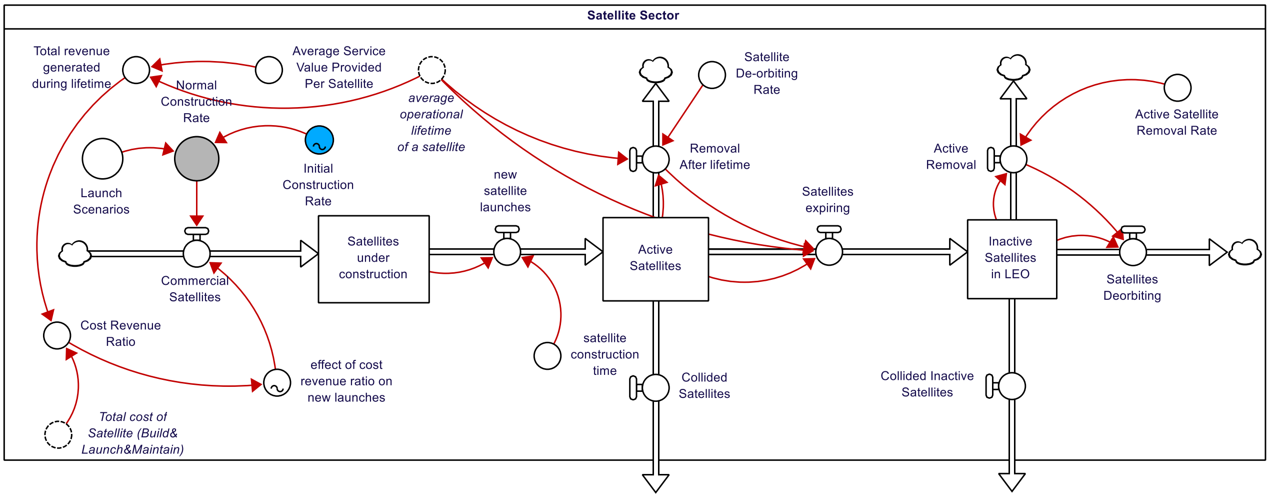


Figure 7 Stock and Flow Diagram – Satellite Sector

The satellite stocks are separated into three different categories. 'Satellites Under Construction' stock refers to the total number of accumulated satellites to be launched after they constructed.

The ‘Commercial Satellites’ inflow regulates the number of satellites to be constructed every year. The value for ‘Commercial Satellites’ implicitly includes the total outflow value for active satellites, so the system automatically replaces the satellites that are lost either due to expiration & removal or collision. The initial construction rate is defined as a graphical development in which the number of launches increase over time and stabilises at a certain value.

The launch rate is also affected by revenue creation. This means, higher profitability will result in a stronger incentive to launch more satellites. The delay time for satellite construction is chosen to be 1,5 years. The ‘Launch Scenarios’ variable refers to three different satellite launch alternatives, namely, “normal launch rate”, “aggressive launch rate”, and “sustainable launch rate”. Normal launch rate refers to the business-as-usual scenario in which launch rate equals to “initial construction rate”. Therefore, the satellite construction and consequently the launch rate will be as in today’s standards. The “aggressive launch rate” is 15% higher than the initial construction rate. The “sustainable launch rate” is 15% lower than the initial rate. Ultimately, the scenarios are introduced to analyse the long-term industrial and environmental impact of different launch rates.

‘Active Satellites’ refer to operational spacecraft in the low earth orbit. These satellites create revenue using various services. This stock depletes primarily through expiration after the lifespan is completed. The stock of ‘Active Satellites’ also depletes due to collisions. Expired satellites are either deorbited or become inactive satellites, which means that they are no longer operational and there is no possibility to manoeuvre to avoid collisions. Finally, the ‘Inactive Satellites’ stock, similar to active satellites, could also deplete through collisions and removal. The primary outflow, however, is the orbital decay factor which lowers the altitude of satellites over time and naturally removes them from the orbit.

2.4.2. Debris Sector

The debris sector illustrates the arrayed model structure for different categories of debris. The “Debris in LEO” stocks are arrayed in terms of sizes: large, medium, and small debris. Debris creation occurs as a result of satellite launches and collisions. Debris depletion occurs naturally due to the orbital decay effect.

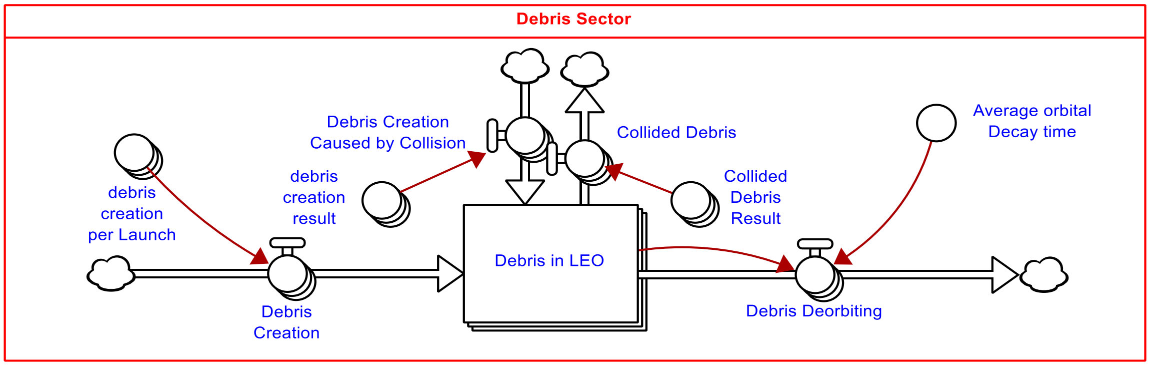


Figure 8 Stock and Flow Diagram – Debris Sector

2.4.3. Collision Sector

The collision sector is by far the most complex structure of this thesis model. It defines in which circumstances two objects could collide and the debris creation as a result of the collision. The collision incident is introduced through a series of stochasticity equations. The collision incidents are triggered by the coverage and spatial intensity rates. The collisions also depend on the ratio of the volume of each object to the total volume of objects. For example, the small debris category occupies the least total volume in low earth orbit and therefore this makes their collision probability with other objects lower. Relatively bigger objects such as large debris and active & inactive satellites have a higher probability of collision due to their larger volume.

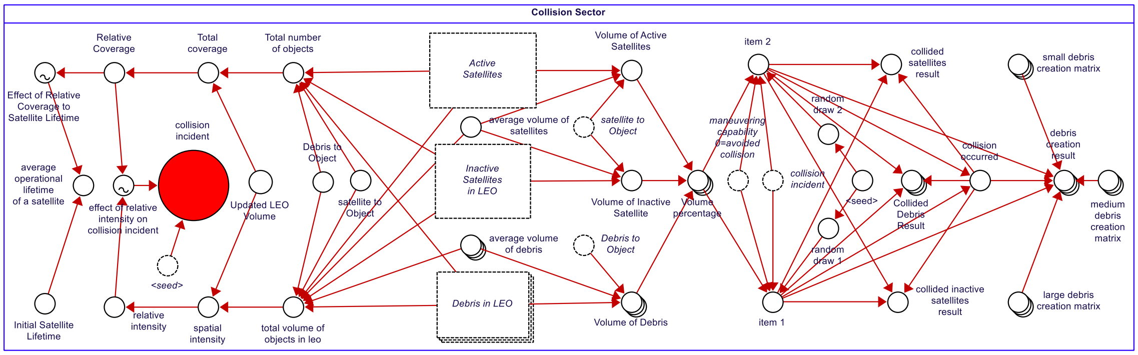


Figure 9 Stock and Flow Diagram – Collision Sector

The collision impact is calculated on the total volume of the objects involved in the collision; therefore, the creation of further debris corresponds to the sum of these volumes. The debris creation is also calculated based on the past collision incidents (Weeden, 2010), where the hyper velocities of the orbital objects are taken into account, and debris creation matrices are defined correspondingly. For example, if two satellites crash, more than 2000 small, 20 medium, and 2 large debris are estimated to generate upon collision. Every possible collision incident and the debris creation coefficients are calculated through these matrices.

The result of the collisions then introduced back to the corresponding stocks of debris. With each collision, the relative coverage increases and therefore the risk of collision becomes greater. This inter-relation within the debris sector could trigger the so-called Kessler Syndrome (1978). This probability is introduced through the effect variables on “collision incident” and on “average operational lifetime of a satellite”. Through their lifespan and the cost of launch, the debris sector has also a significant impact on the revenue creation of satellites. If the relative coverage and relative intensity reach a certain point, the collision incidents will become ever more dangerous for the space infrastructure. The manoeuvring capability has been introduced to the sector in order to decrease the involvement of active satellites in catastrophic collision courses.

2.5. Model Validation

Model validation is an important stage in improving the utility and credibility of the model. John Sterman (2000, p. 846) argues that model validation is an important stage in strengthening the appropriateness of model assumptions, robustness and the sensitivity of the outcomes. This thesis project implements the steps suggested by Sterman and follows the guidelines and instructions presented by various system dynamics scholars such as Barlas, (1996), Forrester and Senge (1980), and Saysel and Barlas (2006).

→Boundary Adequacy

The model boundary includes three fundamental sectors for studying the space debris phenomenon. Satellites, Debris and Collision sectors. This boundary could have been extended towards the industrial aspects of this problem. For instance, the satellite industry and the satellite inputs could be endogenised by incorporating demand and supply structure into the model. By doing so, the industrial dynamics of the satellite industry could be better explored, and the study could analyse the economical dynamics of the space debris issue. The nature of this study, however, is more environmentally focused and therefore aims to contribute to the understanding of the significant environmental sustainability in orbit.

As it can be seen from *Figure 1,* the model setting is directed at investigating the orbital congestion and its impact on the satellite infrastructure. Therefore, the model boundary introduces all the important concepts endogenously. The industrial input is presented mostly exogenously. An important aspect of the exogenous satellite input is the fact that it implicitly considers the number of satellites lost and compensates through replacement. Thus, the model both conceptually and practically avoids potential steady-state errors.

The study employs a relatively simple model structure in exploring the “super wicked” problem occurring in space. As Saysel and Barlas (2006, p. 259) suggest, simplicity should be aimed in problem formulation and model installation. This model structure incorporates the essential aspects articulated in the problem statement and the hypothesis section and it includes the model causal loop diagrams, model subsystems, feedback relations between satellite and debris & debris collision sectors relevant to the existing literature. Therefore, the model boundary is relevant and consistent with the purpose of this study, as well as with the principles presented by Forrester and Senge (1980, p. 419).

→Structural confirmation

In comparison with the real system, the model structure does not create logical contradictions. The stock and flow mechanisms are relevant to the real orbital system including the satellites, orbital debris and the risk of collision and how they correlate with each other over time. The interactions between different type of objects are consistent and relevant with the descriptive knowledge of the system (Sterman, 2000). The model structure includes several critical assumptions, specifically in the collision sector. These assumptions are elaborated in the later sections of this study (please see the last chapter). Moreover, it is important to emphasise that this study is not particularly aimed at validating the existing studies or at generating better quantitative results. The methodology of this thesis is, in fact, not suitable for accurately estimating the probability of so-called Kessler Syndrome or the future population of debris and the collisions that can take place in low earth orbit.

The structure of this model is more aggregate in nature and computationally undemanding. It aims to explore the problem from a more systems management perspective than an astrophysics perspective. That is the reason for having an extensive theoretical background and public policy approach in managing the super wicked nature of the space debris problem. With that being said, the model structure still attempts to capture the fundamental dynamics affecting the collision probability (May, et al., 2018; Foster, 1992) and the subsequent debris creation (Pardini & Anselmo, 2014; Pardini & Anselmo, 2017) quantitatively. A similar system dynamics model has been built by Drmola and Hubik (2018) and the stock formulation short, the model structure of this thesis is not necessarily intended to mathematically estimate and to analyse the future orbital debris growth and collision probability, but to propose policy structures to manage it sustainably. Ultimately, therefore, it is reasonable to state that the model has confidence in replicating the real-world structure within its boundary selection and structural preferences.

→Parameter confirmation and Dimensional consistency

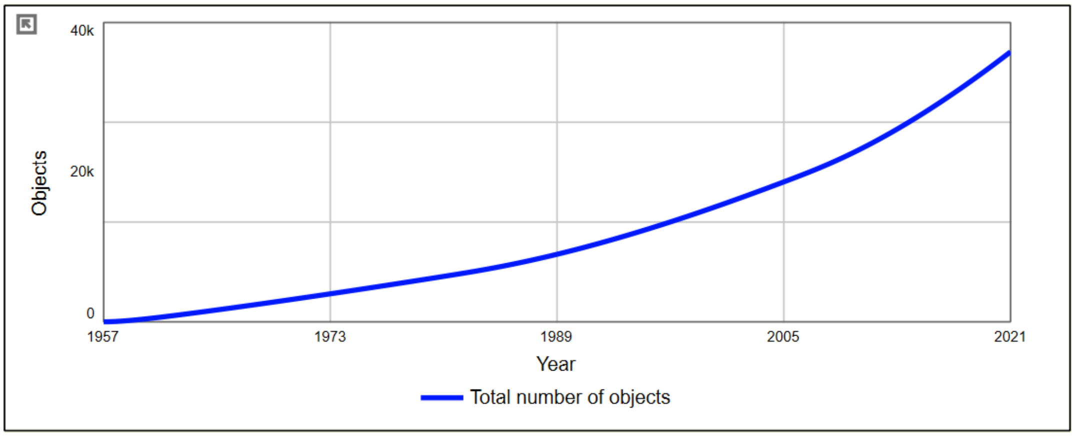
The parameter values used in this model are consistent with and relevant to the existing descriptive and numerical knowledge in the literature. The financial parameter values have been collected and verified through various resources (Adilov, et al., 2014 ; Rouillon, 2020; EuroConsult, 2020). The debris creation parameter values are inspired by the past collisions impacts and the number of debris created as a result (Weeden, 2010; Weeden, 2010; Pardini & Anselmo, 2017). Primary assumptions were made in calculating the collision probability. A detailed description of model equations and unit selection is provided in the documentation section.

A primary divergence between this study and the literature in calculating the collision course was that in most cases the literature focuses on the cross-sectional area of space objects in calculating the collision probability (May, et al., 2018; Liou & Johnson, 2008; Braun, et al., 2020). This thesis on the other hand incorporated three factors: total spatial intensity, coverage, and object volume. These parameters are utilised in order to provide a more simplistic approach to studying the orbital population and its development over time. Despite the differences in formulating the model structure, the model has good confidence in its parameter assessment. Moreover, the equations are dimensionally consistent with the existing knowledge. There are four unit errors in the model structure primarily related to the software inconsistency in processing knowledge to the material. The errors are in the collision sector and the

Other validation tests suggested by Barlas (1996; 2006), Sterman (2000), and Forrester and Senge (1980) are indicated in detail in the following Analysis section and the Appendixes.

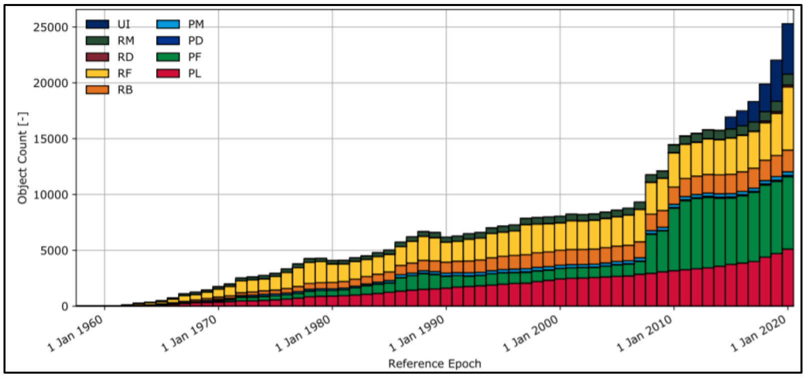
→Behaviour Validation

The model behaviour reproduces the debris behaviour pattern observed in the real orbit environment. Since the launch of Sputnik, the number of objects in orbit has increased exponentially. By 2021 the number of objects stands approximately at 36 thousand in the model result. On the other hand, according to the European Space Agency, the number of objects greater than 10 cm is around 34 thousand (ESA, 2021).



Graph 2 Total Number of Objects: Generated by the Model. This includes Active Satellites, Inactive Satellites, Large – Medium and Small Debris in Low Earth Orbit

The below graph shows the different categories of objects in orbit. This graph can be indicated as the reference mode for the model behaviour. It can be observed that the model generates a quantitatively and qualitatively similar outcome. Initially, the number of objects is relatively low as a result of low launch rates. During the Cold War era, the number of launches steadily increase. Finally, during the last decade, increased launch rate amplified object creation and enhanced the exponential growth in the numbers. Moreover, according to the same source (ESA, 2021), the number of inactive satellites in orbit is 2900 by 2021 April. The model behaviour, on the other hand, results in the creation of 1770 inactive satellites by 2021.



Graph 3 Total Number of Objects in different categories (Credit: European Space Agency)

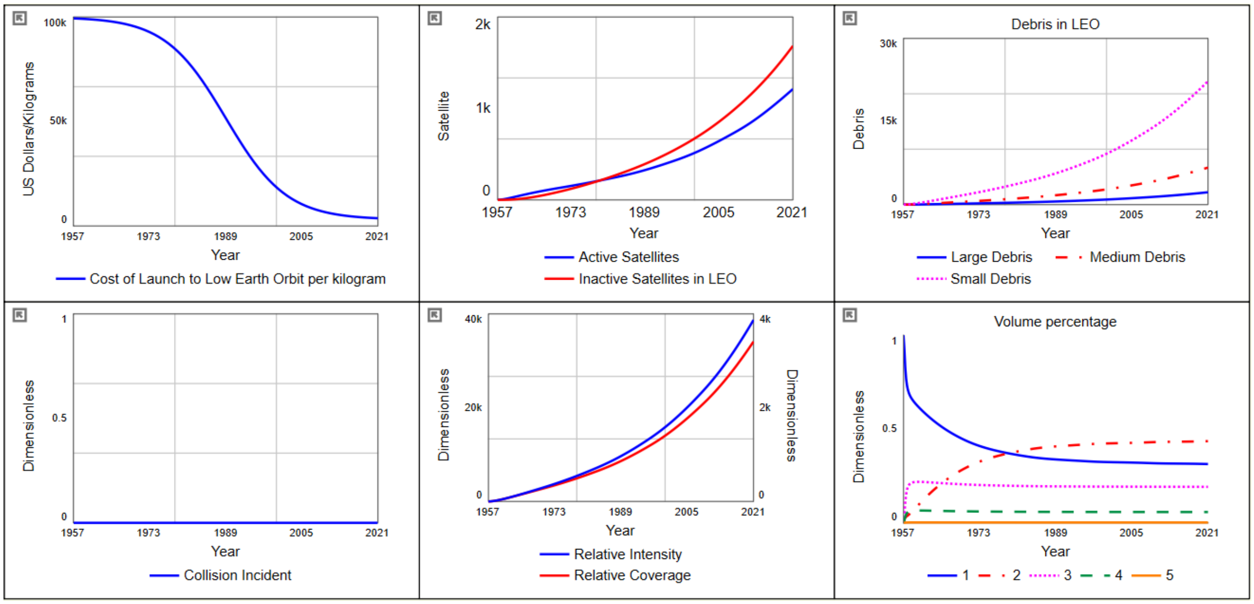
In terms of behaviour reproduction, the model, therefore, generates a similar pattern in replicating the reference mode. However, there are minor and some major quantitative differences in the modes of other observed behaviour. The limitations section of this study analyses these divergences in detail.

3. Analysis

This chapter of the thesis is aimed at analysing the growth of debris population in orbit and its ramifications for the long-term sustainability of low earth orbit. Given the extreme uncertainties in the future space policies, there is a substantial need for variation in launch policies therefore, the analysis will be founded on diverse time horizons and launch scenarios. The important aspects of the model structure are analysed in order.

3.1. Debris Situation in 2021

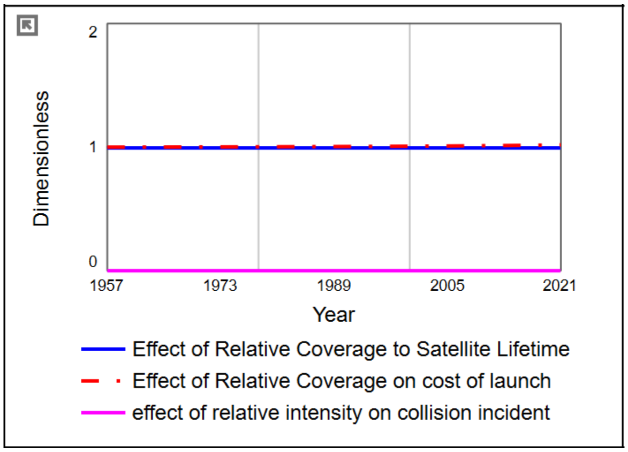
The model results indicate a significant reduction in the cost of launch per kilogram. The cost reduction in launching spacecraft to orbit is estimated to decrease even further (Coopersmith, 2011). This makes launching satellites more cost-efficient and higher in number. However, the model assumption on the cost remains stable after 2021 and stands at around 3.65k $ per kilogram. The model behaviour on the satellites indicates that after the year 1980 the number of inactive satellites surpasses the active satellites. This can also be seen in the volume percentage graph where the volume of active satellites decreases over time. By the year 2021, inactive satellites become the largest occupant of the orbit with around 43%. The amount of debris in LEO also increases exponentially in parallel with the launches. Small debris is the highest in quantity, the lowest in volume. Large debris accounts for 20% of all the objects in terms of volume.



Graph 4 – Model Behaviour Results – 2021 -

__1:__ Active Satellites __2:__ Inactive Satellites __3:__ Large Debris __4:__ Medium Debris __5:__ Small Debris

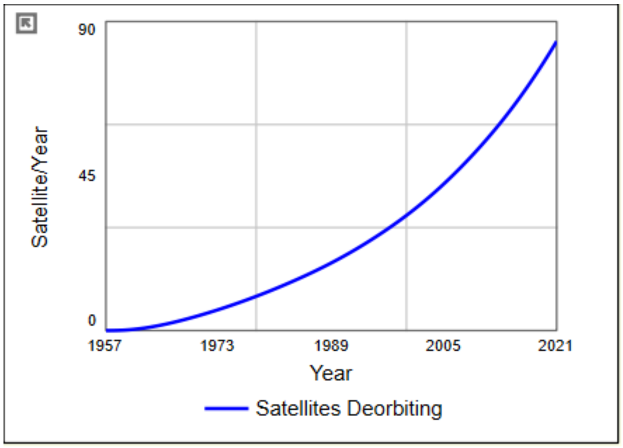
It is important to note that the model behaviour generates randomised collision incidents based on the rate of relative coverage and intensity. Both factors are relatively low. Thus, there is no recorded collision by 2021. The reinforcing loop (R1) shown in *figure 2* implicitly dominates the model behaviour during the first 60 years of model simulation. The industry creates revenue through various satellite services, and this results in higher demand for such services, this factor has been indicated clearly by Coopersmith (2011) and Rouillon (2020). The model employed this model structure exogenously through launch rate and the price of launch per kilogram. The growth in the satellite industry is therefore well replicated.



Graph 5 - 2021 - Effect variables on Satellite Lifetime, Cost of Launch, and Collision Incident

Previously in the problem structure, the first balancing factor is introduced as the orbital population loop (B1). This feedback loop has not been triggered through collisions yet, however, every new launch after 2021 is expected to increase this probability. The seed Moreover, the following loops through Kessler Syndrome (R2) and the loop increasing the cost of launch (B2) are yet to be observed in the behaviour. The effect variables on the collision, satellite lifetime, and collision incident indicate that the relative coverage and intensity are not high enough to pose a collision threat; that the relative coverage has not reached a point to negatively reduce the satellite lifespan, as well as to increase the cost of launches.

Thus, the first model simulation result until 2021 suggests that the low earth orbit environment has not reached an unsustainable stage. The orbital congestion is far from any cascading debris generation risk. Because the orbital decay factor is naturally reducing the number of inactive satellites and other debris in an average period of 20 years. This result suggests that the number of active satellites could be radically increased if only debris and inactive satellites are actively removed from the orbital environment.



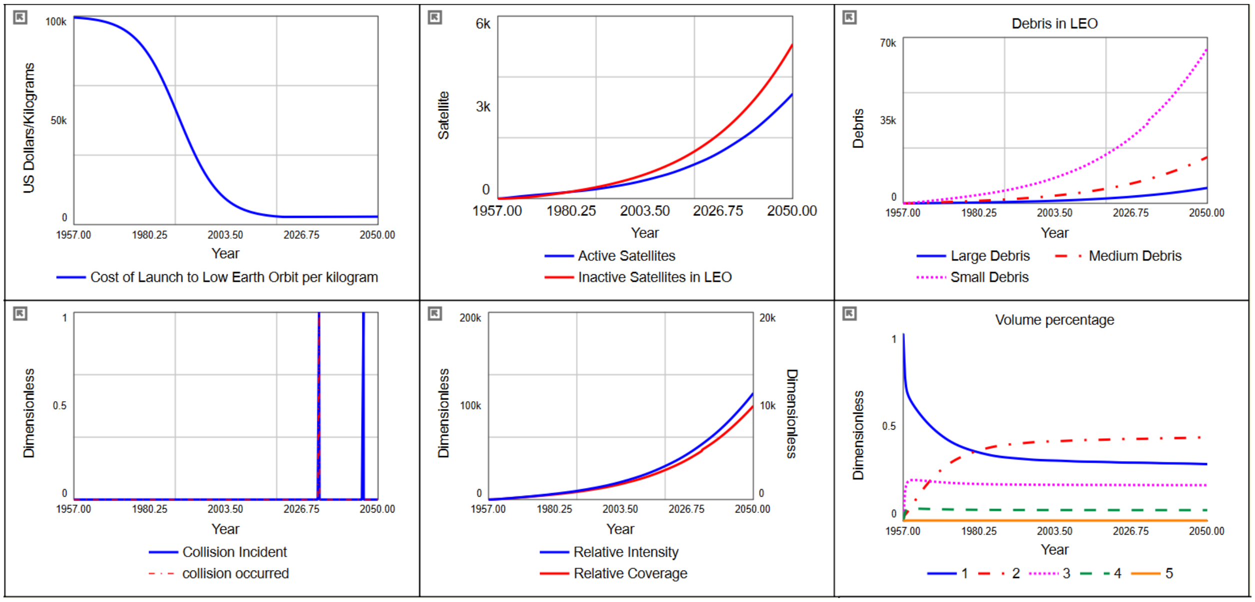
Graph 6 - 2021 – Satellites Deorbiting – Orbital Decay reduces the number of non-operational satellites.

3.2. Debris situation in 2050

3.2.1. Business as usual scenario – Standard Launch Rate

When the model was run until 2050, with a standard launch policy, it is possible to observe some important changes. First of all, the total number of objects increases significantly and reaches 100k. The volume share of active satellites drops to 30% and quantitatively, satellites account for only 3.44%. This means that there are only 3 to 4 satellites for every 100 objects in low earth orbit. This is a significant sign of congestion. Moreover, because this model structure only takes objects larger than 10 cm into account, the real figures including all the objects in smaller sizes, this proportion should be extremely lower.

