Sustainability Impacts of Satellite Internet:

Digital Inclusion vs Environmental Sustainability

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Abstract:

An estimated 450 million people globally do not have access to a fixed or mobile broadband signal. Recently satellite communication companies announced the concept of Mega-constellations which are large networks of inexpensive low Earth-orbiting satellites. These constellations aim to provide internet access across the planet. Many people believe these constellations will offer an opportunity to bridge the digital divide between developed and developing countries. However, according to the UN development agenda, it is crucial to harmonize three core elements: economic growth, social inclusion, and environmental protection, while achieving the Sustainable Development Goals (SDGs). Although many are enthusiastic about the possibility of closing the digital gap, some researchers have concerns about the environmental impacts of these mega-constellations. Some studies explored how satellites' mega-constellations would increase the collision rate among space objects. This by increased amount of space debris which would negatively impact the Low Earth Orbit and the planet and thereby would be inconsistent with environmental sustainability. This study aims to investigate this claim by examining the impacts of future capabilities of satellites on offering inclusive healthcare and education systems while investigating their environmental impacts.

Keywords:

Mega-constellations, Sustainability, Satellites internet.

Sustainability impacts of satellite internet: Digital inclusion vs environmental sustainability

Research Summary

"The Broadband (or high-speed) internet access is not a luxury, but a basic necessity for economic and human development in both developed and developing countries" (WorldBank, 2016). The internet is an impactful tool for delivering critical services like education and healthcare. However, according to the GSMA report (2021), less than half of the world's population remains on the dark side and does not utilize the internet. In recent years thousands of satellite mega-constellations have been planned to be launched by companies such as SpaceX, Amazon, and Samsung, this to offer high-speed internet to every part of the globe using satellite mega-constellations. However, these satellites consume many resources at an unsustainable