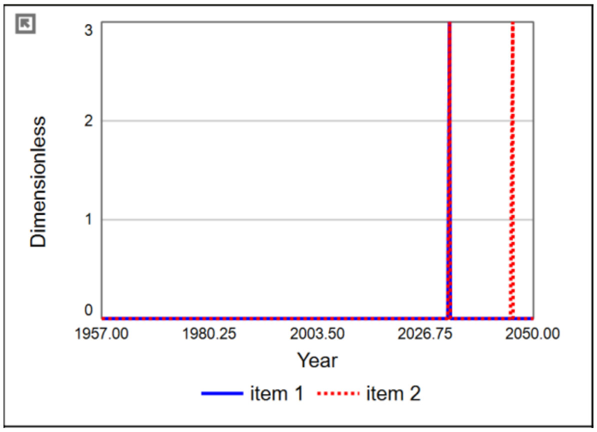
The overall results suggest that the industry growth is taking place at a very high pace. The number of satellites increased almost three times compared to 2021. However, the model figure for active satellites is comparatively low than the proposed satellite constellations in recent years. (Venkatesan, et al., 2020). Some suggest that this number will reach 100k until the next decade whereas the model only suggests up to 4k satellites until 2050 (ITU, 2020). It is hard to estimate how many satellites will there be in low earth orbit in about 30 years. The model assumes a relatively large volume for a satellite (3 cubic metres). Today, many companies manufacture cubic satellites (10 cubic centimetres) and even smaller nano satellites (AlenSpace, 2021). However, most of the satellite constellations are comprised of larger satellites. Ultimately, the volume is set to be standard for model simplicity.



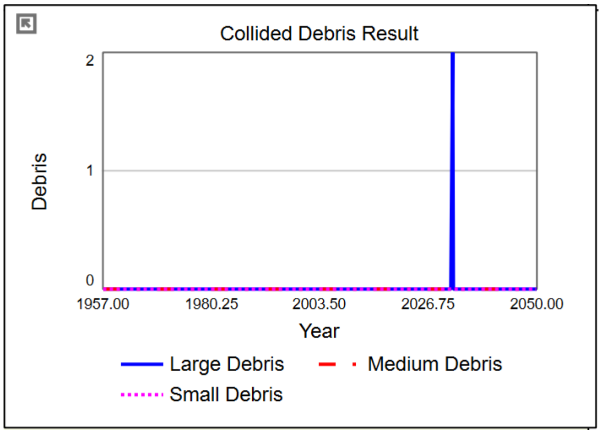
Graph 7 - 2050 – Business as usual Scenario

The business-as-usual scenario results also show two collision incidents. Before analysing the collision result and its consequences, it is important to draw attention to the difference between the "collision incident" and "collision occurred" variables. The "collision incident" variable demonstrates that a potential collision course is due to happen. In other words, two objects are on a certain collision trajectory, and they will collide. However, as explained previously, the model structure has implemented collision evasion capability for active satellites, similar to the real-world structure, where active satellites can be controlled to manoeuvre and avoid collisions. This possibility is introduced through "manoeuvring chance" and is set to be 20% for every collision. Therefore, there is a possibility of collision avoidance, if one or two of the objects is active satellites. The "collision occurred" variable, on the other hand, confirms that the collision has certainly occurred.

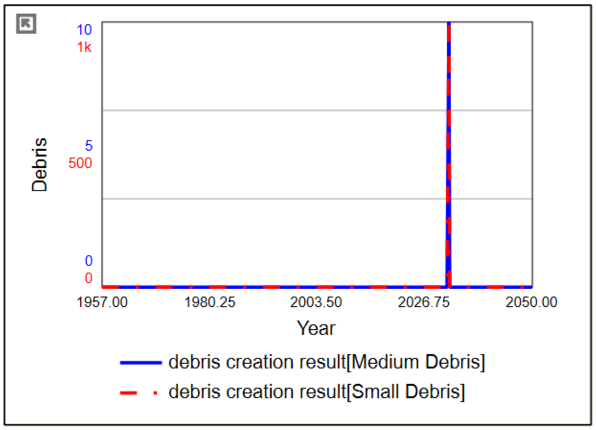
The graph on the bottom left of *Graph 5* indicates that there are two confirmed collision incidents. The first is in 2031 and the second is in 2045. Every collision depends ultimately on the increased relative coverage and spatial density and these two objects are stochastically selected based on their share of volume in the total volume of all objects. *Graph 5* demonstrates objects involved in a collision. “Item 1” refers to the first object and “Item 2” refers to the second object. All objects are numbered from 1 to 5 order, which is indicated in the description of *Graph 2.* The first collision in the model behaviour indicates that both of the items were “large debris”. This can be confirmed by the variable “Collided Debris Result”. *Graph 7* shows two large pieces of debris involved in collisions. These debris are removed from the “Large Debris” stock through the “Collided Debris” outflow. Because these debris can no longer be categorised as “large” debris as they have collided and generated smaller debris (medium and small) through fragmentation. Therefore, collided objects should be removed from respective stocks to avoid errors in debris values. For every collision, the model structure ensures that fragmented debris is added and collided debris is subtracted.



Graph 9 - 2050 – Business as usual Scenario - Item Selection for Collision



Graph 8 - 2050 – Business as usual Scenario – Collided Debris Result



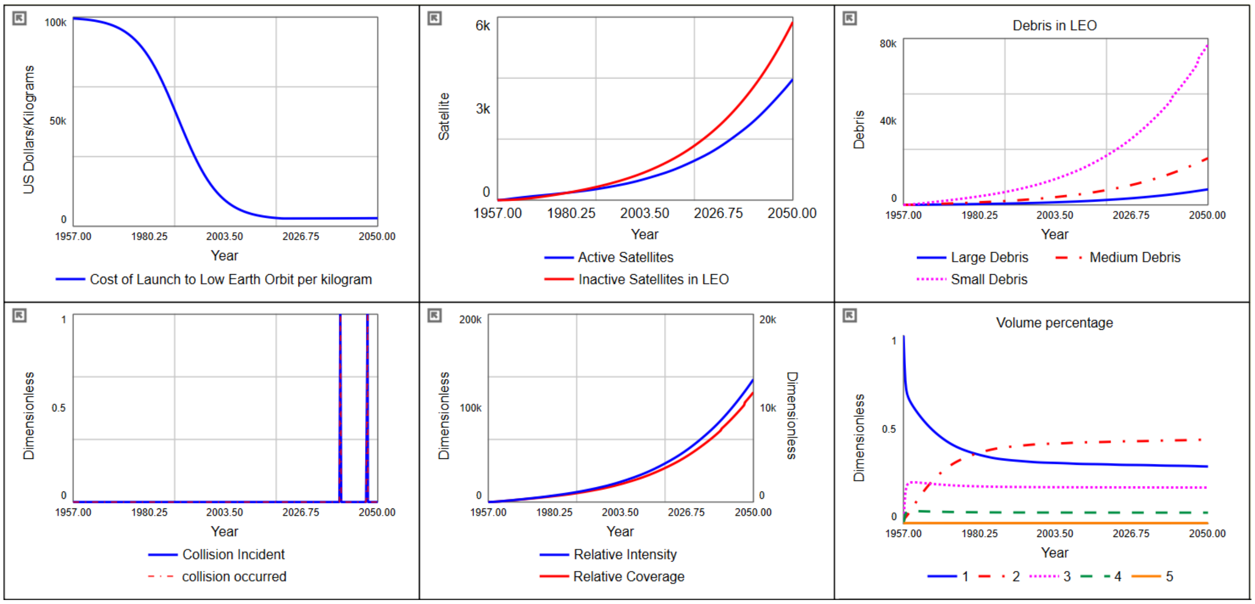
Graph 10 - 2050 – Business as usual Scenario - Debris Creation Results for Medium and Small Debris

The first collision in 2031 results in the creation of 10 medium debris and 1000 small debris. The fragmented debris is always equal to the total collided debris volume. The second "collision incident" in 2045, on the other hand, only involves one object, which is large debris. The value for "Item 1" in the second collision is 0. In this instance, the model result suggests that the "Item 1", was an "Active Satellite" and the collision is avoided. Therefore the "collision occurred" variable is observed as zero in *Graph 5.*

In short, in the business-as-usual scenario, there is only one recorded collision, and one other collision is avoided. However, the spatial intensity and the relative coverage has significantly increased. It can also be observed that the effect variables increase slightly after 2040.

3.2.2. Aggressive Launch Scenario – 15% increased Launch Rate

The second scenario results with an increased launch rate demonstrate relatively increased congestion in orbit. The relative coverage and spatial intensity rate increased around 30% compared to the last run. The volume share of active satellites dropped to 3%. Inactive satellites and large debris account for more than 60% of all volume.

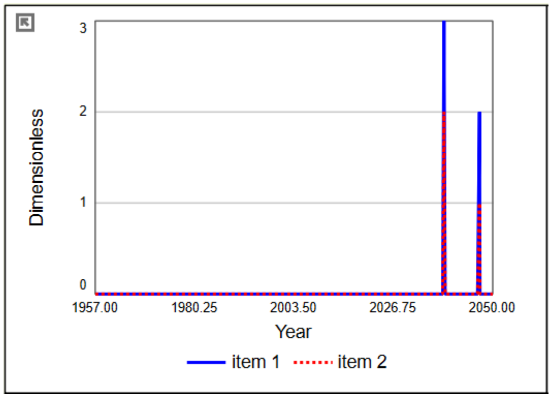


Graph 11- Model Behaviour Result – 2050 – Aggressive Launch Scenario

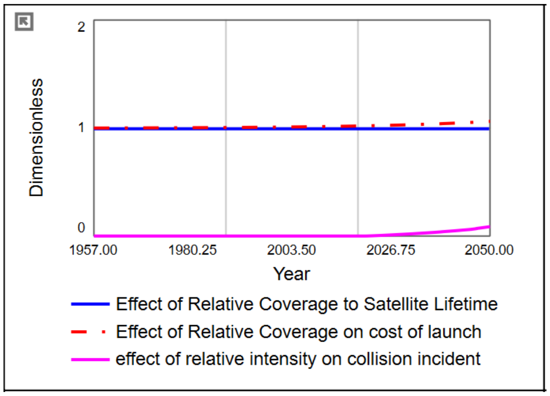
Overall, the system behaviour is still dominated by the first reinforcing loop. The growth of the satellite industry is yet to be disrupted by debris congestion in orbit.

An important result from this scenario is that this time the collisions involve both active and inactive satellites. The first collision occurred in 2038 between an inactive satellite and large debris. As a result of the collision 1000 small debris 20 medium debris and 1 large debris generated. The second collision took place in 2046 between an active and inactive satellite. In the business-as-usual scenario, a collision with an active satellite was avoided. However, this time the collision has occurred, and it has generated 2000 small, 20 medium and 2 large debris.

It is possible to observe a slight increase in the effect variables on collision incident and the cost of launch. Therefore, the collisions are now more likely and the cost of launching satellites is slightly more expensive. In short, the model results suggest that the balancing loops B1 and B2 through the orbital population and the cost of launch started affecting the system behaviour. Except for these minor differences, the simulation results do not differ much from the previous 'business as usual' scenario.



Graph 13 - 2050 – Aggressive Launch Scenario - Collided Objects Result

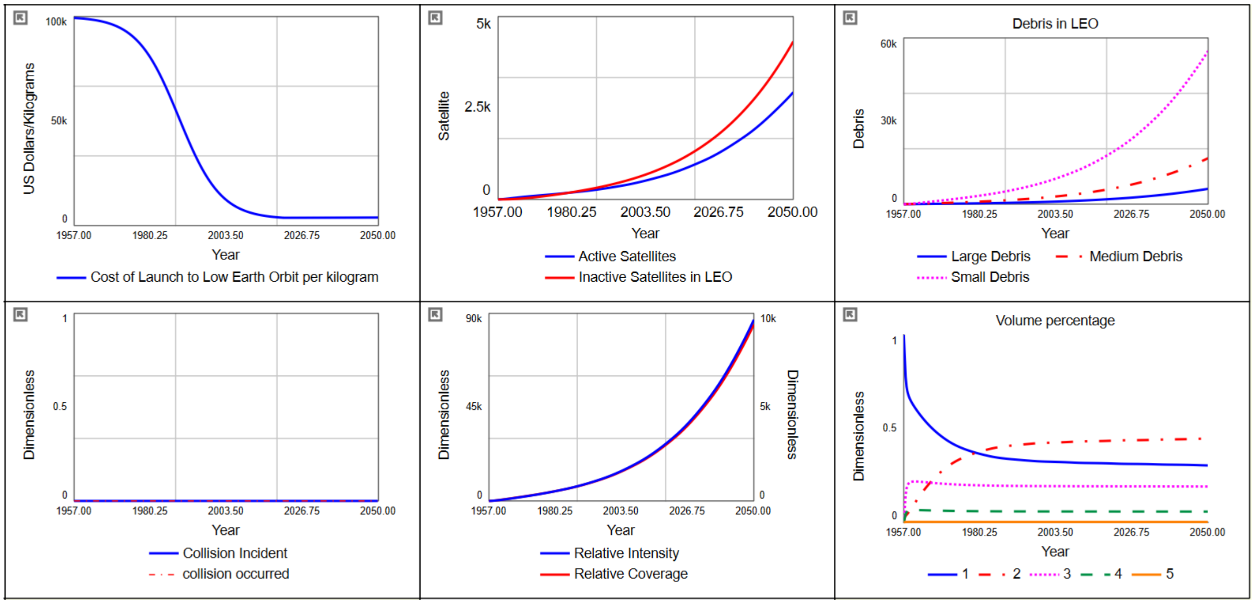


Graph 12 - 2050 - Aggressive Launch Scenario - Effect Variables

3.2.3. Sustainable Launch Scenario – 15% decreased Launch Rate

One important thing to mention in advance is the fact that 15% reduction is not made in comparison to the aggressive launch rate. The reduction was made based on the default 'business as usual' scenario. Given the high uncertainty in the future launch policies, various launch assumptions were made based on these three different launch scenarios. The sustainable launch rate is the third and final scenario this thesis has implemented in partially addressing these uncertainties and exploring the potential outcomes they generate over time.

The sustainable launch scenario was simulated multiple times and only 3 out of 10 runs have produced collisions. Therefore, the simulation with no collisions was recorded and demonstrated in this thesis. Since there is no collision in the system behaviour, there is no additional debris creation, and the system is predominantly driven by the first reinforcing loop centred on the industry growth. The relative intensity and relative coverage values are significantly lower compared to the previous scenarios.



Graph 14 – Model Behaviour Result – 2050 – Sustainable Launch Scenario

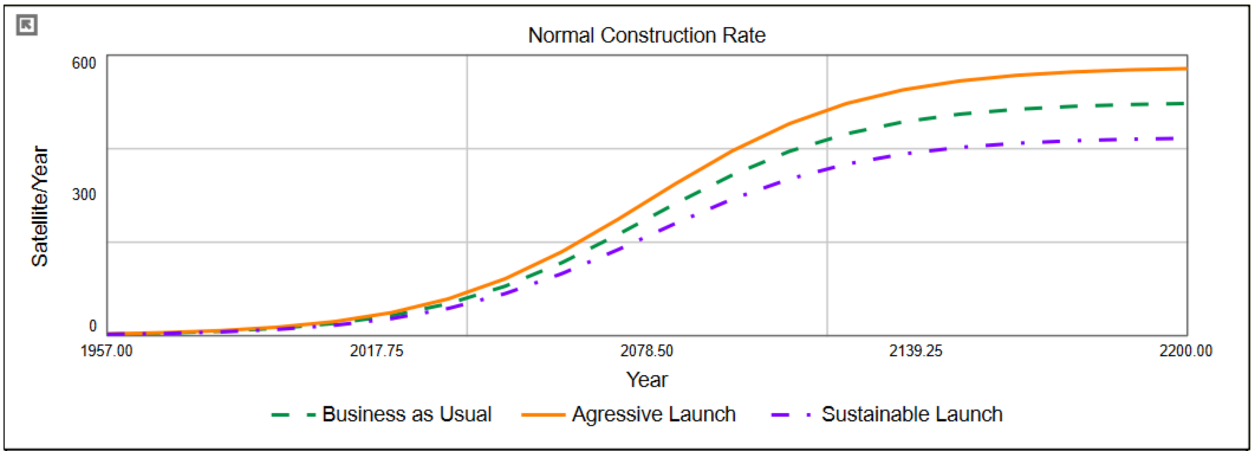
	Business as Usual	**Aggressive Launch Rate**	**Sustainable Launch Rate**
Active Satellites	3.45k	3.96k	2.93k
Inactive Satellites	5.08k	5.84k	4.32k
Large Debris	6.51k	7.49k	5.53k
Medium Debris	19.5k	22.5k	16.6k
Small Debris	65.5k	77.1k	55.3k

Table 1- Differences between the Launch Scenarios – 2050

The above graph shows the number of objects based on these launch scenarios. The sustainable launch rate produces the least amount of debris. However, the number of active satellites is considerably lower compared to the two other runs. The total revenue generated in the industry is therefore considerably lower. The long-term ramification of this policy is yet to be explored. The model result in 2200 and 2300 is expected to generate better results in comparing these scenarios.

3.3. Debris Situation in 2200

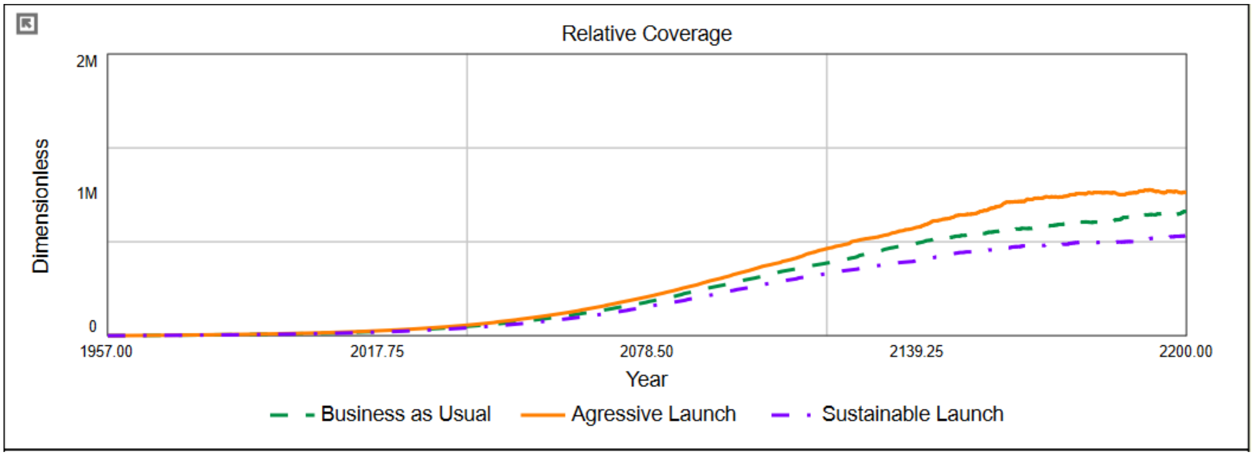
Running the simulation model until 2200 delivers some major highlights. Different from the previous runs, the model behaviour for individual scenarios is not reflected, instead, a comparison between the simulation results is provided.



Graph 15 –2200 – All Scenarios – Satellite Construction Rate

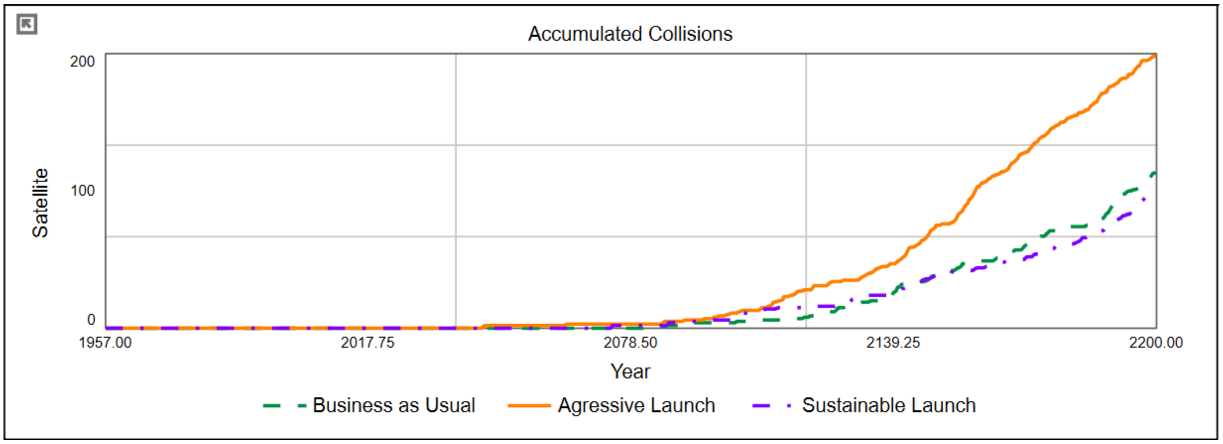
Graph 13 indicates the input value of satellites. Initially, the differences between the satellite construction rates were relatively insignificant. However, over the years this difference becomes observable. In 2200, the difference between the sustainable and aggressive launch rate is around 150 satellites per year. This divergence has resulted in substantial differences in the number of total objects and the volume and area they occupy in low earth orbit. Ultimately, however, the number of satellite inputs are also affected by the balancing loop on cost, which is indicated later in this section.

Graph 14 shows how the relative coverage increased in proportion to the satellite construction and launches over time. With additional rocket bodies released to orbit over hundreds of years, the difference between the relative coverage becomes multiplied.



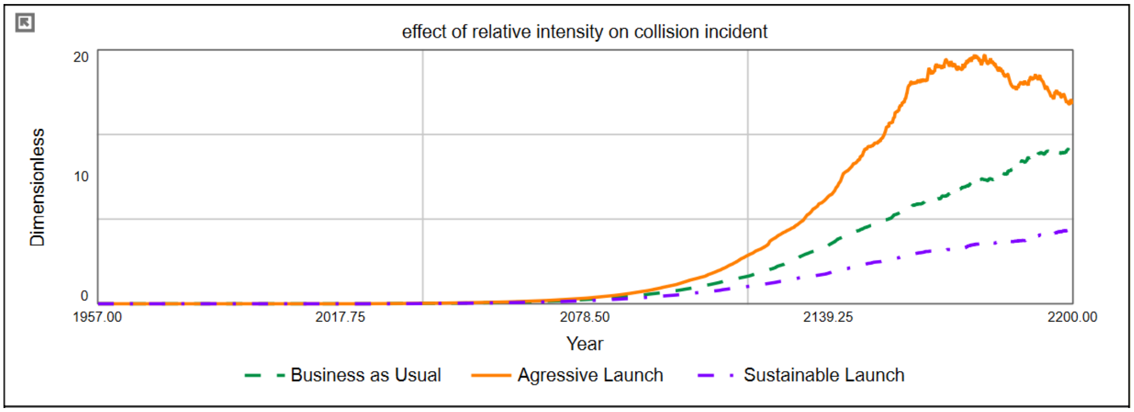
Graph 16- 2200 – All Scenarios – Relative Coverage

Additionally, the graph starts showing fluctuations especially after 2100. This is due to the increased rate of collision that can be seen in *Graph 15* which indicates the cumulative number of active satellites lost. There is a large difference between the collided active satellites in aggressive launch rate and the other two scenarios. 198 active satellites are lost compared to 103 and 113 for sustainable and business as usual scenarios, respectively.



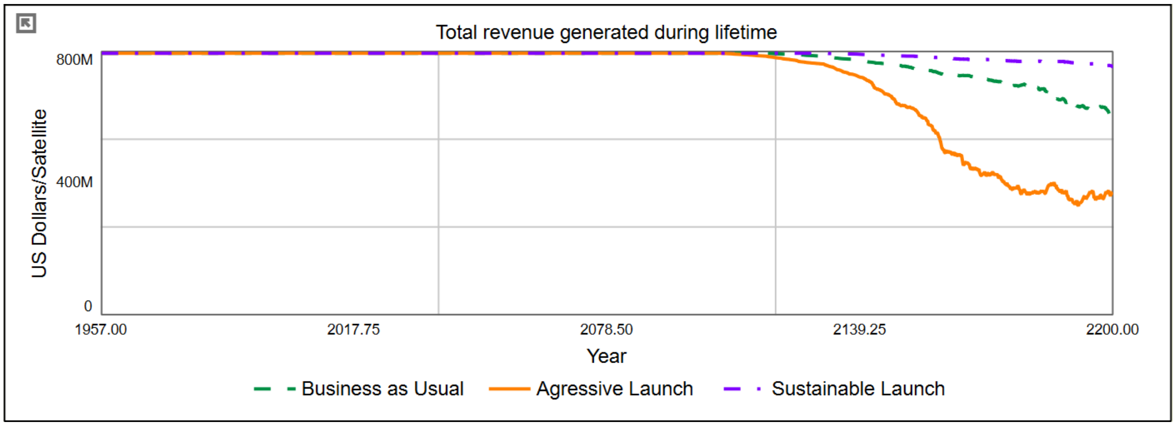
Graph 17 – 2200 – All Scenarios – Cumulative number of Active Satellites Collided

This, however, does not reflect the full picture of the collision incidents taking place. The collision figures for inactive satellites are much higher in all scenarios due to non-maneuverability. This shows, how relative coverage and intensity increase the magnitude of collisions once a certain threshold is surpassed in orbit. *Graph 16* shows the development of relative intensity and its effect on collision incidents. Over 100 years, from 2070 to 2170, the collision incidents became 20 times more likely in the case of an aggressive launch scenario.

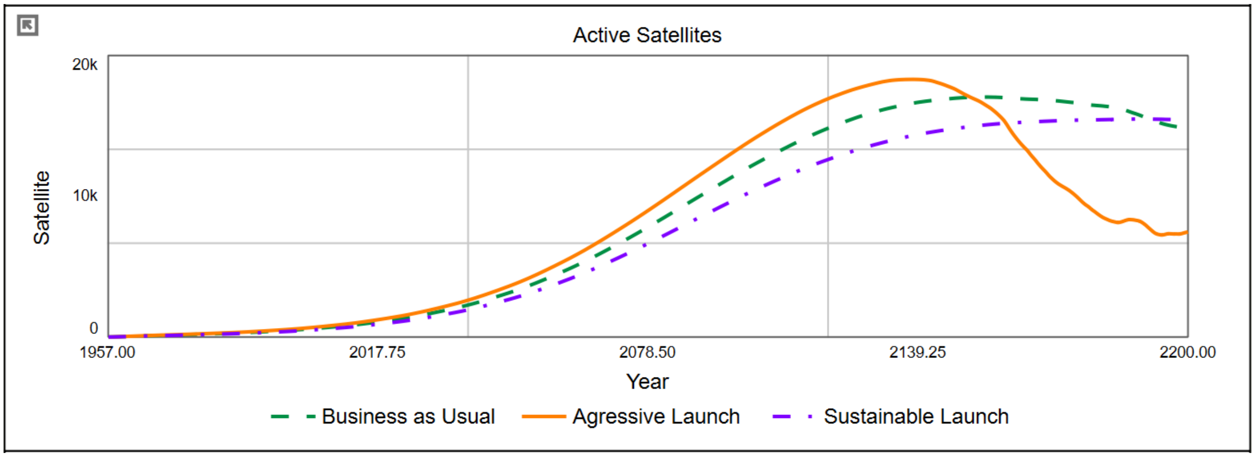


Graph 18- 2200 – All Scenarios – Effect of Relative Intensity on Collision Incidents

At this point, in the case of an aggressive launch scenario, the Kessler loop (R2) has become the dominating factor in the system behaviour in which avoiding collisions become much harder and the frequency of annual collisions is expressed in thousands. However, the sustainable launch rate produces a much more sustainable outcome in which, the Kessler loop (R2) is weaker, and congestion is still manageable. The cascading collision effect in the case of an aggressive launch scenario indicates a reduction in value after reaching its peak. Because the strength of the Kessler loop amplifies the cost loop (B2) in which, the revenue generation drops significantly, and fewer and fewer satellites are being launched to space and ultimately reducing the amount of all objects in orbit. The long-term sustainability of the orbital environment at this point is severely damaged and as shown in *Graph 18*, more than half of the space infrastructure is lost due to collisions and following reduction in the satellite launches. The model results suggest a much more manageable case for the business as usual and sustainable launch rate scenarios.

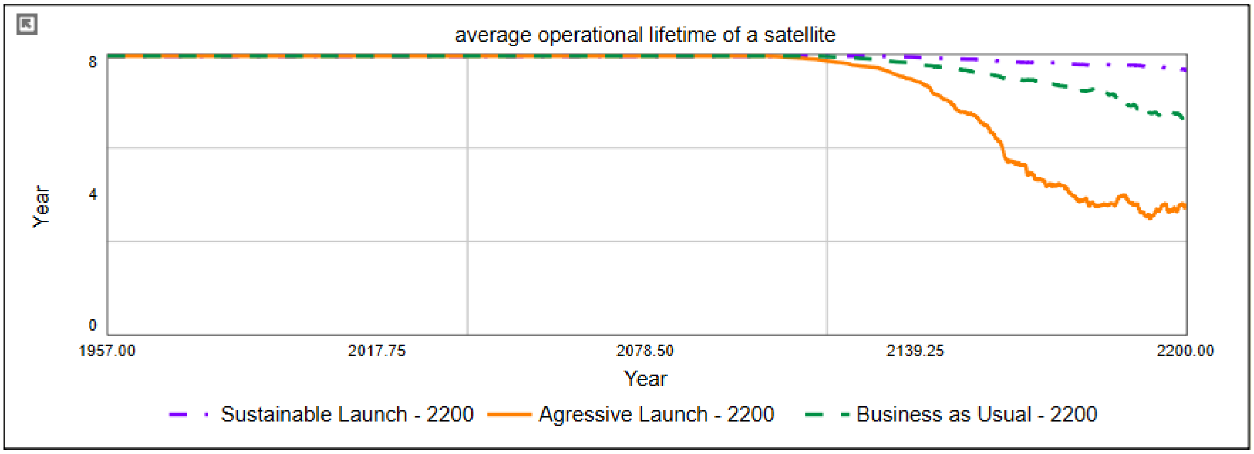


Graph 19- 2200 – Revenue Generation during Lifetime



Graph 20- 2200 – Number of Active Satellites

Moreover, *Graph 18* indicates that even though the number of satellites was much higher initially, the debris congestion is hazardous enough to cause significant reduction when the effect of Kessler Loop starts dominating the system behaviour. Diminishing revenue value is directly correlated with satellites' lifespan. A satellite launched in the aggressive launch policy has an average of 3.7 years of lifetime, whereas a satellite launched within the sustainable policy operates twice as long, with 7.5 years of lifespan.



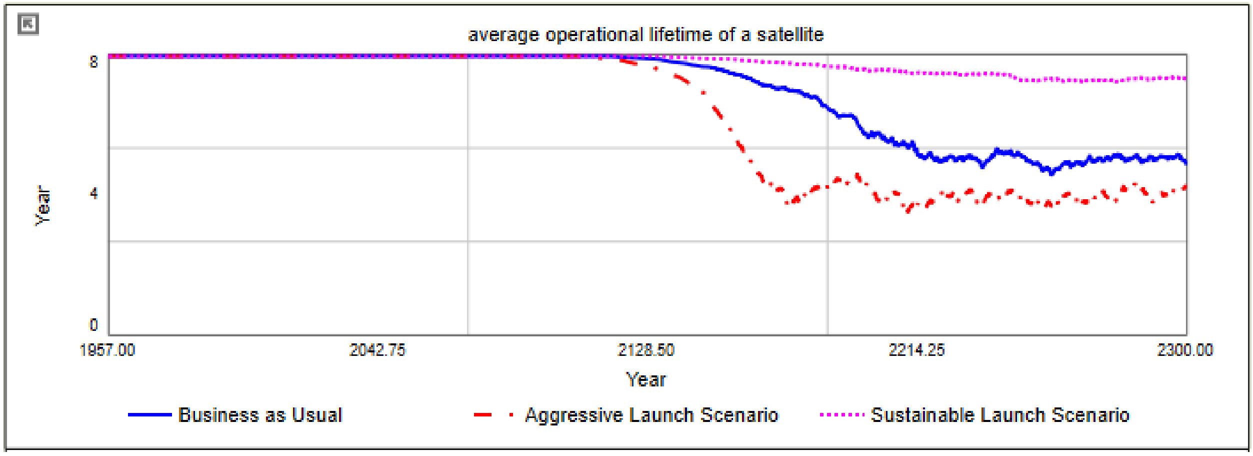
Graph 21 –2200 – Average Operational Lifetime

In short, the model results suggest that the aggressive launch scenario create severe long-term consequences both for the orbital environment and for the industry. The feedback loops in the system become increasingly sensitive for increased launch rate after 2100. The sustainable launch rate proves to be much more financially and environmentally sustainable. However, in all scenarios, increasing launch rates are observed to be exponentially amplifying the collision risk.

3.4. Debris Situation in 2300

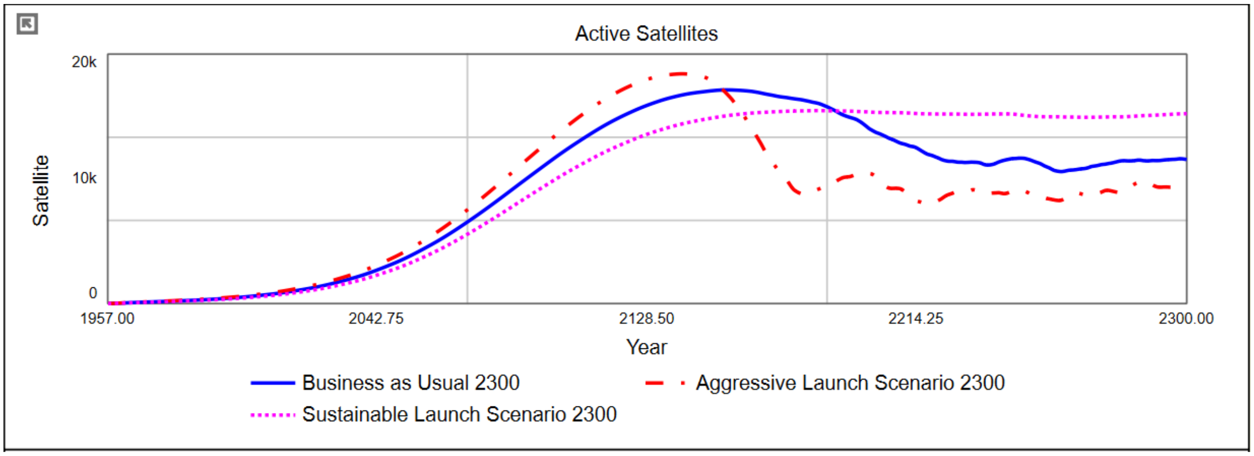
The previous scenario demonstrated that the cost of over-exploitation of orbital resources generates destructive outcomes. On the other hand, moderate launch rates produced better long-term equilibrium in terms of orbital population and the satellite infrastructure. Under these settings, it is also possible to observe and define an orbital carrying capacity under open access. All three scenarios deliver a linear increase in the accumulated collisions. At this juncture, an extra century could produce a better equilibrium for all three scenarios.

Graph 19 indicates the lifetime of satellites in 2300. Different than the previous runs, the business as usual scenario was observed to be producing similar results as of the aggressive launch scenario further in 2300. Previously, satellites launched as part of the business-as-usual scenario was generating similar results compared to sustainable launch policy (see *Graph 19)*. In the long run, this advantage seems to be diminishing until 2300 (see *Graph 20)* due to the increased orbital congestion and collision risk. The model behaviour also suggests that the unstable environmental dynamics, caused by severe congestion, causes fluctuations in the system behaviour. A sustainable launch rate produces by far the most environmentally stable behaviour over time.



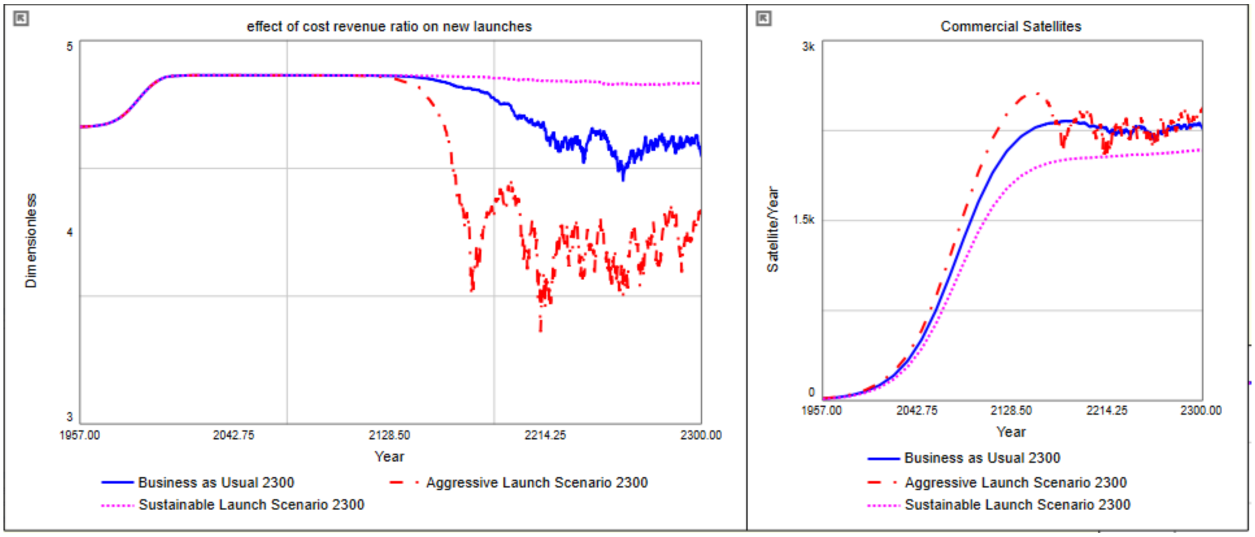
Graph 22- 2300 – Average Operational Lifetime of a Satellites

In terms of the number of active satellites, the difference between the business as usual and sustainable launch policies also enlarges in the year 2300. The below graph *(Graph 21)* shows how the number of active satellites reduces after 2200 in the business-as-usual scenario. Even though the launch rate is stabilised after 2200, the relevant intensity keeps increasing due to amplified collision frequency.



Graph 23 –2300 – Number of Active Satellites

Moreover, as mentioned, increased cost along with reduced revenue results in the cost loop being more influential in the system behaviour. *Graph 22* indicates this feedback effect in which the business-as-usual scenario produces a much less stable behaviour in new launches. The next graph on the right side indicates how this effect is influencing the yearly satellite constructions and ultimately launches. Although the launch rate is still higher in the first two scenarios, the orbital environment is much more accommodating in the case of a sustainable launch scenario.



Graph 24- 2300 – Cost Revenue ratio on New Launches – New Launches

3.5. Final Discussion

The above analysis has shown that a simplified orbital simulation model can generate prominent results from different scenarios in exploring the dynamics of the orbital environment and its ramifications. Concentrating on the long-term impact, satellite launches presented as an external agent to the system. The model behaviour suggests that a certain carrying capacity in the orbital medium exists. Once the threshold is surpassed, an environmental tragedy takes place in the form of cascading collisions and increased frequency of fragmentation first suggested by Donald Kessler (1978). The tragedy and the wickedness of this problem, in fact, carry crucial implications not only for the long-term orbital sustainability and security but also for the satellite industry and the world economy that relies on the services provided by satellites. In the short-term, the results suggest that the situation in low earth orbit is not close to a catastrophic chain reaction, yet. However, if the business-as-usual scenario persists, satellites, an important aspect of our modern civilisation, might as well become the very reason hindering space exploration.

This analysis inherently proposes a policy proposal indicated in the "sustainable launch scenario". By simply controlling the orbital population by limiting the yearly launch rate, future orbital congestion can partially be avoided. However, this policy practically impossible to implement as of 2021 because the orbital resources are considered as one of the global commons and therefore, they are open access in nature (Dunk, 2001). The governing bodies in space commons lack binding international agreements and current guidelines are simply ignored by various stakeholders. There is a strong need for a set of regulations and liability measures in space just like other global commons, the Antarctic treaty and International Law of the Sea are some of the examples (Button, 2013). As discussed before, the space debris problem is "wicked" in nature, and it evolves over time. Thus, the legal and institutional framework should be established to accurately identify the problem and to constantly measure the changes in the environment to manage it sustainably. The next section of this study offers a policy structure that attempts at addressing this governing inadequacy and further it provides with policy and implementation structure for managing the growing threat of orbital congestion in orbit.

4. Policy and Implementation

This thesis argues that that the issue of space debris, in general, a product of an international governing deficiency that is evolving into a global environmental crisis. This governing deficiency is influenced by the lack of collective action from agencies involved in space activities. As the Kessler syndrome becoming an ever-present threat due to the continuing negligent actions in outer space, many countries are now discovering ways to tackle the wickedness of the space debris issue (EuropeanSpaceAgency, 2021; NASA, 2021). “Space Situational Awareness” and “Space Traffic Management” are now a well-recognised programme among governments (Weeden, 2020) and other commercial actors (Maclay & McKnight, 2021).

The results observed in the model analysis are alarming similar to other studies conducted in the field (Adilov, et al., 2014 ; Rouillon, 2020; Venkatesan, et al., 2020; Pardini & Anselmo, 2014). In addressing the proliferation, however, the only existing remediation factor currently is the nature itself, atmospheric drag which manifests itself through orbital decay. Debris mitigation guidelines provide promising outcomes in the long-term. For instance, the “25-Year Rule by the Inter-Agency Space Debris Coordination Committee” (2019), was projected to increase the total number of objects by 110% in 200 years if the guideline complied 90%, compared to a 330% increase with no mitigation and compliance (Liou, 2020). According to Liou (2020) the compliance rate for the global 25-year rule is far less than 50%. He also argues that these policies and practices are very promising, however, the global implementation of these requirements is insufficient (Foust, 2020).

Liou’s emphasis supports the previous claims made within the previous sections of this thesis; that the orbital congestion problem is, as a super wicked problem, span across government agency boundaries, and each of these agencies has its agendas and perspectives often in conflict with one another (Sydelko, et al., 2020). Moreover, it is also possible to observe the divergence, uncertainty, and complexity agents presented by Koppenjand and Klijn (2004) for the wicked problems, in the context of the space debris issue. The orbital environment presents substantial uncertainty along with complexity. And the approaches highly variable between the actors in space.

Nancy Roberts (2000) suggests three essential strategies in tackling wicked problems which can also be revaluated in the context of space debris problem: Authoritative, Competitive, and Collaborative. Similar to the other global commons, the space commons are not possible to be acted upon neither authoritatively nor competitively. Firstly, because the stakeholders who have authority in the space arena have proven to be producing more harm than good (Skinner, 2017; Dunk, 2001; Devezas, et al., 2012). Simply relying upon the hands of few spacefaring countries could perhaps make decision making and action easier, however, 'divergence' in the perspectives and approach of spacefaring countries could expectedly produce wrong outcomes.

Secondly, the cost of space debris removal and mitigation is far too extreme to handle competitively (O'Gorman, 2018; Rouillon, 2020; Wen, 2017). Although there is a possibility of inventing better methods and technologies in mitigation efforts when states allocate resources individually in creating resolutions, the financial cost of doing so would exceed the benefits of potential solutions. Therefore, only the collaborative strategy remains as the alternative in managing the super wicked nature of the space debris problem. Because 'power' in collaborative strategy is distributed and uncontested among the stakeholders and thus provides a better platform for further coordination (Roberts, 2000). Participants in a collaborative strategy could perform mitigation activities from pooled resources and thus could share the cost of mitigation activities. Such collaboration must be manifested in financial institutional, and legal forms.

At this juncture, this thesis argues that a binding legal framework for space debris mitigation activities is most certainly required for an effective mitigation regime. Despite the scope of this thesis does not include detailed legal and political discussions, an emphasis on the legal dimension of the space debris issue was of great importance for the realisation of the policy proposals offered in this chapter. The socio-ecological nature of this problem requires a series of effective transdisciplinary approaches, which cannot be merely realised by scientific methods. Acknowledging this fact about the super wicked character of orbital congestion can yield better results when combined with the systems thinking approach. Building upon the conceptual and quantitative evidence presented in the previous chapters, an inter-agency approach was found suitable in countering the proliferation of space debris in low earth orbit.

4.1. Mitigation Operations under International Space Agency

The idea of establishing an international space agency is not new (Oz, 2018; Pedersen, 1993; Cockell, 2015). An inter-agency institution has long been considered one of the key factors in managing wicked problems (Sydelko, et al., 2020; Norris, et al., 2016). Because interagency communications and actions could combine the perspective and values of each participant and could very likely provide better outcomes for all and the environment. The purpose of establishing an International Space Agency would be to foster common understanding and coordination, over issues happening inside, outside, and beyond the orbital environment, including orbital debris. Although the profound focus here in this thesis is not to elaborate on how to establish this unifying institution as the details have already been studied (Oz, 2018) but to demonstrate the potential utilisation of its merits, in the context of system dynamics. With that being said, it is important to emphasise that Elinor Ostrom's design principles (Ostrom, 2002) are also applicable and could potentially be implemented in the initiation of the International Space Agency.

The policy proposals of this thesis and the following implementation structures are heavily dependent on the economic, institutional, and legal presence and effectiveness of such coordination, collaboration, and collective intelligence and engagement in space. It is rational to state that with no effective governing regime the following policies cannot be simply actualised.

4.2. Space Debris Mitigation Policies

The policies are focused on passive debris mitigation strategies. The first policy is similar to the above-mentioned 25-year rule, in which the satellites should be de-orbited within 25 years (IADC, 2019). Different from the 25-year rule, this policy is proposing to deorbit operation after the satellite completes its lifetime. As the model structure assumes 8 years of satellite lifespan, the deorbit operations are projected to be performed after 8 years. This policy could not only decrease the number of inactive satellites significantly and reduce the overall orbital congestion and subsequently collision risk but also provide access to more satellites. The second policy has a parallel approach to passive debris removal. It aims to minimise the mission-related objects released upon launch. These policies are achieved by deploying additional fuel both in the payload (satellite) and the rocket body used in employing it to a specific orbit altitude. The policies also require additional research and development both for the space crafts and the ground-based infrastructure in executing and facilitating post-mission deorbit missions.

4.2.1. Policy 1 – Deorbiting Satellites After Lifetime

The first policy is structured based on the goal of deorbiting 90% of all active satellites after their lifetime. Currently, the explanatory structure of the model has a 20% of the deorbiting rate. Therefore 70% of the gap constitutes the initial step of the first policy's structure. Considering the concentration of upcoming satellite constellations, the study reduced the long-recognised 25-year rule (IADC, 2019) to an average lifetime of 8 years.

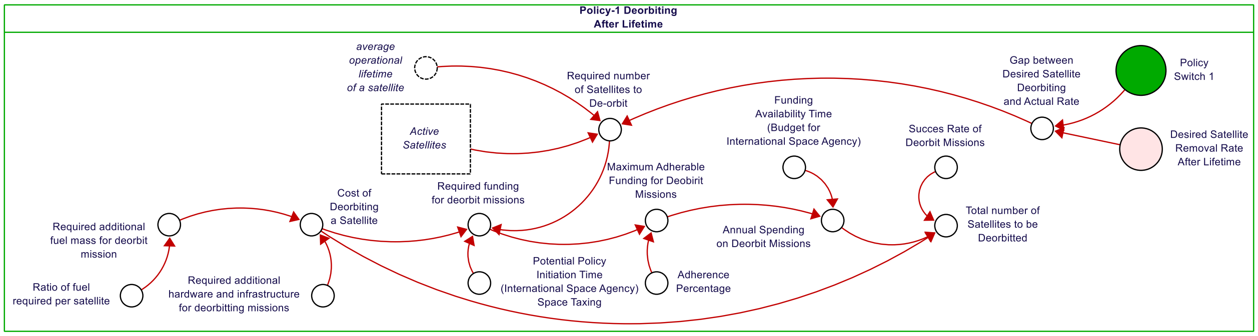


Figure 10 Policy 1 - Deorbiting Satellites After Lifetime

Following the gap structure, the policy follows with updating the required initial number of satellites to be deorbited after a lifetime. However, the policy structure takes various delays and cost structure into account. Firstly, every satellite requires additional fuel to be spent during re-entry missions. The amount of fuel varies depending on the total mass of the payload. As the volume and the mass are standardised for the sake of model simplicity, an average of 1630kg is determined for a satellite, similar to what is also commonly assumed in the literature (Rouillon, 2020). 10% of the mass ratio is assumed to be the required fuel for a successful re-entry mission. This means an additional 16.3kg of propellant is required to be carried on-board until the mission is completed and then spent subsequently to travel to lower altitudes by reducing velocity and to complete re-entry into the atmosphere. In addition, the model structure included the required hardware and infrastructure for deorbiting missions, the amount is for the second expenditure structure is determined to be 1 million U.S. Dollars.

The cost of launching a satellite with extra fuel, developed infrastructure, and equipment are added to the total cost of satellite manufacturing and launch. The total cost of implementing the policy depends on the average cost of launching per kilogram plus the 1 million U.S. Dollars additional expense. Because the orbital congestion affects the cost structure (as shown previously). At the policy start time, however, this amount is determined to be 2.6 million U.S. Dollars.

Once the cost of deorbiting a single satellite is established, the policy structure continues with ascertaining the total cost of deorbiting missions for all the satellites that are to be deorbited. This amount is calculated through the multiplication of active satellites completed their lifespan and the total cost mentioned above. The total calculated deorbiting programme is then combined with the policy delay time. The policy, namely International Space Agency, in the model structure, is assumed to take 9 years of delay until it is established. Therefore, the amount could only be available after the year 2030. Moreover, 70% of the adherence rate to the policy is introduced to the policy structure. In other words, only 70% of the funding required could be collected and allocated to the deorbiting missions. This is an important assumption since the international compliance rate in space legal frameworks and relevant guidelines are famously known to be low amongst spacefaring countries (Dunk, 2001; Foust, 2020). In this policy, a compliance rate of 70% could be considered very idealistic, however, the increasing threat of space debris has long been creating a common foundation for mitigation policies among stakeholders (Imburgia, 2011; Lewis, 2015).

Furthermore, this adherence rate is combined with another two years of delay with “Funding Availability Time” in the policy structure. Finally, the model structure assumed that based on the eventual funding, approximately 95% of the satellites could be successfully deorbited after their effective lifetime. Once all the structure is completed, the total number of satellites to be deorbited subtracted from the “Active Satellites”, previously shown in the satellite sector.

4.2.2. Policy 2 – Deorbiting Large Debris After Launch

Very similar to the previous structure, the Large Debris Removal policy is a part of passive mitigation measures recommended by the IADC (2019) This policy is aimed at removing mission-related large debris from orbit right after the placement of payload. In general, these debris are the second stage of rockets used in the placement of satellites to their designated altitude in low earth orbit. At most times, these rocket bodies spend decades before deorbiting naturally (Castronuovo, 2011). Removing these debris through active debris removal methods costs more than 100 million U.S. Dollars according to the European Space Agency's latest agreement (ESASafety&Security, 2020).

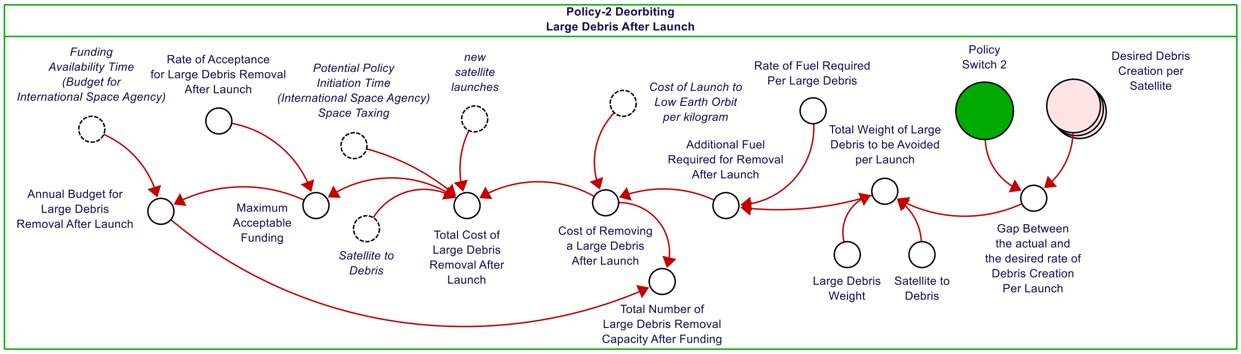


Figure 11 Policy 2 - Deorbiting Large Debris After Launch

At this juncture, the policy is aimed at proactively interfering and removing these large objects before they become completely non-operational and non-controllable. The policy is only targeting the large debris with onboard engines therefore the medium and small-sized debris are not considered suitable for the purpose of the policy. Although further mitigation is indeed possible with better rocket design and technology, the feasibility and the pricing of such launch activities are out of the scope of this thesis.

The second policy structure follows the same direction and initialised with the gap structure. In general, every launch result in the creation of one large debris. The desired value for large debris released after launch is zero. Similar to the satellite removal strategy, the cost of deorbiting is estimated through the total mass of the object. An empty secondary stage weight varies depending on the rocket type. An empty Falcon 9 second stage, for instance, weighs around 3900 kg (SFI, 2018), whereas the second stage of Ariane 5 weighs 1200kg. Therefore, the model structure assumed an average of 1500kg of the empty second stage for the model structure. Based on the total empty mass, again, 10% of the fuel is estimated to be required for successfully deorbiting large debris.

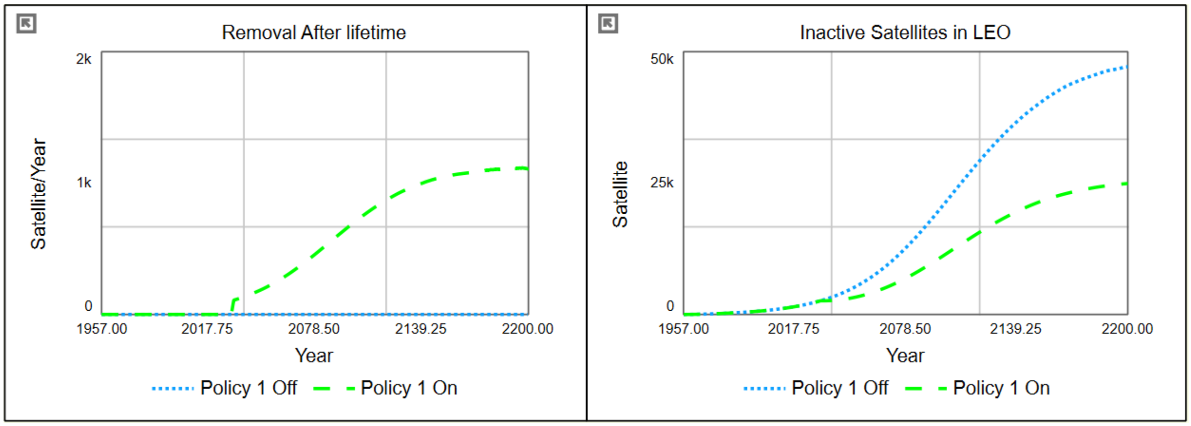
The same structure was implemented in the following stages of the second policy, which derives from a single rocket body, a total amount of funding required for all deorbiting after launch missions for large debris is calculated. Different than the previous policy, only a 30% of adherence rate is estimated for the second policy. In contrast to the 25-year rule and other mitigation guidelines for the satellites, the international community is yet to create efficient mitigation policies for large debris in low earth orbit. Therefore, it would be safe to estimate that this trend will be more or less similar during the upcoming decade. Finally, the same delay structures are also implemented here, in which 9 years delay for the establishment of the International Space Agency (2030) and following economic and financial frameworks, as well as the 2 years delay of funding availability times are added to the large debris removal policy structure.

4.3. Policy Analysis

The analysis is made based on two time horizons (2200,2300). The effectiveness of the policies is tested both individually for the time horizon until 2200. The policies are then tested collectively to observe the cumulative impact overall in the system until 2300. Business as usual scenario launch rate is taken as the default launch rate. Finally, the worst- and the best-case scenario for the year 2300 is analysed by simulating the model with policies of and on within the aggressive and sustainable launch scenarios, respectively.

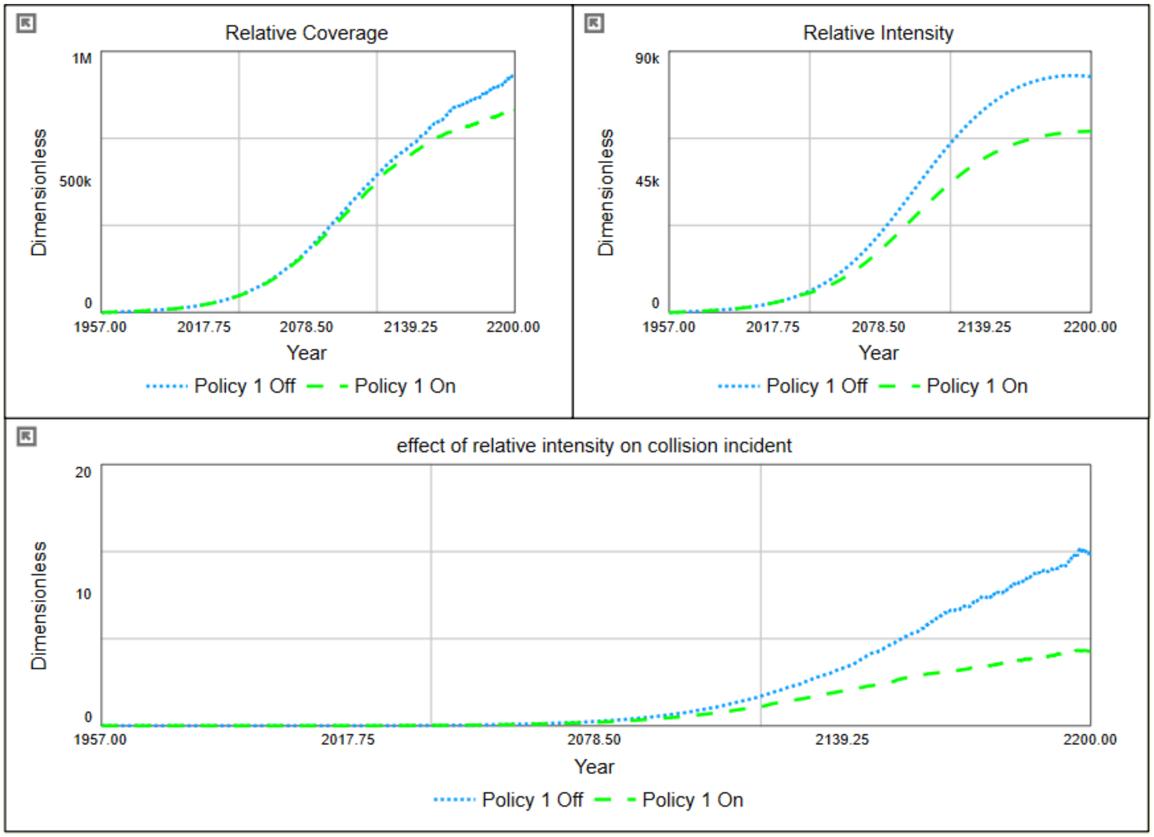
4.3.1. Policy Results – 2200 Business as Usual – Policy 1

Graph 25 indicates the removal after lifetime rate and the difference in the number of inactive satellites it creates over time.



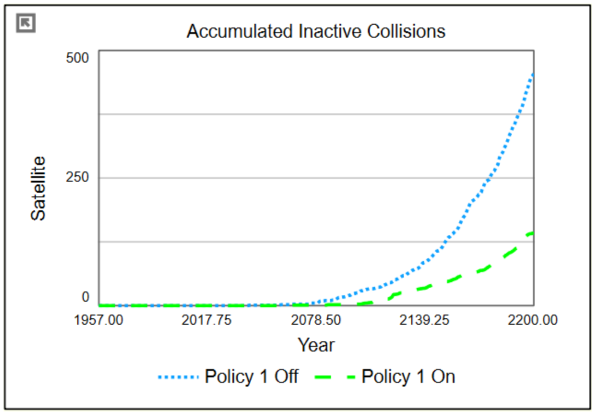
Graph 25 Policy 1 Results - 2200 - Satellite Removal After Lifetime - Inactive Satellites

The number of satellites removed after lifetime reaches 1.11k/year by 2020. This removal rate creates a considerable gap in the number of inactive satellites over time as it reduces the population to its half by 2020. This, expectedly, creates a chain reaction in the entire orbital system in which, the relative coverage and relative intensity values are shown in *Graph 26.* The “effect of relative intensity on collision incident” variable is less than half of the policy-off result.

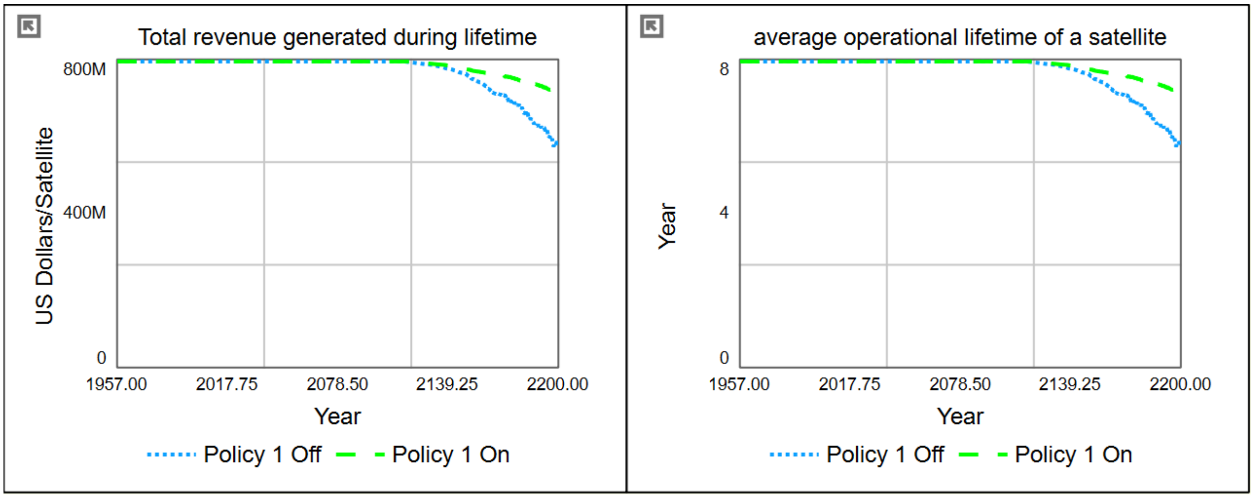


Graph 26 Policy 1 Results - 2200 - Relative Coverage, Relative Intensity, Effect on Collision Incident

The reduced collision incident risk is very much observable in the cumulative inactive satellite collision values. The policy impact was so significant, the reduction was recorded more than three times lower compared to the policy-off result (455 to 143). Moreover, the side effects of this policy are also visible in the cost results and overall satellite lifetime.



Graph 27 Policy 1 Results - 2200 - Accumulated Inactive Satellite Collisions

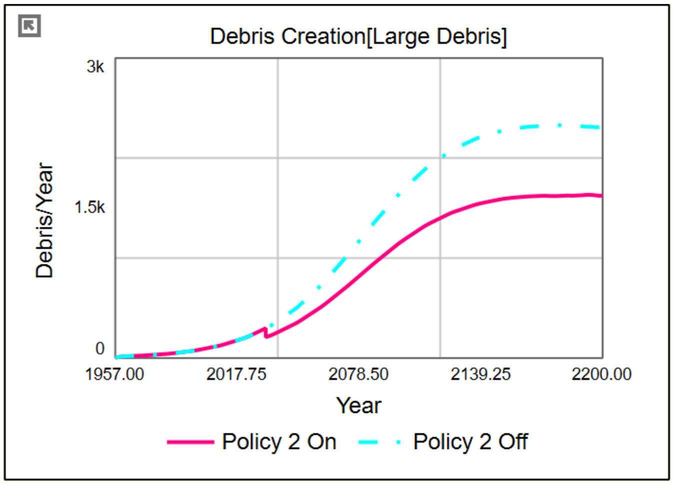


Graph 28 Policy 1 Results - 2200 - Revenue Generation - Lifetime

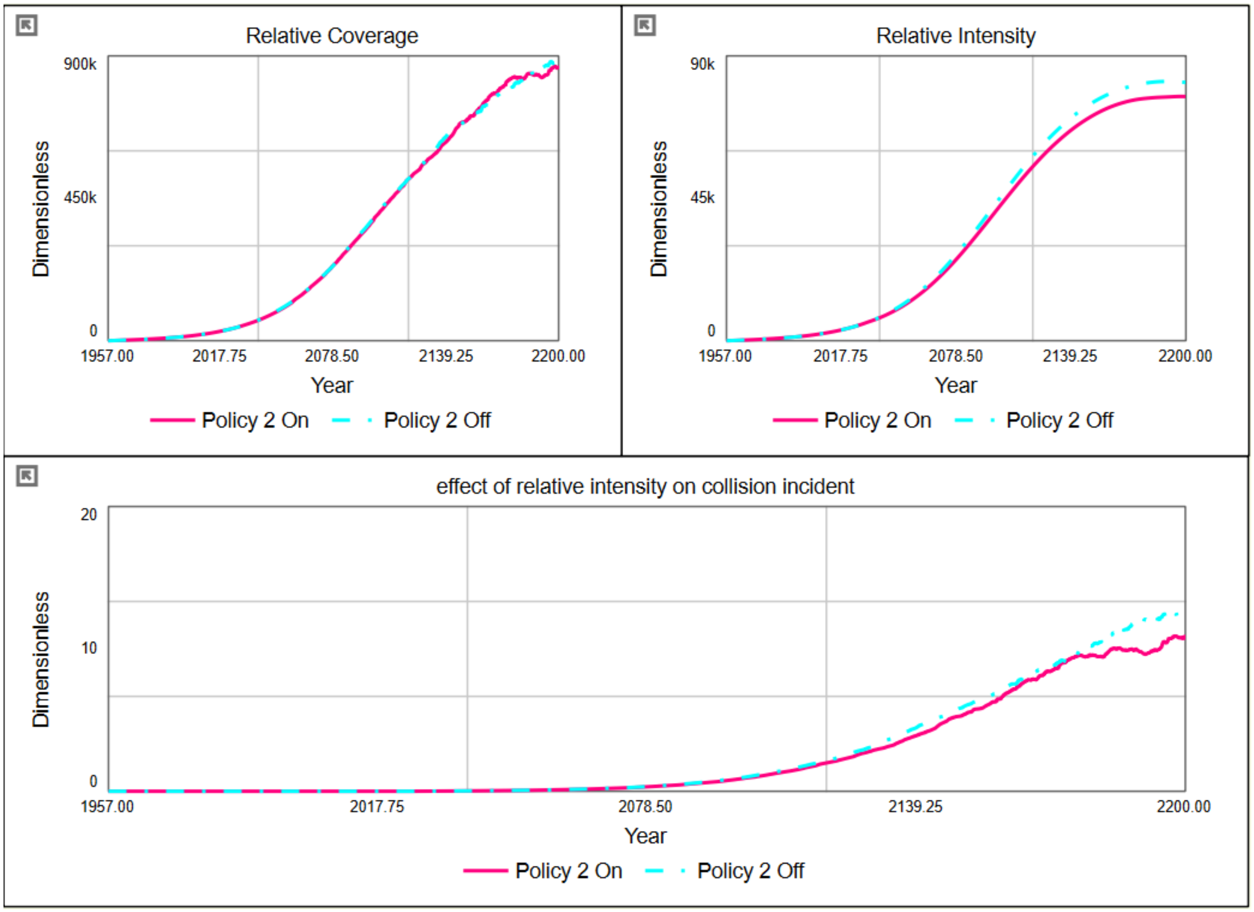
Although the cost of the policy was increasing the total cost of manufacturing and launching satellites, the long-term benefit of the policy was significant. The policy has not only resulted in a longer operational lifetime (1.3 years longer) and increased revenue over time (134 U.S. Dollars additional revenue creation) but also decreased the orbital congestion significantly. In short, the policy has significantly weakened the Kessler Loop (R2) and Cost loop (B2). The orbital congestion is far more manageable.

4.3.2. Policy Results – 2200 Business as Usual – Policy 2

In contrast to Policy 1, the second policy has not resulted in a drastic change in the system behaviour. However, the large debris creation rate reduced significantly (2.31k to 1.62k/year). Both relative coverage and relative intensity are lower in the policy on case, although the difference is hard to notice. In the long run, however, this impact could increase the magnitude of the potential consequences. The reason the second policy did not generate similar results compared to the first policy is the lower adherence rate (30%).



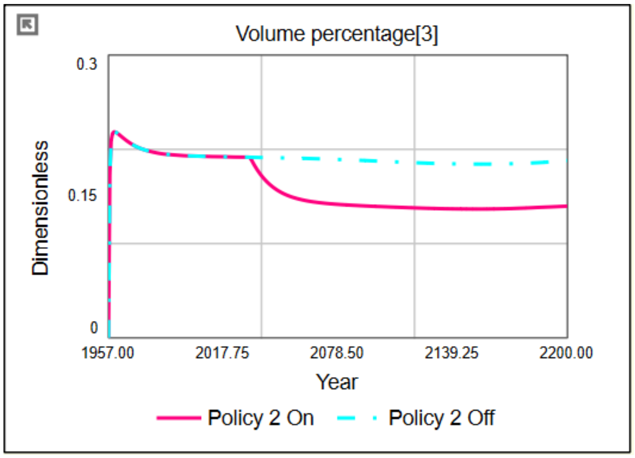
Graph 29 Policy 2 Results - 2200 - Large Debris Creation Rate



Graph 30 Policy 2 Results - 2200 - Relative Coverage, Relative Intensity, and Effect on Collision Risk

Graph 30 indicates the long-term impact of Policy 2. Towards the end of the simulation, the effect variable on collision incident risk is increasing in value in the case of policy off. Although there is some noticeable difference in the values of relative intensity, the relative coverage behaviour in both cases seems to be quite similar.

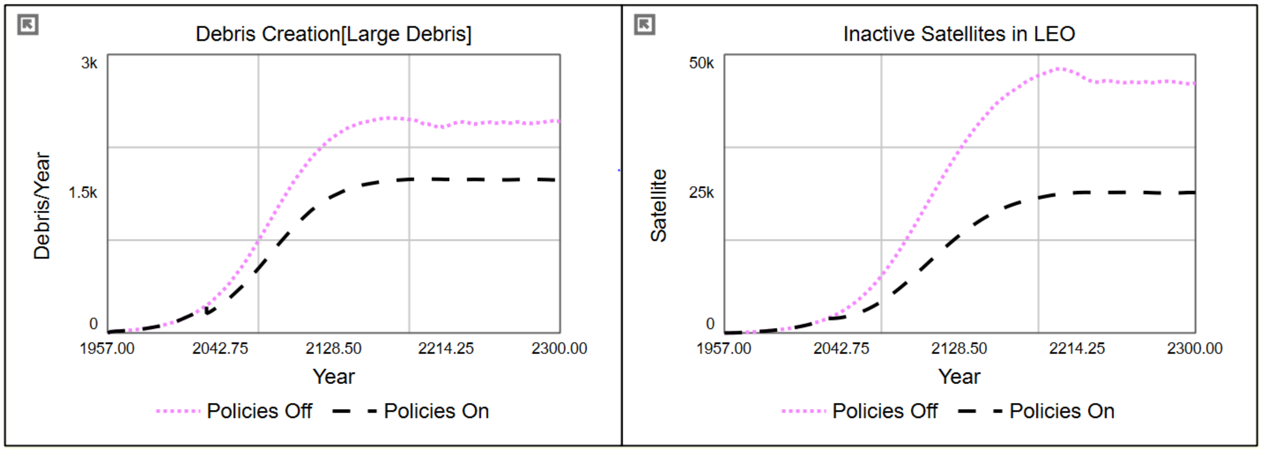
Graph 31 Policy Results - 2200 - Large Debris Volume



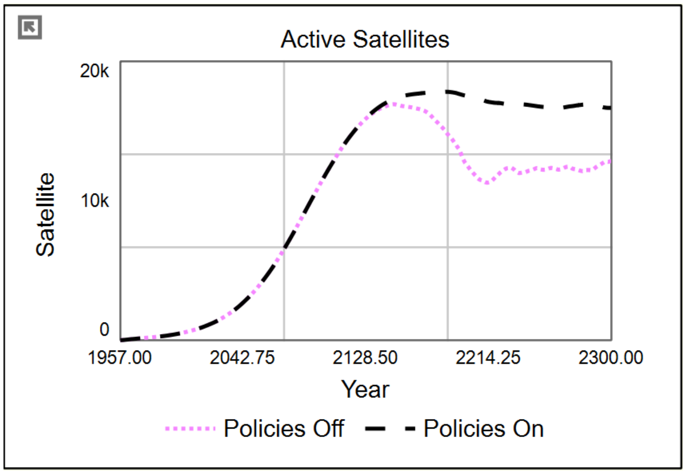
Another highlight from the second policy is the reduction in the total volume share of large debris in the orbit environment (18.8% to 14%) (see *Graph 31*). The reduction in the volume also decreases the total large debris collision figures. Overall, despite the noteworthy reduction in the policy impact, the second policy also produces better results.

4.3.3. Policy Results – 2300 Business as Usual – Both Policies

When both policies are on, the results become much more visible in the long run. Similar to the individual results presented previously both debris creation rate and inactive satellite numbers remained stable, largely unchanged.

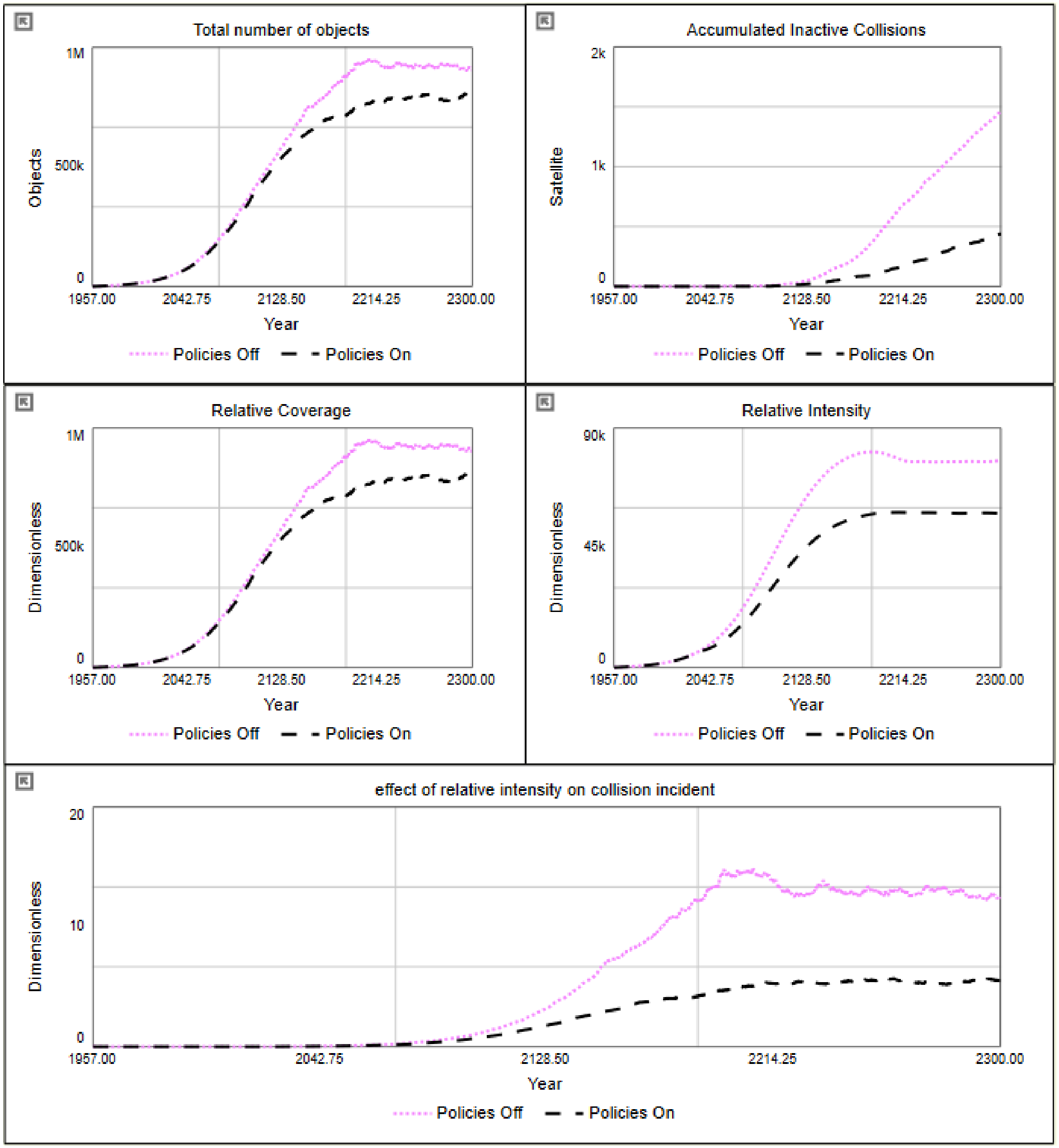


Graph 32 Policy 1-2 Results - 2300 - Debris Creation Rate and Inactive Satellites



Graph 33 Policy 1-2 Results - 2300 - Active Satellites

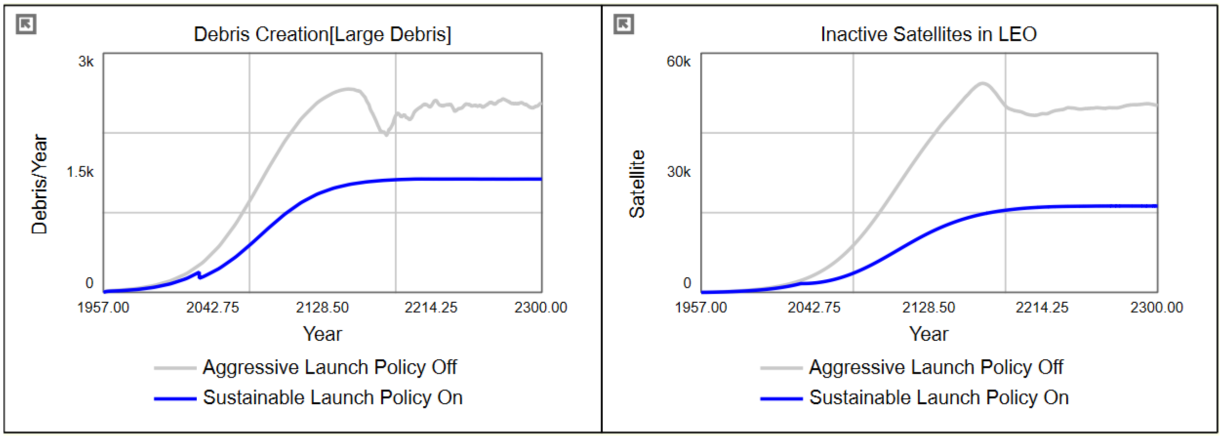
Even though the policies are activated, the business-as-usual scenario seems to be disturbing the orbital sustainability in the long run. *Graph 33* indicates how the active satellite starts fluctuating due to a stable increase in relative coverage. The previous analyses have indicated that the fluctuations are largely caused by the dominating Kessler Loop (R2). This feedback loop constantly increases the number of objects despite the stabilised satellite input after 2200. Another indicator for the R2 domination is the total volume of all objects (see Relative Intensity) is completely stable after 2200. However, the objects still increase in quantity (see Relative Coverage) due to collisions and subsequent fragmentations. This is also seen in the “total number of objects” variable, where the behaviour keeps gradually increasing after 2200 and then starts fluctuating once the Kessler Feedback loop starts affecting the system behaviour. Despite the increasing Kessler loop, the policies are still providing better outcomes in which the number of collisions both for the active and inactive satellites is significantly lower.



Graph 34 Policy 1-2 Results - 2300 - General

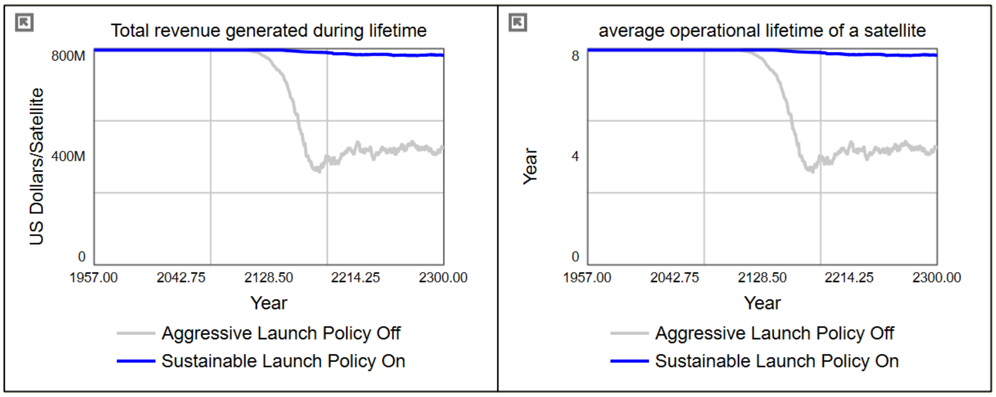
4.3.4. Worst/Best-Case Scenario Policy with Aggressive and Sustainable Launch Scenario

The final analysis of the policy section compares the absolute best and absolute worst-case scenarios in the longest possible time horizon. In the best-case scenario, the model is simulated within the sustainable launch scenario and both policies in place, as the worst-case scenario, the model is simulated within the aggressive launch scenario with no policies. The results are expectedly exceedingly different.

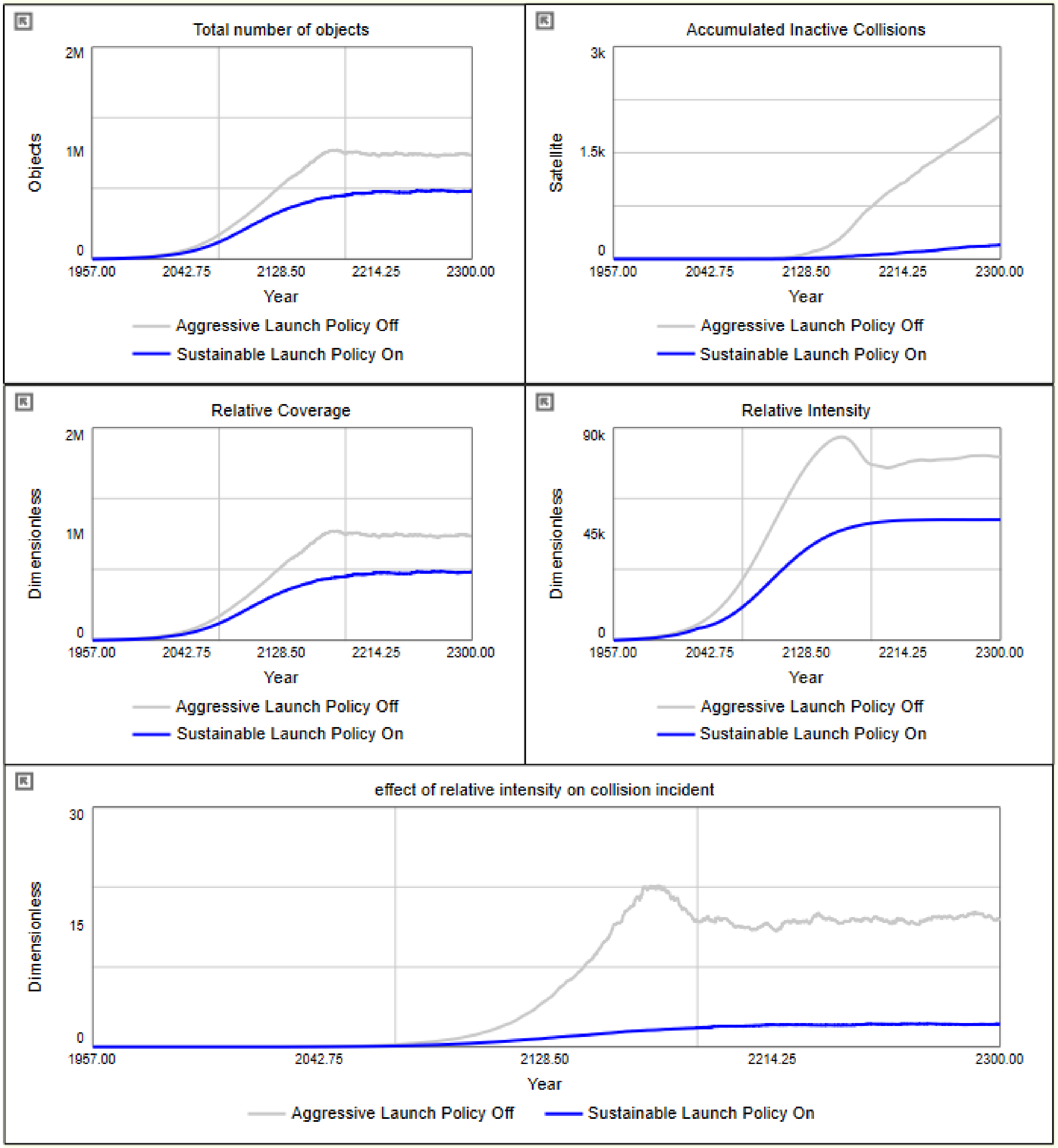


Graph 35 Best- and Worst-Case Scenario Results - Debris Creation and Inactive Satellites

First of all, the large debris creation rate is 70% lower in the best-case scenario, compared to the worst. The difference is far more significant in the case of inactive satellites in which the value is more than twice in the worst case (46.9k to 21.7k). In all graphs, the results are exceptionally in the favour of best-case scenario. The orbital environment is stable, the behaviour is largely dominated by the first reinforcing loop (R1 - industrial growth) and the first balancing loop has a minor effect in the behaviour. The system behaviour is on a very stable equilibrium. The Kessler loop (R2) and the Cost loops (B2) are almost unnoticeable. The satellite lifetime only decreases by a quarter of a year (7.75 years). The revenue generation is only 25 Million U.S. Dollars less than the initial value (800 Million).



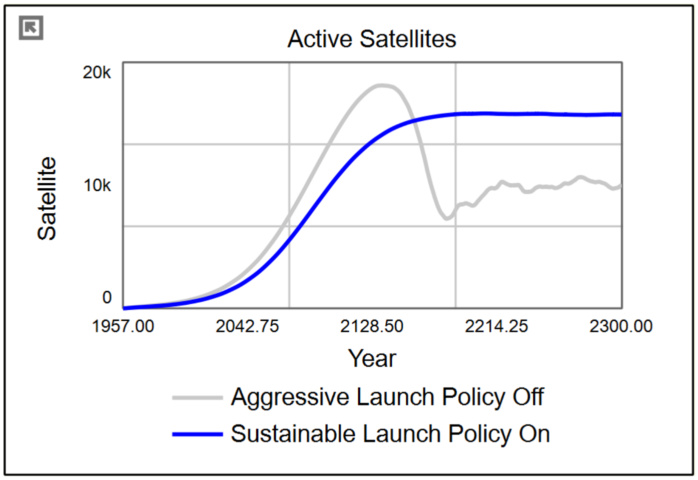
Graph 36 Best- and Worst-Case Scenario Results - Revenue Generation and Lifetime



Graph 37 Best- and Worst-Case Scenario Results - General

In the case of the Aggressive Launch with no policies, the environment is largely disrupted by the Kessler Loop (R2) and very unstable due to constant fragmentation and fluctuations in the price change and the new launches. The satellite lifetime is as low as 4 years. Collision values for inactive satellites are 10 times more than the Sustainable scenario.

Finally, the space infrastructure is largely destructed due to the (R2) Kessler Loop and the subsequent reduction in the launch rate due to increased cost and reduced lifetime (B2).



Graph 38 Best- and Worst-Case Scenario Results - Active Satellites

4.3.5. Additional Policy Recommendation – Active Debris Removal

The international community is focusing on limiting the growth of orbital debris more than ever. The above-mentioned policies and beyond have already been discussed and implemented to a certain scale. However, another seriously considered debris mitigation policy is Active Debris Removal (ADR) (Bonnal, et al., 2013; Braun, et al., 2013; Liou & Johnson, 2008). ADR is a debris avoidance method that involves launching specific spacecraft to capture non-operational objects with a relatively long lifespan and return to the Earth's atmosphere to lessen the collision risk. Some argue that the Kessler Syndrome is an environmental fact only to get worse after the major collisions occurred since 2007 (Bonnal, et al., 2013). At this point, ADR is considered a serious method to clean up orbit in an active way to avoid further large fragmentation in orbit. Just before completion of this study, two major incidents featured the international headlines concerning the threat of space debris on space infrastructure and humans both in space and on Earth.

The first issue is the Chinese rocket body from Long March 5B, which re-entered the atmosphere on the 8th of May 2021 (Howell, 2021). Given the uncertainties on where the rocket may re-enter, the international community has drawn attention to the importance of avoiding large debris due to the high risk they impose during unknown and uncontrolled re-entry and the potential danger they present if they land on human settlements. The second debris headline was about a collision that occurred on the International Space Station (ISS). On May 12, during a routine inspection, the astronauts in the space station have discovered a hole on Canadam2 that caused my tiny space debris impossible to track (CSA, 2021). Such small debris is fast enough to puncture through practically any unprotected spacecraft.

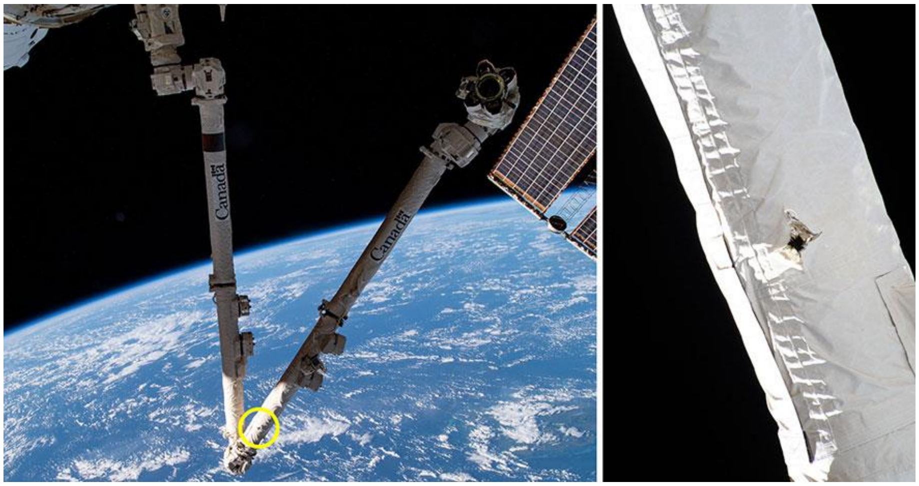


Image 2 Hole on Canadarm2 punctured by Small Debris (Credit: NASA / Canadian Space Agency)

At this point, as some argue, in addition to the passive/proactive measures to prevent orbital debris, a more aggressive approach, ADR, must be *"seriously considered to remediate the environment*" (Liou, et al., 2010). Further Liou et al. (2010) argue that combining ADR measures in parallel with the other mitigation measures is the only way to preserve the long-term sustainability of low earth orbit environment for future generations. This study on the other hand argues that, in fact, ADR is required for a stable LEO environment. However, the international community, first, must focus on successfully creating a legal framework incorporating binding regulations for proactive debris mitigation measures. The population of debris in LEO could be controlled much more efficiently by regulating the future launches and subsequent debris creation caused by new launches. Although this study does not include a policy & implementation structure for ADR methods. It is important to emphasise the importance of ADR policies for the long-term sustainability of orbital resources. Remediation of the orbital environment depends heavily on international cooperation. Without international cooperation, none of these policies can be implemented on a large-scale and thus cannot have a considerable impact in the long-term.

5. Limitations & Conclusion

Similar to any future orbital environment simulations, this study is also relying on a number of assumptions. These assumptions vary from how the collisions are calculated and how many objects get generated as a result of these collisions to how the orbital decay effect causing a balancing role in the environment. In this study, moreover, a series of cost calculations were also presented both in the explanatory and the policy model structures. This section of the study elaborates on these assumptions and the limitations they pose on the simulation results. Moreover, an overall summary of the findings and conclusion remarks are also presented.

5.1. Primary Model Assumptions

→**Collision Calculation:** As mentioned previously, in contrast to the common method of calculating collisions (Pardini & Anselmo, 2017; Klinkrad, 1993), this thesis project does not consider the 'cross-sectional' area for estimating the collision probability. Instead, the model assumption is made primarily based on the object's volume. Moreover, in collision calculation, various other parameters should be included in correctly estimating the time, place, and position of the collision. In addition to the cross-sectional area of objects, altitude, velocity, trajectory of objects should also be taken into account for accurate outcomes. Higher precision in the estimation of orbital collision risk requires higher competitional power. This study only attempts to observe a potential Kessler Syndrome in orbits near the Earth and how this could affect the long-term sustainability in orbit and the space infrastructure therein. Therefore, categorising the object populations in different altitudes and other important parameters are not considered within the scope of this thesis.

→ **Orbital Decay Time:** The model assumption on the orbital decay time is 8 years. Moreover, this study's target range in the low earth orbit is between the most populated areas between 400-1200 km altitudes. However, the effective orbital lifetime between these altitudes varies significantly. Objects in 400km have roughly 1 year of lifetime, whereas objects at an altitude of 1200km can have a lifetime of hundreds of years, if not thousands (Haneveer, 2017). The study's assumption on the orbital decay delay time therefore could be problematic for objects in relatively higher altitudes. Since the objects were not classified in different stocks, for different altitudes, this assumption was made for the sake of simplicity. An average of a 20-year lifetime is determined based on the assumptions made in similar studies in the literature (Drmola & Hubik, 2018).

→**Cost Calculation:** The model assumption on the satellite cost is also one dimensional and simplified, meaning that the cost variation for a different type of satellite was disregarded and an average cost for satellite manufacturing and launching was assumed in the model structure. The cost of satellites alters depending on the purpose, material used, weight, and the designated altitude. In this study, however, these aspects are not considered. An average cost for an average satellite is determined based on the relevant literature.

→**Policy Foundation & Structure:** The model policy structure necessitates a major policy shift in the context of international space governance. The proposed institutional body, namely the "International Space Agency" (ISA), has not been mentioned or considered by any major spacefaring country. In fact, as of today, the most prevalent example of international cooperation takes place in the International Space Station Programme established by the Space Station Intergovernmental Agreement in 1998 (NASA, 2020). For a programme like ISA to be founded, there need to be various legal arrangements and collective political action. Moreover, the space activities need to be carried out and under the auspices and supervision of such a legal and/or institutional body.

The policies presented in this thesis, therefore, require the commitment of member countries and their financial assurance in implementing designated debris mitigation methods. The idea of establishing ISA, in the context of debris mitigation, is essentially symbolic. This collaboration can take place in a form of legally binding agreements or an international interagency organisation (Global Version of ESA). Given the uncertainties in future collaboration and law-making, as well as the wicked nature of the space debris problem, the policies offered in this thesis require developments in both technical and political spheres of the international space governance regime.

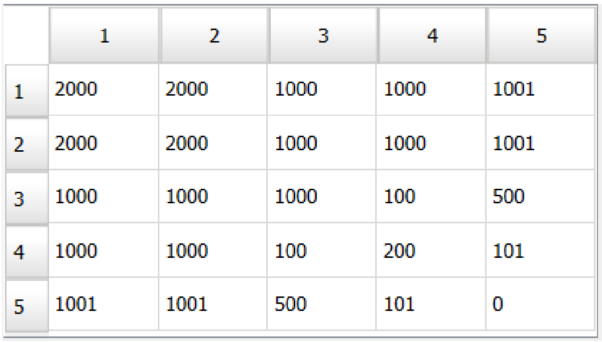
Provided that the ISA is founded (or any other international cooperation regime in space), the mitigation strategies must be implemented in a way where monitoring of launching activities should be very well established. The governing body must have conflict resolution mechanisms in addressing the problems encountered between the stakeholders. Moreover, the body must ensure that sanctions are properly instigated in case of violations.

The reason for articulating the details of the proposed international governance regime is the fact that the debris problem is very much a public policy problem in its foundation. Scientific approaches to the problem contribute to the understanding of space debris and its future development. However, approaches with debris mitigation and removal proposals, in general, not only undermine the difficulties of establishing such a regime, which is essential in implementing these proposals, but also disregard the potential catastrophic collisions in the near future triggered by intentional practices, such as ASAT missions.

At this juncture, the model policy structure implements a series of obstacles in replicating similar difficulties that could potentially be encountered in formulating this regime. First, approximately 12 years of delay time was introduced to the model structure. This delay time is utilised based on the assumption of the lengthy and challenging process of constituting ISA or any similar governing body. Second, the model structure introduced an adherence rate in which, some stakeholders assumed to be not participating in the practices enforced by this regime. The adherence rate is determined to be 70% for the satellite deorbiting policy, whereas only 30% determined for the large debris removal policy.

Moreover, in terms of the technical properties of model policy structure, several limitations require further attention. Firstly, the fuel requirement for both the satellites and large debris is determined to be 10% of the total mass of the spacecraft. However, similar to the other limitations shown above, the prepollent requirement for deorbiting varies depending on the altitudes and the type of propulsion system used during the re-entry mission. The fuel requirement increases linearly for high altitudes (Wittig, 2015). The assumed 10% fuel ratio to mass is therefore one of the other primary assumptions the model structure implemented. Moreover, the model structure considers the chemical propulsion system to be used in the missions. However chemical propulsion systems more expensive compared to electrical and ED tether-based propulsion systems (Guido, 2014). The pricing of the policy could therefore vary significantly for different types of deorbiting propulsion systems. Secondly, in addition to the fuel type and the propulsion system, the policy incorporates another cost structure for the implementation of deorbiting strategies through the “Additional Hardware and Infrastructure for Deorbiting Missions” variable. The model assumption on this cost is 1 million U.S. Dollars per mission. Again, the cost of such structural changes on satellites may result in additional expenses in all stages of a mission.

→**Debris Creation (Launch & On-Orbit):** The model assumption on the debris creation for launches and collision constitutes another profound impact on the simulation results. The model assumes that every launch result in the creation of 1 large, 3 medium, 10 small-sized debris in orbit. Every stage presents a potential for further debris generation (Anz-Meador & Shoots, 2019). The model assumes that only 1 large rocket body, in general, is released to the orbit environment. Following that, 3 medium debris assumed to be generated as a result of break-ups and de-coupling. Finally, 10 small-sized debris is assumed to be created as a result of all on-orbit activities. These values vary significantly based on the type of launch and the number of stages used on the rocket. Therefore, the model structure on debris creation for launches is simplified. Additionally, debris creation on-orbit collisions reflected in matrices. The below graph indicates an example debris creation matrix for small debris. Based on this graph, for example, if object 5 (Small Debris) and object 2 (Inactive Satellite) collide, the impact is assumed to generate 1001 small debris. However, it is impossible to predict how many debris could such a collision possibly create. In some cases, the impact could be so minor just like in the case in the case of Canadarm2 (See *Image 2),* where the debris simply punctures through the spacecraft without causing a lot of fragmentation. It is impractical to estimate how collisions can take place and how many debris will be created as a result. A simplification is therefore very much required in the completion of the debris sector of this model.



	1	2	3	4	5
1	2000	2000	1000	1000	1001
2	2000	2000	1000	1000	1001
3	1000	1000	1000	100	500
4	1000	1000	100	200	101
5	1001	1001	500	101	0

Table 2 Small Debris Creation Matrix

5.2. Concluding Remarks

The purpose of this thesis was to (1) indicate the factors influencing the number of debris in low earth orbit; (2) to explore the fundamental characteristics of orbital collisions and their impact on the orbital congestion; (3) to understand the ramifications of increased launch rates and excessive use of orbital resources on long-term environmental sustainability and space infrastructure; (4) to discover potential policy interventions that could reduce the long-term impact of space debris in low earth orbit and further to find robust implementation methods to actualise these policies.

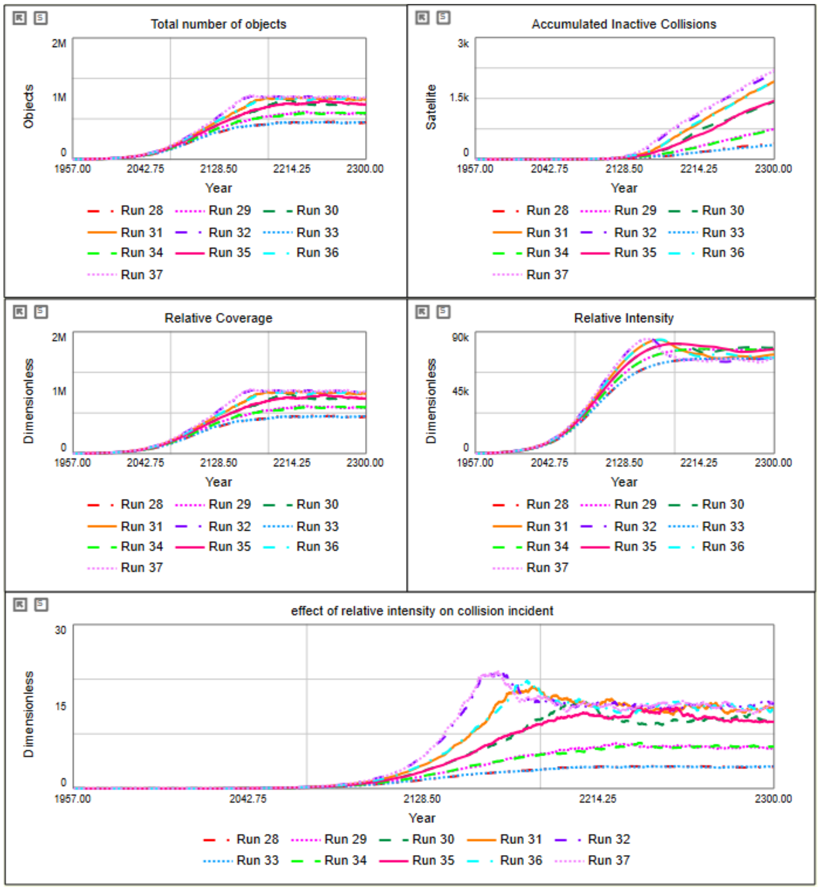
The model results indicated that the growth in the industry is the initial cause for the increase in the number of debris. In the following decades, however, with the increased collision probability, the growth is likely to be dominated by the cascading collisions, suggested by Kessler (1978). Orbital debris, in its nature, is very unpredictable and poses a number of uncertainties for quantitative studies like this. One thing is certain, the model behaviour generates a chaotic picture for the orbital environment and the satellite infrastructure in the long run when the launch rate is increased. Debris mitigation methods, therefore, must be fastened with controlled launch rates. In addition to the proactive debris remediation methods, active debris removal methods must also accompany mitigation strategies in an effort to keeping the common heritage of mankind sustainable, in the orbital medium.

Appendix – A Sensitivity Analyses

Explanatory Model Sensitivity Analyses

1. Average orbital Decay Time

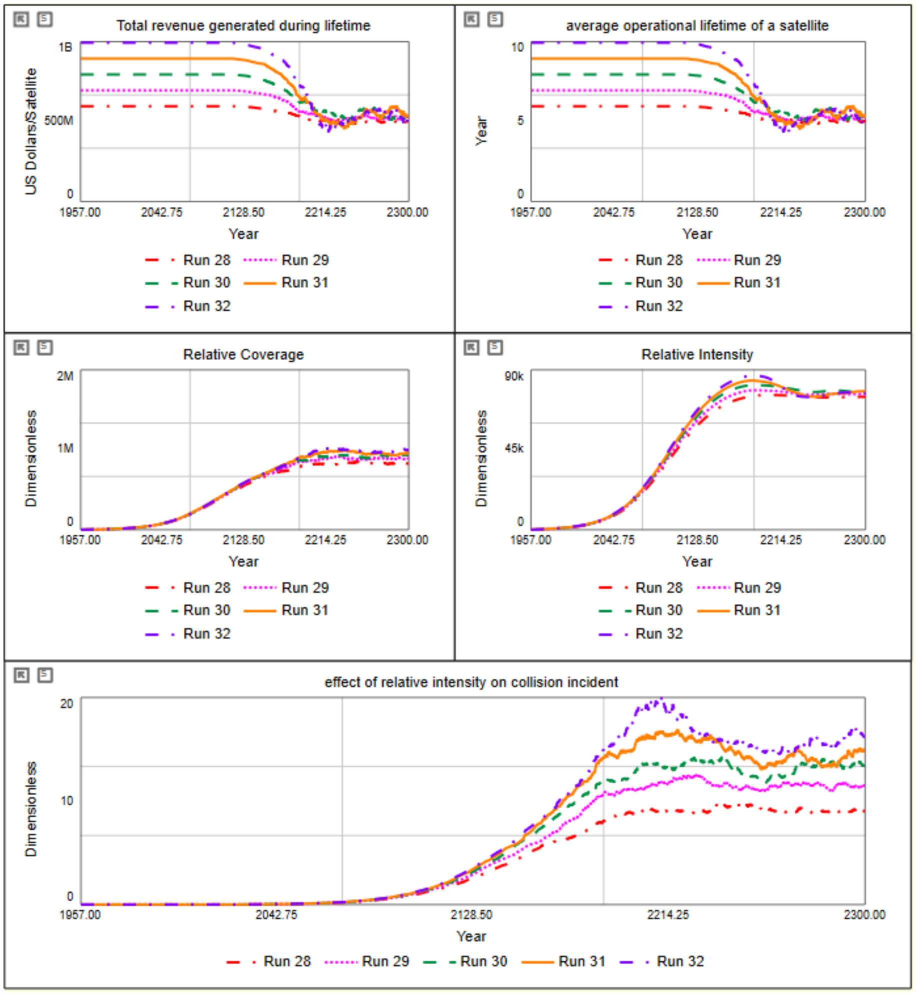
Run 28	18
Run 29	19
Run 30	20
Run 31	21
Run 32	22
Run 33	18
Run 34	19
Run 35	20
Run 36	21
Run 37	22



→Orbital decay time constitutes the most fundamental balancing factor in the orbital environment. It is a natural effect that reduces the velocity of objects in orbit through fraction and solar activities. The orbital decay factor varies depending on the altitude of objects. Objects closer to the earth's atmosphere are subject to more fraction and therefore their lifetime shortens. The lifetime of objects increases exponentially for higher altitudes. In this sensitivity analysis, it is possible to observe this impact. The shorter the orbital lifetime, the lower the population in orbit. For higher populations, the congestion rate is higher and thus the collisions are more likely. The above graph shows that RUN 32 and 37 have the longest orbital decay delay. Therefore, the congestion is harsher, and the subsequent collisions cause a higher fragmentation rate, in which the population is highest. The sensitivity test, in this case, has not resulted in unexpected behaviour.

2. Initial Satellite Lifetime

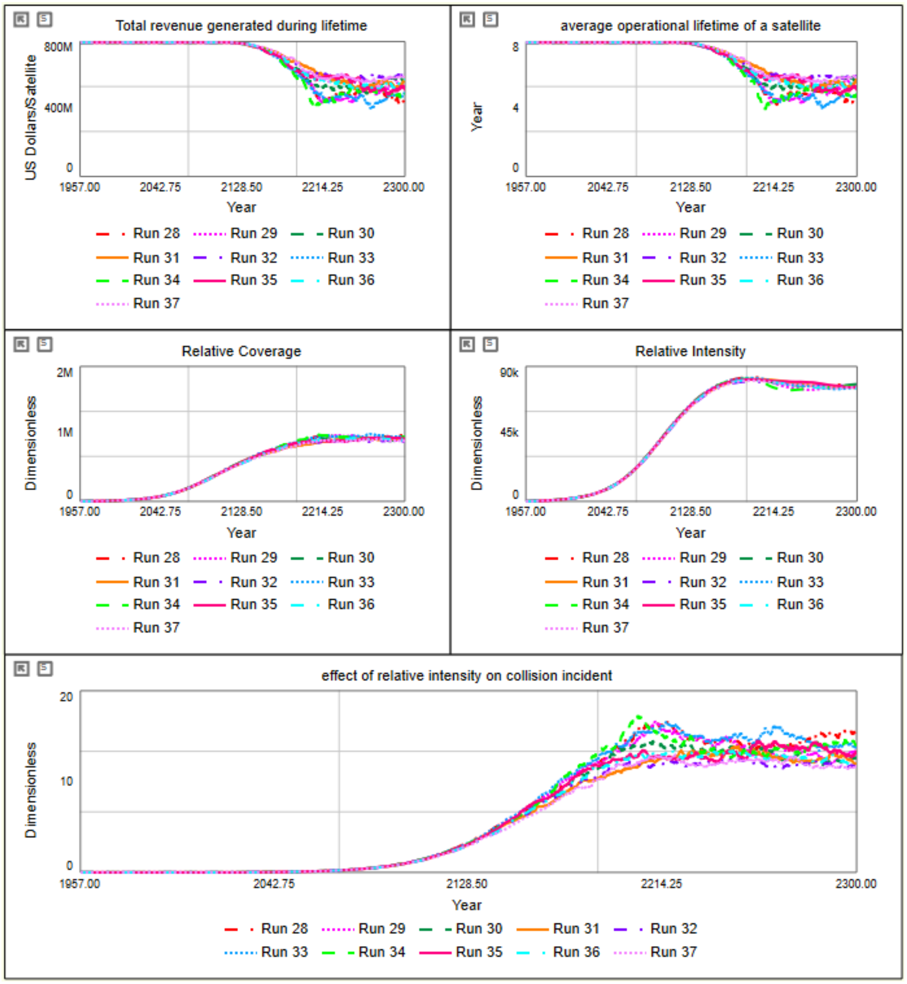
Run 28	6
Run 29	7
Run 30	8
Run 31	9
Run 32	10



→ Satellites have a certain lifetime in earth orbit. The documentation section describes what influences the lifetime of satellites. However, the average satellite lifetime chosen for this study is 8 years. For the longer lifespan duration, the population will be naturally higher. It is possible to observe that the higher the lifespan the more revenue there is for the initial stages. However, the congestion reaches a cascading fragmentation rate (R2). As suggested by Kessler (1978), the cascading collision effect can create a chain reaction in the orbital environment that can result in loss of significant space infrastructure. Run 32 shows in the "effect of relative intensity on Collision incident" that the longer the object lifetime, the higher the collision risk.

3. Average Hardware and infrastructure Expenses

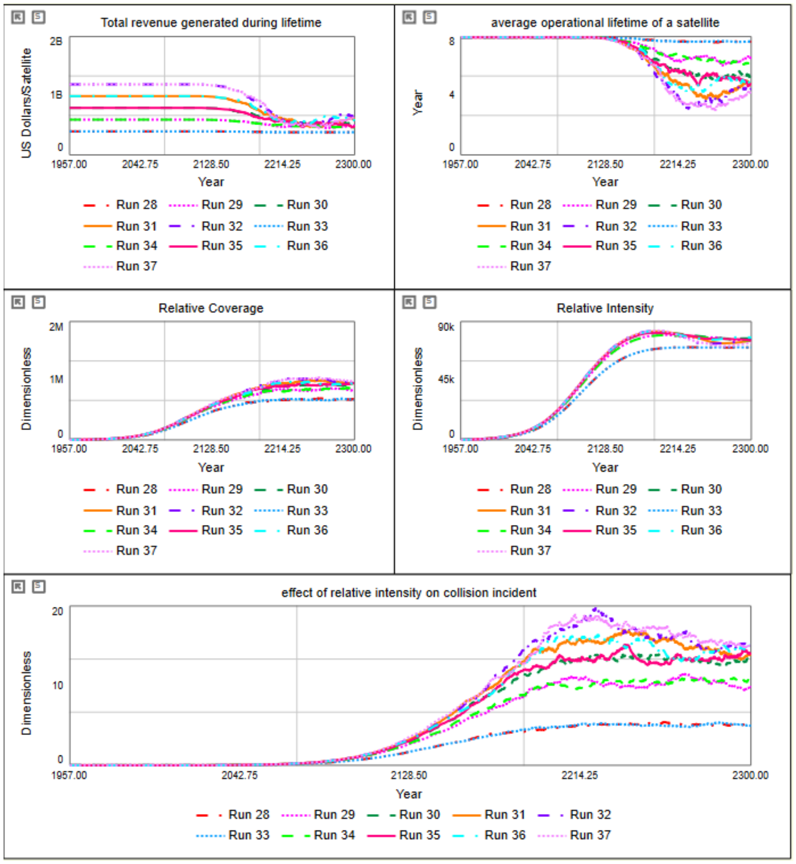
Run 28	250000000
Run 29	275000000
Run 30	300000000
Run 31	325000000
Run 32	350000000
Run 33	250000000
Run 34	275000000
Run 35	300000000
Run 36	325000000
Run 37	350000000



→ The model behaviour does not produce an unexpected behaviour for the external cost variable of "average hardware and infrastructure expenses".

4. Average Service Value Provided Per Satellite

Run 28	50000000
Run 29	75000000
Run 30	100000000
Run 31	125000000
Run 32	150000000
Run 33	50000000
Run 34	75000000
Run 35	100000000
Run 36	125000000
Run 37	150000000

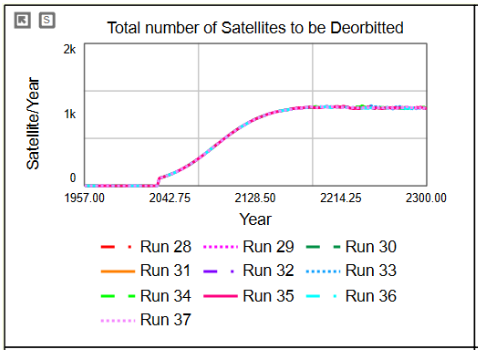


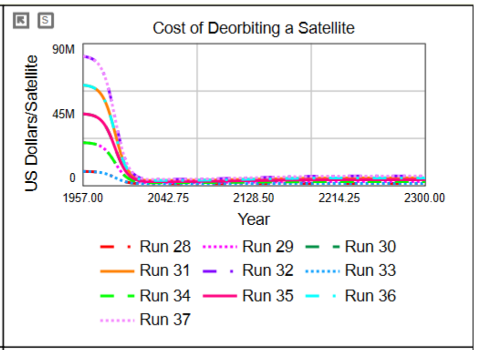
→ Every satellite generates revenue depending on its service type and its effective lifetime in orbit. The feedback loop on cost is structured in a way that the number of launches increases based on the revenue increase. Therefore, Run 37 and Run 32, with the highest revenue amount, produce the highest number of objects in orbit. This affects the collision risk in the long term. Although having the highest revenue creation, the simulated 32 and 37 run results generate the shortest lifespan due to increased congestion. The sensitivity results, therefore, generate expected results.

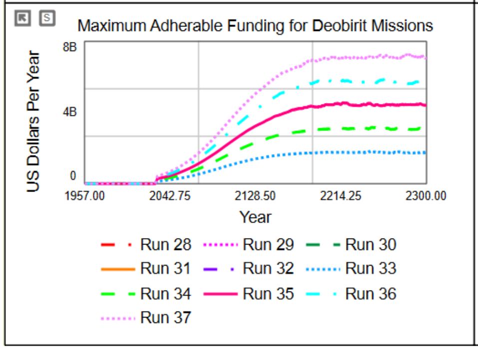
Policy Model Sensitivity Analyses

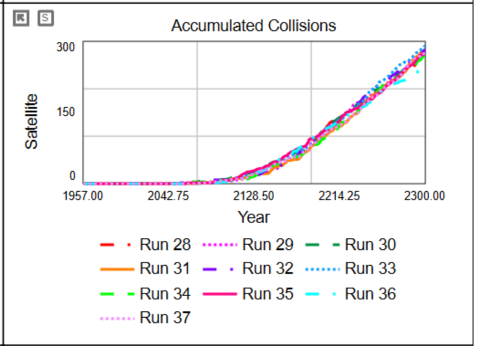
→Ratio of Fuel Required per Satellite

Run 28	0.05
Run 29	0.1625
Run 30	0.275
Run 31	0.3875
Run 32	0.5
Run 33	0.05
Run 34	0.1625
Run 35	0.275
Run 36	0.3875
Run 37	0.5



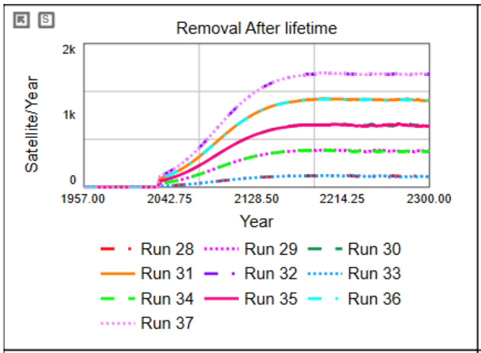


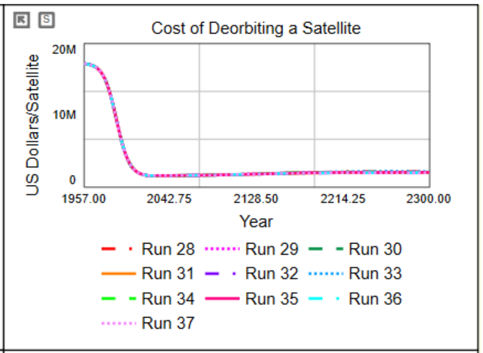


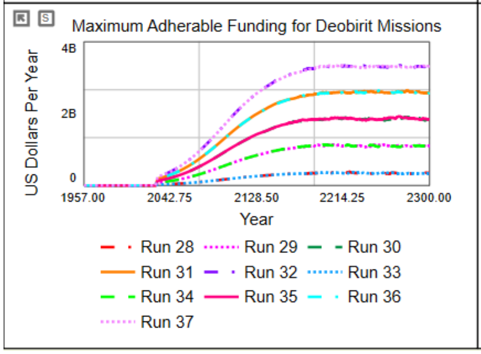


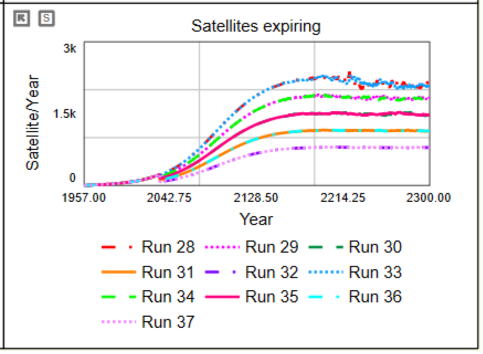
→Adherence Percentage

Run 28	0.1
Run 29	0.325
Run 30	0.55
Run 31	0.775
Run 32	1
Run 33	0.1
Run 34	0.325
Run 35	0.55
Run 36	0.775
Run 37	1



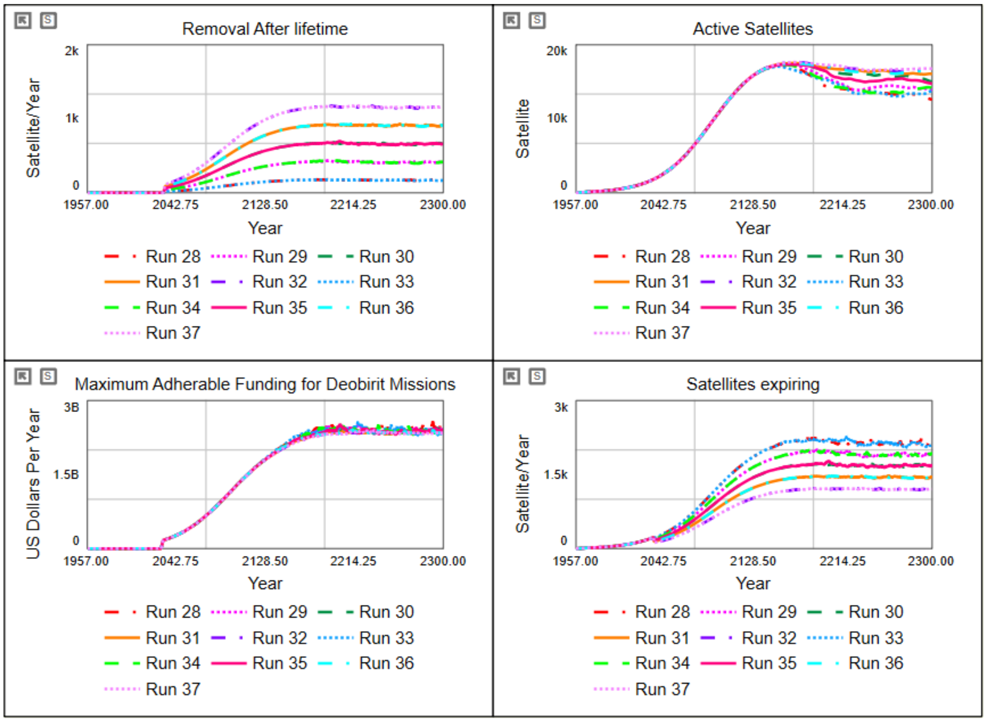






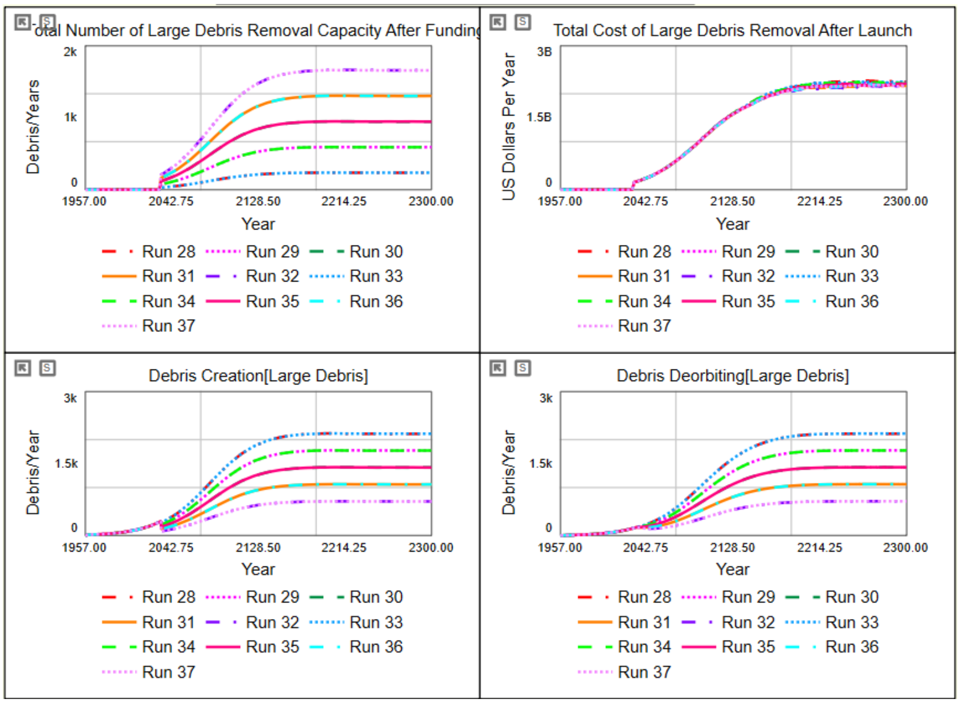
→Success Rate of Deorbit Missions

Run 28	0.15
Run 29	0.3625
Run 30	0.575
Run 31	0.7875
Run 32	1
Run 33	0.15
Run 34	0.3625
Run 35	0.575
Run 36	0.7875
Run 37	1



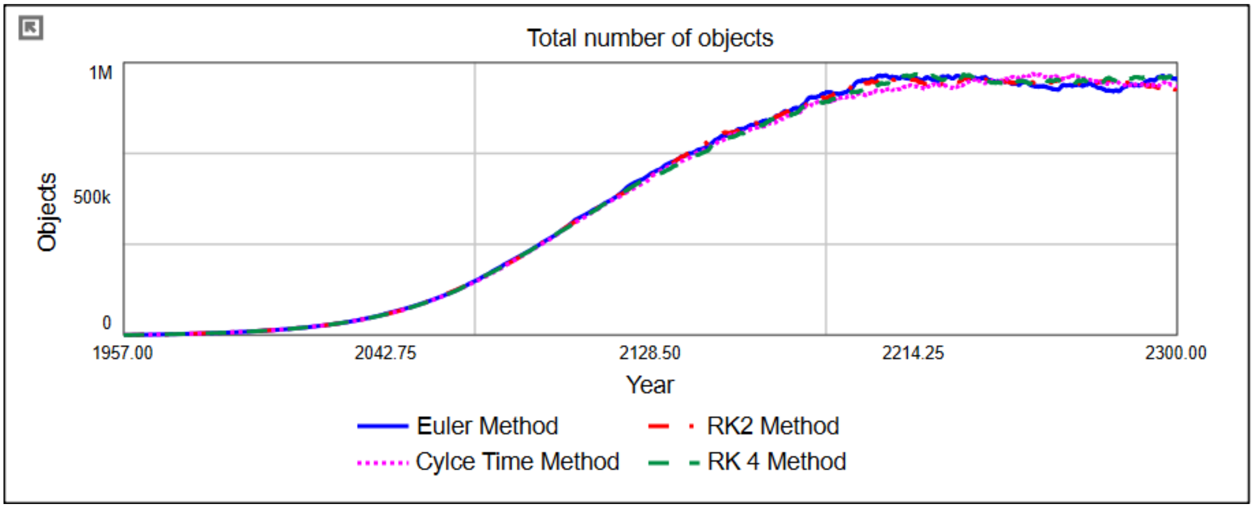
→Rate of Acceptance for Large Debris Removal After Launch

Run 28	0.1
Run 29	0.25
Run 30	0.4
Run 31	0.55
Run 32	0.7
Run 33	0.1
Run 34	0.25
Run 35	0.4
Run 36	0.55
Run 37	0.7



→Integration Method Tests

The model has been tested in different integration methods and the observed behaviour is similar in all four simulations. The model has also been tests in different DTs and the produced behaviour is similar.



Appendix – B Documentation

Variable Properties	**Units**
Accumulated_Collisions(t) **Equation:** Accumulated_Collisions(t – dt) + (Collided_Satellites) * dt **Description:** This stock demonstrates the cumulative number of active satellites involved in collisions.	Satellite
Accumulated_Inactive_Collisions(t) **Equation:** Accumulated_Inactive_Collisions(t – dt) + (Collided_Inactive_Satellites) * dt **Description:** This stock demonstrates the cumulative number of inactive satellites involved in collisions.	Satellite
Active_Satellites(t) **Equation:** Active_Satellites(t – dt) + (new_satellite_launches – Satellites_expiring – Collided_Satellites – Removal_After_lifetime) * dt **Description:** This stock demonstrates the number of active satellites in the low earth orbit. As the new satellite launch the number increases.”Collided Satellites” outflow decreases the number of satellites though the collision calculations determined in the collision sector. “Satellites Expiring” outflow decreases the stock value as the satellites reach at their operational lifetime. And some satellites are removed through “Removal After Lifetime” outflow. Similar to the other primary stocks of this System Dynamics Modelling project, this stock has also a key role in model structure and behaviour. Increases in the number of satellites will not only cause increase in the total revenue generated by the satellite industry and the other industries directly or indirectly connected with satellites services but it also increases the potential debris due to launches. Potential revenue is attracting more investment and therefore more satellite launches. However, as the number of man-made objects increase, the orbital environment becomes less and less accommodating for the new objects.	Satellite
Debris_in_LEO[Debris_Size](t) **Equation:** Debris_in_LEO[Debris_Size](t – dt) + (Debris_Creation[Debris_Size] + Debris_Creation_Caused_by_Collision[Debris_Size] – Debris_Deorbiting[Debris_Size] – Collided_Debris[Debris_Size]) * dt **Description:** Low earth orbit debris stock is arrayed by the object size. It increases through the “Debris Creation” and “Debris Creation Caused by Collision” inflows and decreases through “Collided Debris” and “Debris Deorbiting” outflows. As the time horizon of this study starts at 1957, the year which first man-made object reached to the outer space, it initialised to 0.	Debris

Debris stocks are an essential part of this study as it directly contributes to the total number of objects and the volume which they occupy in the orbital environment. Increases in debris stock ultimately cause a major proliferation of debris in low earth orbit which threatens the sustainability of the low earth orbit. Therefore, these stocks play a central role in both problem definition and policy creation of this study.	
Inactive_Satellites_in_LEO(t) **Equation:** Inactive_Satellites_in_LEO(t – dt) + (Satellites_expiring – Satellites_Deorbiting – Collided_Inactive_Satellites – Active_Removal) * dt **Description:** This stock refers to objects which are no longer operational and still in the orbital environment. The number of inactive satellites increase as the satellites expire or malfunction for various reasons and therefore is not possible to manoeuvre or deorbit by using the propellant on board. It decreases through natural decay and collisions with other objects. Inactive satellites, along with other debris, constitute large risks as they are not controllable. This is because, similar to active satellites and debris stocks, they increase the total number of objects and their volume in the low earth orbit.	Satellite
Satellites_under_construction(t) **Equation:** Satellites_under_construction(t – dt) + (Commercial_Satellites – new_satellite_launches) * dt **Description:** This stock shows the number of satellites under construction. As the new commercial satellites added to the sector, this stock increases in value. This stock does not contribute to the total number of objects in low earth orbit as it only indicates the satellites before they are launched.	Satellite
Active_Removal **Equation:** MAX(Inactive_Satellites_in_LEO*Active_Satellite_Removal_Rate, 0) **Description:** Active Debris Removal decreases the number of inactive satellites and is determined by the "Active Satellite Removal Rate".	Satellite/Year
Collided_Debris[Debris_Size] **Equation:** Collided_Debris_Result/DT **Description:** This outflow subtracts the number of debris that have collided with other objects. It is affected by the "Collided Debris Result" variable which calculates the number of debris involved in the collisions. The value is divided by the DT to accurately identify the number of debris involved in collisions.	Debris/Year
Collided_Inactive_Satellites **Equation:** collided_inactive_satellites_result/DT **Description:** This outflow is affected by the "Collided Inactive Satellites" and decreased the "Inactive Satellite" stock. It flows into the "Accumulated Inactive Collisions" stock.	Satellite/Year

Inactive Satellite collisions are calculated in the collision sector. Division by DT in the equation ensures that the number of inactive satellites involved in collisions are calculated precisely.	
Collided_Satellites **Equation:** collided_satellites_result/DT **Description:** Similar to Collided "Collided Inactive Satellites" this flow subtracts the "Active Satellites" that are collided with other objects. The equation involves a division by DT which ensures that Collision figures are calculated correctly.	Satellite/Year
Commercial_Satellites **Equation:** Normal_Construction_Rate*effect_of_cost_revenue_ratio_on_new_launches **Description:** This inflow is affected by the "Normal Launch Rate" and the "Effect of cost revenue on new launches" variable. As the effect increase the launch rate per year will increase as well. Decreased rate will result in lower launch rates per year.	Satellite/Year
Debris_Creation[Large_Debris] **Equation:** (new_satellite_launches*debris_creation_per_Launch[Large_Debris])-Total_Number_of_Large_Debris_Removal_Capacity_After_Funding **Description:** Debris Creation inflow constitutes the number of debris to be added to the Debris stocks. Three sized debris, large medium and small, is added to the stock through this inflow. The equation demonstrates that for every satellite launch, there will be a number of objects released into the low earth orbit. These object types are arrayed by their sizes and each object is multiplied with the corresponding number of creations for every launch. An exception is made for the large debris which is ultimately affected by the policy intervention. The policy affects the number of large debris creation per satellite, and it subtracts the total number of large debris to be removed after launch as a result of funding from the overall large debris creation.	Debris/Year
Debris_Creation[Medium_Debris] **Equation:** new_satellite_launches*debris_creation_per_Launch[Medium_Debris]	
Debris_Creation[Small_Debris] **Equation:** debris_creation_per_Launch[Small_Debris]*new_satellite_launches	
Debris_Creation_Caused_by_Collision[Debris_Size] **Equation:** debris_creation_result/DT **Description:** This inflow adding up the debris that is caused by collisions. The inflow is arrayed by the size of debris. Additional debris are calculated in the collision sector. The value is divided by the DT to calculate the accurate number of debris creation.	Debris/Year
Debris_Deorbiting[Debris_Size]	Debris/Year

Equation: Debris_in_LEO/Average_orbital_Decay_time **Description:** This outflow subtracts the number of debris subjected to the “Average Orbital Decay Time” variable. Every object in space is affected by the gravitational pull generated by our planet. The delay effect generated by the orbital decay factor, all debris are slowly decaying back to the Earth’s atmosphere and ultimately burning during re-entry. At the time of writing this thesis, a core module of 5B rocket launched by the Chinese Space Agency was about to de-orbit back to earth. It created massive speculations over where it was going to re-enter. Long March 5B rocket is a rare example of how impactful rocket bodies can be not only in orbital environment but also during re-entry (Howell, 2021; Rourke, 2021).	
new_satellite_launches **Equation:** Satellites_under_construction/satellite_construction_time **Description:** This outflow connects “Satellites Under Construction” with “Number of Satellites in LEO”. Satellites under construction are added to the active satellites in orbit after the completion delay.	Satellite/Year
Removal_After_lifetime **Equation:** MIN(((Active_Satellites*”Satellite_De-orbiting_Rate”)/average_operational_lifetime_of_a_satellite), 0)+Total_number_of_Satellites_to_be_Deorbitted **Description:** This outflow is initially affected by the “Satellite De-orbiting Rate”. If the policy is activated, the removal rate changes based on the funding generated for de-orbiting missions. “Average Operational Lifetime of a Satellite” variable ensures that de-orbiting activities only for the satellites which completed their lifetime. The MIN function ensures that the flow is not subtracting more satellites than there is in the stock of Active Satellites.	Satellite/Year
Satellites_Deorbiting **Equation:** (Inactive_Satellites_in_LEO/Average_orbital_Decay_time)-Active_Removal **Description:** This outflow decreases the number of “Inactive Satellites in LEO”. It is affected by the “Average orbital Decay Time” factor. The equation suggests that certain number of inactive satellites will naturally decay over a period of twenty years every year. In case of a policy in place to remove inactive satellites from orbit, this value will be subtracted by the removal rate.	Satellite/Year
Satellites_expiring **Equation:** MAX((Active_Satellites/average_operational_lifetime_of_a_satellite)-Removal_After_lifetime, 0) **Description:** This outflow indicates the number of “Active Satellites” expiring after their lifetime. If the “Policy_1” is active “Removal After Lifetime” outflow will be subtracted from this outflow. Normally, the rate of de-orbiting after	Satellite/Year

lifetime has only 20 percent adherence initially. The equation suggest that the total number of active satellites will be divided by their lifetime and every year and a certain number of satellites will expire upon completion of their operational lifetime “Removal After Lifetime” will be subtracted from the total value. The delay factor is determined by the spatial density and total coverage in low earth orbit. The MAX function ensures that the stock value does not drop below zero.	
“<seed>” **Equation:** INT(UNIFORM(1, 10000)) **Description:** This seed variable is used to generate values for the random draw variables.	Dimensionless
Active_Satellite_Removal_Rate **Equation:** 0 **Description:** As of 2021 there has not been a single Active Debris Removal (ADR) mission conducted in low earth orbit. However, there are proposals and ongoing projects to capture and deorbit objects from orbit. http://www.esa.int/Safety_Security/Space_Debris/Active_debris_removal	Dimensionless /Year
Additional_Fuel_Required_for_Removal_After_Launch **Equation:** Total_Weight_of_Large_Debris_to_be_Avoided_per_Launch*Rate_of_Fuel_Required_Per_Large_Debris **Description:** Additional weight is calculated based on the fuel ratio and the weight of large debris. Multiplication of these two variables will present the total fuel required for de-orbiting a single large debris.	Kilograms/Debris
Adherence_Percentage **Equation:** .7 **Description:** It is assumed that only 70% of all the stakeholders will adhere to deorbit satellites after lifetime.	Dimensionless
Annual_Budget_for_Large_Debris_Removal_After_Launch **Equation:** IF TIME < “Funding_Availability_Time_(Budget_for_International_Space_Agency)” THEN 0 ELSE Maximum_Acceptable_Funding **Description:** It is assumed that the policy to get its full 75affect, there will be two more years of delay after the first delay. This variable indicates the amount of money that is utilised every year on after launch debris removal missions. The equation ensures that the amount is not collected by and or allocated to the launch operators.	US Dollars Per Year
Annual_Spending_on_Deorbit_Missions	US Dollars Per Year

Equation: IF TIME < "Funding_Availability_Time_(Budget_for_International_Space_Agency)" THEN 0 ELSE Maximum_Adherable_Funding_for_Deobirit_Missions **Description:** With two more extra years added to the delay structure, the study assumes that it will take until 2032 to finally seeing the results of the policy.	
Average_Hardware_and_infrastructure_Expenses **Equation:** 300000000 **Description:** Although the cost of satellite can highly vary an average of 300 million dollars is a safe assumption for an average satellite. It includes, bandwidth costs, research and development, hardware, and manufacturing, as well as other relative costs (GLOBALCOM, 2021).	US Dollars/Satellite
Average_operational_lifetime_of_a_satellite **Equation:** Initial_Satellite_Lifetime*Effect_of_Relative_Coverage_to_Satellite_Lifetime **Description:** The effect variable changes the average lifespan of a satellite. For lower coverage rates, the satellite lifetime stays around 8 years. However, if the relative coverage increases drastically, the lifespan of satellites will decrease. This will affect the total revenue generated during lifetime of a satellite. Early expiration of satellites will also require early deorbiting operations. Reductions in average service value provided from satellites will negatively affect the industry.	Year
Average_orbital_Decay_time **Equation:** 20 **Description:** This converter constitutes one of the key balancing factors in the model structure. Every object, depending on their altitude, have an average orbital lifetime. As the altitude decreases, the atmospheric drag increases its impact on objects and slows them down through fraction. In the higher altitude this impact loses its strength. Along with loosened atmospheric drag, solar flux activities also affect the orbital velocity of objects and decreases their velocity. Therefore, all objects in space are subject to a slowing impact of various factors. This thesis is primarily focused on the most populated altitudes of low earth orbit and therefore assumes the average orbital decay time to be twenty years. However, overall length of objects increases drastically as the altitude increases. For instance, objects as high as couple of thousands of kilometres can have hundreds of years of orbital lifetime until they naturally decay back to orbit. The duration chosen for this study is twenty years which generally corresponds to the objects having altitude between 600-800 kilometres which has the highest spatial density in low earth orbit. This value is changed in various sensitivity analyses to see the overall impact it is generating in the model behaviour. The variable creates a delay factor for the debris and inactive satellite stocks. The	Year

main reason for not including the decay factor for the active satellites is that, satellites have propellant on board which is used to adjust altitude during their lifetime. Therefore only "Debris Deorbiting" and "Satellites Deorbiting" are affected by the average orbital decay factor. (Wittig, 2015; Guido, 2014)	
Average_Service_Value_Provided_Per_Satellite **Equation:** 100000000 **Description:** (Statista, 2021; Rouillon, 2020)	US Dollars/Satellite/Year
Average_volume_of_debris[Large_Debris] **Equation:** 1 **Description:** Debris volumes were made based on the existing debris types in the low earth orbit. Sizes and volumes of debris vary depending on the rocket type size which they were used. The largest types of debris are rocket bodies, solid boosters, and similar other mission related objects. The smallest types of debris are the ones larger than 10cm.	cubic meter
Average_volume_of_debris[Medium_Debris] **Equation:** 0.1	
Average_volume_of_debris[Small_Debris] **Equation:** 0.001	
Average_volume_of_satellites **Equation:** 3 **Description:** Average volume of satellite is expressed in cubic meter. Although the volume of satellite varies on their functionality, this study assumes an average of 3 cubic meters for every satellite (NESDIS, 2015).	cubic meter
Average_weight_per_satellite **Equation:** 1630 **Description:** Average weights are calculated based on the total satellite mass on low earth orbit as of May 2021. The total mass was divided to the existing number of satellites and 1630 kilograms of was found to be the average weight of satellites in low earth orbit. Therefore, this study assumes that the mass of future satellites will remain around the same.	Kilograms/Satellite
Collided_Debris_Result[Large_Debris] **Equation:** ((IF item_1 = 3 THEN 1 ELSE 0)+(IF item_2 = 3 THEN 1 ELSE 0))*collision_occurred **Description:** Collided Debris result involves arrayed third fourth and fifth space object types: small medium and large debris. The equation suggests that if "Item 1" or "Item 2" are one of the three debris categorised space objects and if the collision has indeed occurred, the result is 1. Or if both "Item 1" and "Item 2" is selected for as the "Item 1" and "Item 2" the	Debris

result will be 2. Because in some cases both of the Item converters will involve Debris rather than active or inactive satellites. This demonstrates that there is also a possibility of collision between debris. The possibilities are calculated in terms of their total volume and coverage in the orbital environment. Although there is a possibility of two “Small Debris” to collide to each other, the collision do not generate any debris. The matrices also show that in case of a collision between two object 5, the debris creation is 0. This study only focuses on the traceable objects larger than 10cm. However, it is critical to note that, even objects as small as a paint chip causes significant damage on the space infrastructure. One of the shortcomings of this study is that it does not consider the threat of such small objects and the further debris creation which they can cause. (Christiansen, et al., 2004; NASAexplores, 2009) The unit error is due to the model software tendency to categorise objects quantitatively. However, the Collision sector incorporates information rather than the quantity.	
Collided_Debris_Result[Medium_Debris] **Equation:** ((IF item_1 = 4 THEN 1 ELSE 0)+(IF item_2 = 4 THEN 1 ELSE 0))*collision_occurred **Description:** The unit error is due to the model software tendency to categorise objects quantitatively. However, the Collision sector incorporates information rather than the quantity.	
Collided_Debris_Result[Small_Debris] **Equation:** ((IF item_1 = 4 THEN 1 ELSE 0)+(IF item_2 = 4 THEN 1 ELSE 0))*collision_occurred **Description:** The unit error is due to the model software tendency to categorise objects quantitatively. However, the Collision sector incorporates information rather than the quantity.	
Collided_inactive_satellites_result **Equation:** ((IF item_1 = 2 THEN 1 ELSE 0)+(IF item_2 = 2 THEN 1 ELSE 0))*collision_occurred **Description:** Similar to the other collision result variables, the equation ensures that if “Item 1” or “Item 2” is selected as the “Space Object Type” number 2 which is inactive satellites, and if the collision has happened with no manoeuvring the result is 1. Or in some cases, both “Item 1” and “Item 2” is “Inactive Satellites”, the result will be 2. This ensures that there is also chance for two inactive satellites to collide with each other.	Satellite

The unit error is due to the model software tendency to categorise objects quantitatively. However, the Collision sector incorporates information rather than the quantity.	
Collided_satellites_result **Equation:** ((IF item_1 = 1 THEN 1 ELSE 0)+(IF item_2 = 1 THEN 1 ELSE 0))*collision_occurred **Description:** The equation suggests that if “Item 1” and “Item 2” is selected as the space object type 1 which is “Active Satellites” the result will be 1. Or If both “Item 1” and “Item 2” selected as the Space Object Type 1, the result will be 2. This means both sides of the collision is active satellites. Although the chances of this is slimmer than the first one, manoeuvring is not guaranteed. The unit error is due to the model software tendency to categorise objects quantitatively. However, the Collision sector incorporates information rather than the quantity.	Dimensionless
Collision_Incident **Equation:** MONTECARLO(effect_of_relative_intensity_on_collision_incident/DT, “<seed>”+2) **Description:** Collision incident is based on a stochastic equation that relies on MONTECARLO formula. This formula is amplified by the “effect of relative intensity on collision incident” variable. Seed is used to generate values from the distribution specified in the model structure. To increase the probability and risk factor, the seed is set to higher values. The collision incident is determined if the value is 1. Otherwise, collision does not take place. +2 value in the equation makes sure that the seed value is always different than the other seed values used in this model structure.	Dimensionless
Collision_occurred **Equation:** (item_1*item_2)//(item_1*item_2) **Description:** The equation suggests that the collision only occurs if the value on both side of the division is 1. As there is a chance of manoeuvring for active satellites, in some cases, the collision could be evaded. This equation ensures that in case of an avoidance manoeuvre, collision does not take place and therefor collision results are 0. For example, if an active satellite collides with an inactive satellite, the converter should normally indicate the value 1. However, if the “manoeuvring capability” is 0 and the collision is avoided, both sides should be 0 and the result becomes undefined. In this case, the double division sign converts the undefined value to 0 in order to avoid errors.	Dimensionless

Cost_of_Deorbiting_a_Satellite **Equation:** (Cost_of_Launch_to_Low_Earth_Orbit_per_kilogram*Required_additional_fuel_mass_for_deorbit_mission)+Required_additional_hardware_and_infrastructure_for_deorbitting_missions **Description:** Cost of deorbiting a satellite is the sum of additional hardware and fuel required for a single satellite.	US Dollars/Satellite
Cost_of_Launch_to_Low_Earth_Orbit_per_kilogram **Equation:** Effect_of_Relative_Coverage_on_cost_of_launch*Initial_Cost_of_Launch_to_Low_Earth_Orbit **Description:** This variable introduces the effect of relative coverage on the overall cost of launching per kilograms.	US Dollars/Kilograms
Cost_of_Removing_a_Large_Debris_After_Launch **Equation:** (Cost_of_Launch_to_Low_Earth_Orbit_per_kilogram*Additional_Fuel_Required_for_Removal_After_Launch) **Description:** To deorbit after launch, the rocket bodies must carry about 10% of their net mass to the orbit on board. After deployment of the satellite, the rocket can fire back to reduce its velocity and return to the atmosphere. However, carrying extra fuel has financial costs. The cost of removing a large debris is calculated through historical data. Simply, multiplying the weight of large debris with cost per kilogram presents the financial cost of removing a single large debris after launch.	US Dollars/Debris
Cost_Revenue_Ratio **Equation:** “Total_cost_of_Satellite_(Build&_Launch&Maintain)”/Total_revenue_generated_during_lifetime **Description:** Cost revenue ratio defined as the division between the “Total Cost of Satellite (Build Launch and Maintain) and the “Total Revenue Generated During Lifetime” variables. This variable affects the commercial satellite construction flow through the effect variable.	Dimensionless
debris_creation_per_Launch[Large_Debris] **Equation:** 1 **Description:** This variable indicates the number of different sized objects released during mission. This study considers three categories of objects: Large Debris, Medium Debris and Small Debris. Every single launch causes these three categories of objects to be released in orbit and they are all considered as “Mission Related Objects”. The values differ depending on their sizes. Wide-ranging literature and operational studies suggest that in an average sized mission, there are one large, three medium and ten small debris are released	Debris/Satellite

upon launch. Mission related large debris are generally secondary and upper stages of big rocket bodies. In some cases, there are solid boosters and other big rocket tanks also released as a part of mission. In relatively large missions the number of large debris can increase. For this study, only one large debris is an average value. Mission related medium debris are relatively small in size compared to large debris. They are generally comprised of deployment objects such as de-couplers, explosive bolts which are used to separate rocket bodies with payloads. This study assumes that every mission release around three such medium sized debris. Mission related small debris are generally generated as a result separation of rocket stages. This study only considers the objects larger than 10cm and it also assumes that there are around ten pieces of small debris released to orbit for every satellite launch. (ESA, 2019; NationalResearchCouncil, 1995)	
Debris_creation_per_Launch[Medium_Debris] **Equation:** 3	
Debris_creation_per_Launch[Small_Debris] **Equation:** 10	
Debris_creation_result[Large_Debris] **Equation:** collision_occurred*large_debris_creation_matrix[item_1, item_2] **Description:** This variable reflects the results of collisions in terms of debris creation and is multiplied by the debris size matrix. There are always two objects involved in collisions. Every collision possibility has a different debris creation result. Each collision has a potential large, medium and small debris creation coefficient. These coefficients are determined in the debris creation matrices. The unit error is due to the model software tendency to categorise objects quantitatively. However, the Collision sector incorporates information rather than the quantity.	Debris
Debris_creation_result[Medium_Debris] **Equation:** collision_occurred*medium_debris_creation_matrix[item_1, item_2] The unit error is due to the model software tendency to categorise objects quantitatively. However, the Collision sector incorporates information rather than the quantity.	
debris_creation_result[Small_Debris] **Equation:** collision_occurred*small_debris_creation_matrix[item_1, item_2]	

The unit error is due to the model software tendency to categorise objects quantitatively. However, the Collision sector incorporates information rather than the quantity.	
Debris_to_Object **Equation:** 1 **Description:** This variable serves to avoid unit errors due to various conversions between satellite to debris and vice versa.	Objects/Debris
Desired_Debris_Creation_per_Satellite[Large_Debris] **Equation:** 0 **Description:** Existing debris creation per launch results in higher rates of creation of mission related debris in the low earth orbit. Therefore, a policy is created in order to decrease the number of debris creation and to decrease the overall collision risk. This variable is arrayed by the debris sizes. Even though debris creation takes place in different sizes, it is considered extremely costly and unfeasible to tackle with the medium and small sized debris. However, objects like rocket stages and boosters are less costly to de-orbit upon launch. Therefore, the model policy is only aimed at reducing mission related large debris in the orbit. Desired large debris after launch is determined as 0.	Debris/Satellite
Desired_Debris_Creation_per_Satellite[Medium_Debris] **Equation:** 3	
Desired_Debris_Creation_per_Satellite[Small_Debris] **Equation:** 10	
Desired_Satellite_Removal_Rate_After_Lifetime **Equation:** .9 **Description:** The first policy is aimed at reducing the creation of inactive satellites. Because inactive satellites are incapable of manoeuvring and therefore the possibility of avoiding collisions with debris is impossible. At the same time, Inactive satellites increase the orbit population and contribute to the risk of incidents. The objective of this policy is to increase the Satellite Deorbitting rate from 20% to 90% every year in 2032.	Dimensionless
effect_of_cost_revenue_ratio_on_new_launches **Equation:** GRAPH(Cost_Revenue_Ratio) Points: (0.000, 4.9732285963), (0.200, 4.92805516015), (0.400, 4.81029650729), (0.600, 4.52318831191), (0.800, 3.92423431452), (1.000, 3.000), (1.200, 2.07576568548), (1.400, 1.47681168809), (1.600, 1.18970349271), (1.800, 1.07194483985), (2.000, 1.0267714037)	Dimensionless

Description: This graphical variable demonstrates effect the impact of cost revenue ratio on the new commercial satellite constructions. S shaped graphical function utilised in showing that increased cost will result in decreased construction rate effect. In contrast, lower costs will amplify the commercial satellite construction flow and result in higher outputs. Detailed sensitivity analysis is conducted on the variables including graphical functions.	
Effect_of_Relative_Coverage_on_cost_of_launch **Equation:** GRAPH(Relative_Coverage) Points: (0, 1.00), (300000, 1.15796708367), (600000, 1.42931089144), (900000, 1.8954045883), (1200000, 2.69602479056), (1500000, 4.07126910857), (1800000, 6.4335589045), (2100000, 10.4913201378), (2400000, 17.4614328882), (2700000, 29.4341609416), (3000000, 50.00) **Description:** This graphical function ensures that the relative coverage negatively affects the cost of launching objects to orbit. Exponential graph shows the effect is very slim for low coverage rates. However, the effect increases increasingly as the number of objects increase in the orbital environment.	Dimensionless
Effect_of_Relative_Coverage_to_Satellite_Lifetime **Equation:** GRAPH(Relative_Coverage) Points: (500000, 0.993307149076), (600000, 0.982013790038), (700000, 0.952574126822), (800000, 0.880797077978), (900000, 0.73105857863), (1000000, 0.500), (1100000, 0.26894142137), (1200000, 0.119202922022), (1300000, 0.0474258731776), (1400000, 0.0179862099621), (1500000, 0.00669285092428) **Description:** This graphical variable affects the average lifetime of a satellite. The S shaped graph function ensures that the effect is not strong due to the low relative coverage. However, as the relative coverage increase through collisions and new satellites, the number of objects in per cubic kilometer volume will increase. Increased coverage will therefore decrease the lifespan of satellites. This will ultimately make construction and launches of satellites more costly. (Klinkrad, 1993; Ailor, et al., 2010)	Dimensionless
effect_of_relative_intensity_on_collision_incident **Equation:** GRAPH(Relative_Intensity+(Relative_Coverage/7)) Points: (10000, 0.0), (25263.1578947, 0.0614189007755), (40526.3157895, 0.147891092661), (55789.4736842, 0.269636025818), (71052.6315789, 0.441041750899), (86315.7894737, 0.682365326579), (101578.947368, 1.02212683776), (116842.105263, 1.50047995414), (132105.263158, 2.17395736819), (147368.421053, 3.12215193768), (162631.578947, 4.4571231228), (177894.736842, 6.33664038905), (193157.894737, 8.98282870645), (208421.052632, 12.7084197063), (223684.210526, 17.9537109074), (238947.368421, 25.3386009253), (254210.526316, 35.7358502836),	Dimensionless

(269473.684211, 50.3742259342), (284736.842105, 70.9837193013), (300000, 100.0) **Description:** This effect variable is one of the critical components of this modelling project. It is also accommodating some of the essential assumptions that are made in this model structure. The risk of collision is generally predicted through altitude, flight path, size, relative speed, and other geometrical properties that an object has. Calculation attributes and simulating the orbital environment presents various challenges for a System Dynamics simulation project. This study grounds the risk of collision on relative intensity and relative coverage. Lower coverage and intensity values result in very slim effect on collision risk; however, the risk of collision increases exponentially for higher and higher coverage and intensity values.	
“Funding_Availability_Time_(Budget_for_International_Space_Agency)” **Equation:** 2032 **Description:** It is assumed that after the establishment of the international space agency, there will be two more extra years until satellite owners involve in deorbit missions.	Year
Gap_between_Desired_Satellite_Deorbiting_and_Actual_Rate **Equation:** (Desired_Satellite_Removal_Rate_After_Lifetime-“Satellite_De-orbiting_Rate”)*Policy_Switch_1 **Description:** The gap between the actual and Desired rate of deorbiting rate is 70%.	Dimensionless
Gap_Between_the_actual_and_the_desired_rate_of_Debris_Creation_Per_Launch **Equation:** (debris_creation_per_Launch[Large_Debris]-Desired_Debris_Creation_per_Satellite[Large_Debris])*Policy_Switch_2 **Description:** This variable establishes the gap between the actual and desired value for the second policy of this model structure. The policy is aimed at reducing the mission related large debris to zero. Subtraction between the desired and the actual gives the accurate value for the policy to be directed towards to goal of reducing number of large debris creation for every satellite launch.	Debris/Satellite
Initial_Cost_of_Launch_to_Low_Earth_Orbit **Equation:** GRAPH(TIME) Points: (1957.00, 99350.7934603), (1958.00, 99241.8587874), (1959.00, 99114.8131732), (1960.00, 98966.7064485), (1961.00, 98794.1298672), (1962.00, 98593.1527699), (1963.00, 98359.2534131), (1964.00, 98087.2445736), (1965.00, 97771.1951187), (1966.00, 97404.349531), (1967.00, 96979.0484381), (1968.00, 96486.6545811), (1969.00, 95917.4903922), (1970.00, 95260.7954736), (1971.00,	US Dollars/Kilograms

94504.7147451), (1972.00, 93636.3307665), (1973.00, 92641.7565379), (1974.00, 91506.3075663), (1975.00, 90214.7735952), (1976.00, 88751.8103294), (1977.00, 87102.4687008), (1978.00, 85252.8725626), (1979.00, 83191.0440249), (1980.00, 80907.8582466), (1981.00, 78398.0865339), (1982.00, 75661.4596721), (1983.00, 72703.6560794), (1984.00, 69537.0971358), (1985.00, 66181.4218726), (1986.00, 62663.5219851), (1987.00, 59017.050423), (1988.00, 55281.3724067), (1989.00, 51500), (1990.00, 47718.6275933), (1991.00, 43982.949577), (1992.00, 40336.4780149), (1993.00, 36818.5781274), (1994.00, 33462.9028642), (1995.00, 30296.3439206), (1996.00, 27338.5403279), (1997.00, 24601.9134661), (1998.00, 22092.1417534), (1999.00, 19808.9559751), (2000.00, 17747.1274374), (2001.00, 15897.5312992), (2002.00, 14248.1896706), (2003.00, 12785.2264048), (2004.00, 11493.6924337), (2005.00, 10358.2434621), (2006.00, 9363.66923353), (2007.00, 8495.28525487), (2008.00, 7739.20452635), (2009.00, 7082.50960782), (2010.00, 6513.3454189), (2011.00, 6020.95156187), (2012.00, 5595.65046899), (2013.00, 5228.80488127), (2014.00, 4912.75542641), (2015.00, 4640.74658687), (2016.00, 4406.84723006), (2017.00, 4205.87013276), (2018.00, 4033.29355145), (2019.00, 3885.18682675), (2020.00, 3758.14121256), (2021.00, 3649.20653966) **Description:** In 1957, when sputnik was sent to low earth orbit, the cost of sending objects to space was extremely high. However, as the technology advanced, the cost reduced drastically. Today, SpaceX decreased the launch costs even further by introducing reusable rockets (Wikipedia, 2021).	
Initial_Construction_Rate **Equation:** GRAPH(TIME) Points: (1957.0, 3.34642546214), (1969.78947368, 5.63830347497), (1982.57894737, 9.46989883444), (1995.36842105, 15.8219785428), (2008.15789474, 26.2071769307), (2020.94736842, 42.8063317692), (2033.73684211, 68.4012485066), (2046.52631579, 105.759834148), (2059.31578947, 156.140845397), (2072.10526316, 217.293793393), (2084.89473684, 282.706206607), (2097.68421053, 343.859154603), (2110.47368421, 394.240165852), (2123.26315789, 431.598751493), (2136.05263158, 457.193668231), (2148.84210526, 473.792823069), (2161.63157895, 484.178021457), (2174.42105263, 490.530101166), (2187.21052632, 494.361696525), (2200.0, 496.653574538) **Description:** This variable indicates the initial satellite construction rate based on a graphical value. The time horizon is between 1957 to 2021. Launches gradually start 1957 and then increase based on an S shaped graph. The satellite construction rate is calculated annually. One of the main model assumptions here is that launch rates are independent from real world satellite launch rates. Potential analysis and comparison is made	Satellite/Year

in the sensitivity analysis. Although the launch rate does not rely on historical data, it is safe to make such an assumption since the graphical value corresponds to the historical data. One more reason for not having the direct historical data here is that this study is based on future scenario analyses.	
Initial_Satellite_Lifetime **Equation:** 8 **Description:** Initial satellite lifetime is suggested as 8 years. Some satellites in the geostationary orbit can last much longer than satellites in low earth orbit. But in general, it is safe to make an assumption between 5-15 years for satellites in the altitude between 400km to 2000km (MCinnes, 2013).	Years
item_1 **Equation:** Collision_Incident* (IF (random_draw_1) < Volume_percentage[1] THEN "maneuvering_capability_0=avoided_collision" ELSE (IF (random_draw_1) < (Volume_percentage[1]+Volume_percentage[2]) THEN 2 ELSE (IF (random_draw_1) < (Volume_percentage[1]+Volume_percentage[2]+Volume_percentage[3]) THEN 3 ELSE (IF (random_draw_1) < (Volume_percentage[1]+Volume_percentage[2]+Volume_percentage[3]+Volume_percentage[4]) THEN 4 ELSE 5)))) **Description:** Item 1 is determined through random selection of values from 0 to 1. Every object has a volume percentage in the orbital environment and for the objects with higher proportional volume, the collision risk will be higher. In contrast the lower volume will result in lower risks of collision. This is ensured by the distribution of random values in proportion to the volume share for each of the five objects in the orbit. 86eorbited8686y, the selection of the first object which is active satellite, is also determined by the "maneuvering capability". Therefore only Active Satellites have a chance of not being determined as "Item 1" or "Item 2". Selection of the Items will only generate value 1 and therefore determine one of the 5 space object types if the collision incident is 1.	Dimensionless
item_2 **Equation:** Collision_Incident* (IF random_draw_2 < Volume_percentage[1] THEN "maneuvering_capability_0=avoided_collision" ELSE (IF random_draw_2 < (Volume_percentage[1]+Volume_percentage[2]) THEN 2 ELSE (IF random_draw_2 < (Volume_percentage[1]+Volume_percentage[2]+Volume_percentage[3]) THEN 3 ELSE (IF random_draw_2 <	Dimensionless

(Volume_percentage[1]+Volume_percentage[2]+Volume_percentage[3]+Volume _percentage[4]) THEN 4 ELSE 5)))) **Description:** Item 2 is determined through random selection of values from 0 to 1. Every object has a volume percentage in the orbital environment and for the objects with higher proportional volume, the collision risk will be higher. In contrast the lower volume will result in lower risks of collision. This is ensured by the distribution of random values in proportion to the volume share for each of the five objects in the orbit. 87eorbited8787y, the selection of the first object which is active satellite, is also determined by the "manoeuvring capability". Therefore, only Active Satellites have a chance of not being determined as "Item 1" or "Item 2". Selection of the Items will only generate value 1 and therefore determine one of the 5 space object types if the collision incident is 1.	
large_debris_creation_matrix[1, 1] **Equation:** 2 **Description:** The matrix provides debris creation values for large debris. The sum of all matrix values corresponds to the total volume of two items involved in collision. For instance, if an active and an inactive satellite collide, the total volume of the objects collided is 6 cubic meters. Hyper velocities in space cause an incredible release of kinetic energy in case of a collision. Therefore, the impact of the collision creates too many small particles. Relatively high number medium sized particles and finally several pieces. The study assumes that from those 6 cubic meters there will be: 2000 pieces of small debris * 0.001 cubic meters 20 medium sized debris * 0.1 cubic meters 2 large sized debris * 1 cubic meters In total the volume does not change, however the number of objects increase drastically. All possible collisions are calculated in this way and correspond to the total volume of objects involved in the collision.	Debris/Object
large_debris_creation_matrix **[1, 2]** **Equation:** 2	
large_debris_creation_matrix[1, 3] **Equation:** 1	

large_debris_creation_matrix[1, 4] **Equation:** 1	
large_debris_creation_matrix[1, 5] **Equation:** 1	
large_debris_creation_matrix[2, 1] **Equation:** 2	
large_debris_creation_matrix[2, 2] **Equation:** 2	
large_debris_creation_matrix[2, 3] **Equation:** 1	
large_debris_creation_matrix[2, 4] **Equation:** 1	
large_debris_creation_matrix[2, 5] **Equation:** 1	
large_debris_creation_matrix[3, 1] **Equation:** 1	
large_debris_creation_matrix[3, 2] **Equation:** 1	
large_debris_creation_matrix[3, 3] **Equation:** 0	
large_debris_creation_matrix[3, 4] **Equation:** 0	
large_debris_creation_matrix[3, 5] **Equation:** 0	
large_debris_creation_matrix[4, 1] **Equation:** 1	
large_debris_creation_matrix[4, 2] **Equation:** 1	
large_debris_creation_matrix[4, 3] **Equation:** 0	
large_debris_creation_matrix[4, 4] **Equation:** 0	
large_debris_creation_matrix[4, 5] **Equation:** 0	
large_debris_creation_matrix[5, 1] **Equation:** 1	

large_debris_creation_matrix[5, 2] **Equation:** 1	
large_debris_creation_matrix[5, 3] **Equation:** 0	
large_debris_creation_matrix[5, 4] **Equation:** 0	
large_debris_creation_matrix[5, 5] **Equation:** 0	
Large_Debris_Weight **Equation:** 1500 **Description:** Although there are different values for different large debris sizes and weights. This study takes an average around 1500kg for a large debris weight (McKnight, 2015).	Kilograms/Debris
Launch_Scenarios **Equation:** 3 **Description:** There are three launch scenarios. The variable range is arranged based on these three scenarios. Therefore, it serves as a switch variable just to shift between these scenarios.	Dimensionless
"maneuvering_capability_0=avoided_collision" **Equation:** MONTECARLO((1-Maneuvering_Chance)*100/DT)	Dimensionless
Maneuvering_Chance **Equation:** .2	Dimensionless
Maximum_Acceptable_Funding **Equation:** Rate_of_Acceptance_for_Large_Debris_Removal_After_Launch*Total_Cost_of_Large_Debris_Removal_After_Launch **Description:** This study assumes that the policy will have an obstacle when it comes to ensuring that satellite owners whether it be private individuals, cooperation or nations or unions, it will be unfeasible and unrealistic to achieve 100% acceptance rate. Therefore, there will be a certain acceptance rate when it comes to stakeholders deorbiting mission related large debris. This amount is calculated through multiplication the rate of acceptance and the total cost of large debris removal.	US Dollars Per Year
Maximum_Adherable_Funding_for_Deobirit_Missions **Equation:** Adherence_Percentage*Required_funding_for_deorbit_missions **Description:** Adherence rate is multiplied by the total funding required for the deorbiting missions in order to reach at the total funding available every year.	US Dollars Per Year
medium_debris_creation_matrix[1, 1]	Debris/Object

Equation: 20 **Description:** The matrix provides debris creation values for medium debris. The sum of all matrix values corresponds to the total volume of two items involved in collision. For instance, if an active and an inactive satellite collide, the total volume of the objects collided is 6 cubic meters. Hyper velocities in space cause an incredible release of kinetic energy in case of a collision. Therefore, the impact of the collision creates too many small particles. Relatively high number medium sized particles and finally a number of pieces. The study assumes that from that 6 cubic meters there will be: 2000 pieces of small debris * 0.001 cubic meters 20 medium sized debris * 0.1 cubic meters 2 large sized debris * 1 cubic meters In total the volume does not change, however the number of objects increase drastically. All possible collisions are calculated in this way and correspond to the total volume of objects involved in the collision.	
medium_debris_creation_matrix[1, 2] **Equation:** 20	
medium_debris_creation_matrix[1, 3] **Equation:** 20	
medium_debris_creation_matrix[1, 4] **Equation:** 11	
medium_debris_creation_matrix[1, 5] **Equation:** 10	
medium_debris_creation_matrix[2, 1] **Equation:** 20	
medium_debris_creation_matrix[2, 2] **Equation:** 20	
medium_debris_creation_matrix[2, 3] **Equation:** 20	
medium_debris_creation_matrix[2, 4] **Equation:** 11	
medium_debris_creation_matrix[2, 5]	

Equation: 10	
medium_debris_creation_matrix[3, 1] **Equation:** 20	
medium_debris_creation_matrix[3, 2] **Equation:** 20	
medium_debris_creation_matrix[3, 3] **Equation:** 10	
medium_debris_creation_matrix[3, 4] **Equation:** 10	
medium_debris_creation_matrix[3, 5] **Equation:** 5	
medium_debris_creation_matrix[4, 1] **Equation:** 11	
medium_debris_creation_matrix[4, 2] **Equation:** 11	
medium_debris_creation_matrix[4, 3] **Equation:** 10	
medium_debris_creation_matrix[4, 4] **Equation:** 0	
medium_debris_creation_matrix[4, 5] **Equation:** 0	
medium_debris_creation_matrix[5, 1] **Equation:** 10	
medium_debris_creation_matrix[5, 2] **Equation:** 10	
medium_debris_creation_matrix[5, 3] **Equation:** 5	
medium_debris_creation_matrix[5, 4] **Equation:** 0	
medium_debris_creation_matrix[5, 5] **Equation:** 0	
Normal_Construction_Rate **Equation:** IF Launch_Scenarios = 1 THEN Initial_Construction_Rate ELSE IF Launch_Scenarios= 2 THEN Initial_Construction_Rate*1.15 ELSE Initial_Construction_Rate*.85	Satellite/Year

Description: Normal launch rate is the multiplication of “Initial Construction Rate” and the “Launch Scenarios”. The equation ensures that there will be three different set of satellite construction values per year. The first scenario is the business-as-usual scenario which follows the value given in the initial construction rate. The second scenario is the aggressive launch scenario which ensure that there will be 15% more satellites constructed than the initial scenario. The final scenario is the sustainable construction scenario which ensures that there will be 15% reduction in the number of satellite manufacturing and ultimately launches. The model is tested through these scenarios and future analyses are made based on the scenarios.	
Policy_Switch_1 **Equation:** 0 **Description:** This variable is a policy switch variable for the second policy “Deorbiting After Lifetime”	Dimensionless
Policy_Switch_2 **Equation:** 0 **Description:** This variable is a policy switch variable for the second policy “Deorbiting After Launch”	Dimensionless
“Potential_Policy_Initiation_Time_(International_Space_Agency)_Space_Taxing” **Equation:** 2030 **Description:** The policy initiation time is set to be 2030. Therefore a delay of nine years (from 2021) is assumed to be taking until the policy is effectively implemented.	Year
random_draw_1 **Equation:** UNIFORM(0, 1, “<seed>”)	Dimensionless
random_draw_2 **Equation:** UNIFORM(0, 1, “<seed>”+1)	Dimensionless
Rate_of_Acceptance_for_Large_Debris_Removal_After_Launch **Equation:** .3 **Description:** This study assumes that only 30% of the total cost will be accepted and implemented for the removal after launch operations. Detailed sensitivity analysis is made on the value of this rate to analyse its overall impact to the model behaviour.	Dimensionless
Rate_of_Fuel_Required_Per_Large_Debris	Dimensionless

Equation: .1 **Description:** Similar to deorbiting active satellites, large debris also requires fuel on board in order to reduce velocity and de-orbit back to the atmosphere. As objects acquire extreme velocities to reach to the orbit, certain amount of energy must be consumed as propellant to deorbit back. Therefore every object that is in higher altitudes need extra fuel based on their mass to reduce their velocities.The ratio for this variable is chosen to be 10 percent of the total mass of the large debris.	
Ratio_of_fuel_required_per_satellite **Equation:** .1 **Description:** Every satellite must have extra fuel on board for deorbit missions. And this ratio is not higher than 10% of the total mass of the satellite itself.	Dimensionless
Ratio_of_Satellites_in_all_objects **Equation:** (Active_Satellites/Total_number_of_objects)*100	Satellite/Objects
Relative_Coverage **Equation:** Total_coverage/INIT(Total_coverage) **Description:** Relative coverage is the normalised value for the total coverage. The INIT equation is used to reach at the relative value for the coverage in low earth orbit. Relative coverage affects the satellite lifetime, collision incident and the cost of launch. These effects are interconnected. For instance, increased "effect effect of relative intensity and coverage on collision incident ultimately increases the relative coverage and therefore it increases the "effect of relative coverage to average satellite lifetime". Therefore, it is possible to state that overall increase in the number of objects amplifies all three effect variables and their corresponding loops.	Dimensionless
Relative_Intensity **Equation:** spatial_intensity/INIT(spatial_intensity) **Description:** relative intensity is the normalised value for spatial density. The INIT equation is used to reach at the relative value for the intensity in low earth orbit.	Dimensionless
Required_additional_fuel_mass_for_deorbit_mission **Equation:** Average_weight_per_satellite*Ratio_of_fuel_required_per_satellite **Description:** There are a number of deorbiting systems and all of they all have various advantages and disadvantages. This study assumes that all satellites in the model stocks will have chemical propulsion systems as a part of the policy offering. Chemical propulsion systems are the most effective yet most costly system to deorbit satellites. In order to calculate the total fuel mass required per satellite, one can divide the total mass of the satellite to the ratio of fuel required for it to deorbit efficiently (Guido, 2014).	Kilograms/Satellite

Required_additional_hardware_and_infrastructure_for_deorbitting_missions **Equation:** 1000000 **Description:** It is assumed that the satellites must have additional hardware in order to successfully complete deorbiting missions. A cost of average 1 million dollars is set to be the cost of such a hardware (research and development) required for a single satellite (Guido, 2014).	US Dollars/Satellite
Required_funding_for_deorbit_missions **Equation:** IF TIME < "Potential_Policy_Initiation_Time_(International_Space_Agency)_Space_Taxing" THEN 0 ELSE Cost_of_Deorbiting_a_Satellite*"Required_number_of_Satellites_to_De-orbit" **Description:** The equation ensures that the policy is not activated until 2030. It also calculates the total funding required to deorbit certain number of satellites every year.	US Dollars Per Year
"Required_number_of_Satellites_to_De-orbit" **Equation:** (Gap_between_Desired_Satellite_Deorbiting_and_Actual_Rate*Active_Satellites)/average_operational_lifetime_of_a_satellite **Description:** This equation demonstrates the required number of satellites that should be deorbited every year.	Satellite/Year
satellite_construction_time **Equation:** 1.5 **Description:** This study assumes that the average time of construction a satellite is 1.5 years. The construction time of a satellite varies depending on the complexity and the duration of the mission. For example, James Webb Space Telescope was planned to launch in 2007 however it had to be delayed and it went through major structural changes. As of 2021 May the project which has started in 1996 is still due completion. Another example is the Hubble telescope which took decades until it was actually launched. However, these are very sophisticated satellites and require much more detailed testing and research. This study is primarily aimed at analysing the satellites that are being used in low earth orbit and which has a commercial value to an extent. Detailed sensitivity analysis is made on the satellite construction duration and its overall impact to the model behaviour (Wikipedia, 2021; NASA, 2021).	Years
"Satellite_De-orbiting_Rate" **Equation:** 0.2 **Description:** Inter-Agency Space Debris Committee Space Debris Mitigation Guideline recommends all the satellites to be 94eorbited within 25 years.	Dimensionless

However, only some of the space-faring countries follow these guidelines. This variable suggests that the current adherence rate is around 20 percent. This means that only 20 percent of the active satellites are being 95eorbited after their operational lifetime (IADC, 2019; ESA, 2020).	
Satellite_to_Debris **Equation:** 1 **Description:** This variable serves to avoid unit errors due to various conversions between satellite to debris and vice versa.	Satellite/Debris
satellite_to_Object **Equation:** 1 **Description:** This variable serves to avoid unit errors due to various conversions between satellite to debris and vice versa.	Objects/Satellite
small_debris_creation_matrix[1, 1] **Equation:** 2000 **Description:** The matrix provides debris creation values for small debris. The sum of all matrix values corresponds to the total volume of two items involved in collision. For instance, if an active and an inactive satellite collide, the total volume of the objects collided is 6 cubic meters. Hyper velocities in space cause an incredible release of kinetic energy in case of a collision. Therefore, the impact of the collision creates too many small particles. Relatively high number medium sized particles and finally a number of pieces. The study assumes that from that 6 cubic meters there will be: 2000 pieces of small debris * 0.001 cubic meters 20 medium sized debris * 0.1 cubic meters 2 large sized debris * 1 cubic meters In total the volume does not change, however the number of objects increase drastically. All possible collisions are calculated in this way and correspond to the total volume of objects involved in the collision.	Debris/Object
small_debris_creation_matrix [1, 2] **Equation:** 2000	
small_debris_creation_matrix[1, 3] **Equation:** 1000	

small_debris_creation_matrix[1, 4] **Equation:** 1000	
small_debris_creation_matrix[1, 5] **Equation:** 1001	
small_debris_creation_matrix[2, 1] **Equation:** 2000	
small_debris_creation_matrix[2, 2] **Equation:** 2000	
small_debris_creation_matrix[2, 3] **Equation:** 1000	
small_debris_creation_matrix[2, 4] **Equation:** 1000	
small_debris_creation_matrix[2, 5] **Equation:** 1001	
small_debris_creation_matrix[3, 1] **Equation:** 1000	
small_debris_creation_matrix[3, 2] **Equation:** 1000	
small_debris_creation_matrix[3, 3] **Equation:** 1000	
small_debris_creation_matrix[3, 4] **Equation:** 100	
small_debris_creation_matrix[3, 5] **Equation:** 500	
small_debris_creation_matrix[4, 1] **Equation:** 1000	
small_debris_creation_matrix[4, 2] **Equation:** 1000	
small_debris_creation_matrix[4, 3] **Equation:** 100	
small_debris_creation_matrix[4, 4] **Equation:** 200	
small_debris_creation_matrix[4, 5] **Equation:** 101	
small_debris_creation_matrix[5, 1] **Equation:** 1001	

small_debris_creation_matrix[5, 2] **Equation:** 1001	
small_debris_creation_matrix[5, 3] **Equation:** 500	
small_debris_creation_matrix[5, 4] **Equation:** 101	
small_debris_creation_matrix[5, 5] **Equation:** 0	
spatial_intensity **Equation:** total_volume_of_objects_in_leo/Updated_LEO_Volume **Description:** Wide range of literature argue that with increased spatial density, the collision risk increases. The spatial density is calculated through the ratio between all objects and total volume of low earth orbit. Through this equation it is possible to reach at the share of total volume of objects that exist in per cubic kilometres (Klima, et al., 2016; Colombo, et al., 2016; Klinkrad, 1993).	Meters^3*Objects/cubic kilometers
Succes_Rate_of_Deorbit_Missions **Equation:** .95 **Description:** Not every satellite will be successfully removed, therefore a success rate is introduced to the policy structure. It is assumed that 95% of all the satellites involved in deorbiting missions will not be successful.	Dimensionless
Total_Cost_of_Large_Debris_Removal_After_Launch **Description:** **Equation:** IF TIME < "Potential_Policy_Initiation_Time_(International_Space_Agency)_Space_Taxing" THEN 0 ELSE (Cost_of_Removing_a_Large_Debris_After_Launch*new_satellite_launches/Satellite_to_Debris) **Description:** This variable calculates the required total amount of money to be invested in debris removal activities. By simply multiplying a single large debris' removal cost with new launches, we can reach at the total amount required for avoiding mission related large debris in orbit per year. The policy structure only allows this after year 2030. This is because such international collective actions are very rare in history and it takes considerably long times to reach at such an agreement to truly implement guidelines provided by the international institutions. Therefore, the model equation ensures that before the model time reaches to 2030 the policy structure will not be activated. This duration can also be restructured as a Delay function.	US Dollars Per Year

“Total_cost_of_Satellite_(Build&_Launch&Maintain)” **Equation:** (Average_weight_per_satellite*Cost_of_Launch_to_Low_Earth_Orbit_per_kilogram) +Average_Hardware_and_infrastructure_Expenses+ (Cost_of_Deorbiting_a_Satellite*Policy_Switch_1)+ (Cost_of_Removing_a_Large_Debris_After_Launch/Satellite_to_Debris)*Policy_Switch_2 **Description:** Total cost of a satellite is calculated through the sum of total weight of a single satellite multiplied by the cost of launching per kilogram and “Average Hardware and Infrastructure Expenses” as well as the additional policies “ Cost of Removing Large Debris After Launch” and “Cost of Deorbiting a Satellite". Policy switches are used to eliminate the additional cost from adding up on the total cost before the policy activates.	US Dollars/Satellite
Total_coverage **Equation:** Total_number_of_objects/Updated_LEO_Volume **Description:** Dividing total number of objects with the volume of low earth orbit gives the total coverage variable. Therefore, an average number of objects is acquired at a given time in per cubic kilometer.	Objects/cubic kilometers
Total_Number_of_Large_Debris_Removal_Capacity_After_Funding **Equation:** Annual_Budget_for_Large_Debris_Removal_After_Launch//Cost_of_Removing_a_Large_Debris_After_Launch **Description:** This variable calculates the number of large debris removal missions to take place every year based on the annual budget divided by a cost of removing a single large debris after launch. In other words, this variable indicates how many large debris will be deorbited every year as a result of the second policy.	Debris/Years
Total_number_of_objects **Equation:** (SUM(Debris_in_LEO)*Debris_to_Object) +((Active_Satellites+Inactive_Satellites_in_LEO)*satellite_to_Object) **Description:** This variable indicates the total number of all objects in low earth orbit. This objects include "Active Satellites", "Inactive Satellites" and Debris. Sum of all these objects, along with the unit correction variables, provide the total number of objects.	Objects
Total_number_of_Satellites_to_be_Deorbitted **Equation:** (Annual_Spending_on_Deorbit_Missions/Cost_of_Deorbiting_a_Satellite)*Success_Rate_of_Deorbit_Missions **Description:** Total budget is divided by the cost of deorbiting a single satellite, therefore the equation gives the number of satellites that will be deorbitted after	Satellite/Year

their lifetime. the total number is multiplied by the success rate to find the actual number of satellites that will involve in the missions per year.	
Total_Revenue_from_the_Industry **Equation:** Active_Satellites*Total_revenue_generated_during_lifetime	US Dollars
Total_revenue_generated_during_lifetime **Equation:** average_operational_lifetime_of_a_satellite*Average_Service_Value_Provided_Per_Satellite **Description:** Every year a satellite generates a revenue. This variable calculates the total revenue generated during of a satellite lifetime. Multiplication between the average value that a satellite generates and the year that it will operate presents the maximum value that can be generated by a single satellite. This variable is also affecting the cost revenue ratio.	US Dollars/Satellite
total_volume_of_objects_in_leo **Equation:** (((Active_Satellites+Inactive_Satellites_in_LEO)*average_volume_of_satellites)*satellite_to_Object) + ((Debris_in_LEO[Large_Debris]*average_volume_of_debris[Large_Debris])+(+average_volume_of_debris[Medium_Debris]*Debris_in_LEO[Medium_Debris]) +(Debris_in_LEO[Small_Debris]*average_volume_of_debris[Small_Debris]))*Debris_to_Object **Description:** Total volume of objects are calculated through multiplication of the quantity of five different objects with their average volume. The sum of the volumes of these object gives the total volume of all objects in low earth orbit.	Meters^3*Objects
Total_Weight_of_Large_Debris_to_be_Avoided_per_Launch **Equation:** Large_Debris_Weight*Gap_Between_the_actual_and_the_desired_rate_of_Debris_Creation_Per_Launch*Satellite_to_Debris **Description:** Every satellite launch results in debris creation and every debris has a certain weight. Based on the gap between the actual and desired rate of large debris creation a multiplication with average large debris weight will present the weight of debris that should be removed after launch.	Kilograms/Debris
Updated_LEO_Volume **Equation:** 250000000000 **Description:** The model concentrates on the most crowded altitudes of low earth orbit which is in between 400-1200 km altitudes. The total volume of this area is 250000000000 cubic kilometres (ESA, 2019).	cubic kilometers
Volume_of_Active_Satellites **Equation:** Active_Satellites*average_volume_of_satellites*satellite_to_Object **Description:** Total volume of active satellites is calculated through multiplication of the quantity of satellites and their average size in low earth orbit.	Meters^3*Objects

Volume_of_Debris[Debris_Size] **Equation:** Debris_in_LEO*average_volume_of_debris*Debris_to_Object **Description:** Total volume of debris is calculated through multiplication of the quantity total number of debris and their average volume size.	Meters^3*Objects
Volume_of_Inactive_Satellite **Equation:** Inactive_Satellites_in_LEO*average_volume_of_satellites*satellite_to_Object **Description:** Total volume of inactive satellites in low earth orbit calculated through the multiplication of number of satellites with the average volume of satellites.	Meters^3*Objects
Volume_percentage[1] **Equation:** Volume_of_Active_Satellites/(Volume_of_Active_Satellites+Volume_of_Inactive_Satellite+Volume_of_Debris[Large_Debris]+Volume_of_Debris[Medium_Debris]+Volume_of_Debris[Small_Debris]) **Description:** This converter is arrayed by the space object type. These objects are active satellites=1, inactive satellites=2, large debris=3, medium debris=4, small debris=5. The percentage of these objects are calculated through the total volume of all objects. The sum of these arrayed converters always generates 1.	Dimensionless
Volume_percentage[2] **Equation:** Volume_of_Inactive_Satellite/(Volume_of_Active_Satellites+Volume_of_Inactive_Satellite+Volume_of_Debris[Large_Debris]+Volume_of_Debris[Medium_Debris]+Volume_of_Debris[Small_Debris])	
Volume_percentage[3] **Equation:** Volume_of_Debris[Large_Debris]/(Volume_of_Active_Satellites+Volume_of_Inactive_Satellite+Volume_of_Debris[Large_Debris]+Volume_of_Debris[Medium_Debris]+Volume_of_Debris[Small_Debris])	
Volume_percentage[4] **Equation:** Volume_of_Debris[Medium_Debris]/(Volume_of_Active_Satellites+Volume_of_Inactive_Satellite+Volume_of_Debris[Large_Debris]+Volume_of_Debris[Medium_Debris]+Volume_of_Debris[Small_Debris])	
Volume_percentage[5] **Equation:** Volume_of_Debris[Small_Debris]/(Volume_of_Active_Satellites+Volume_of_Inactive_Satellite+Volume_of_Debris[Large_Debris]+Volume_of_Debris[Medium_Debris]+Volume_of_Debris[Small_Debris])	

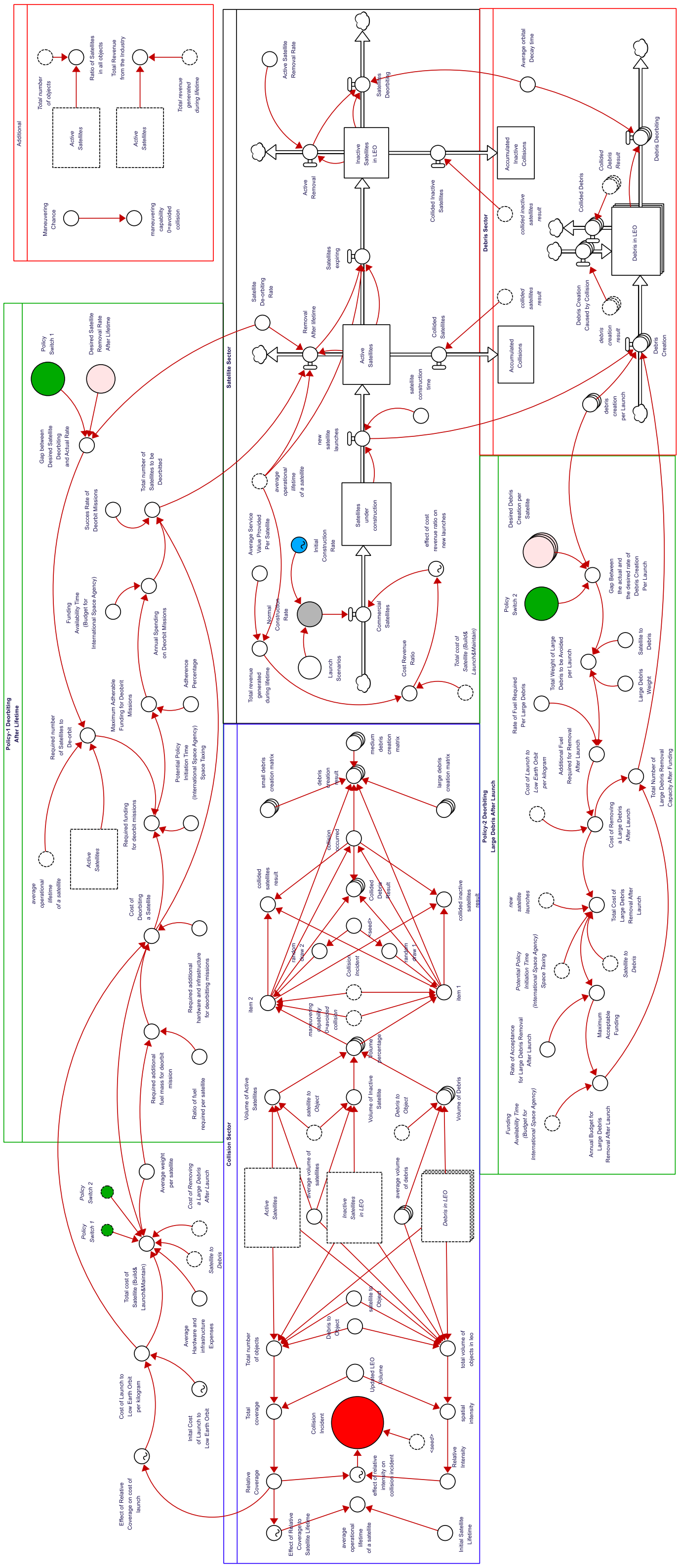
Total	Count	Including Array Elements
Variables	103	201
Sectors	5	
Stocks	6	8
Flows	12	20
Converters	85	173
Constants	33	111
Equations	64	82
Graphicals	6	6

Run Specs	
Start Time	1957
Stop Time	2200
DT	1/64
Fractional DT	True
Save Interval	0.015625
Sim Duration	1.5
Time Units	Year
Pause Interval	0
Integration Method	Euler
Keep all variable results	True
Run By	Run
Calculate loop dominance information	True
Exhaustive Search Threshold	1000

Array Dimension	Indexed by	Elements

Debris_Size	Label (3)	Large_Debris Medium_Debris Small_Debris
Space_Object_Type	Number	5

Model Structure



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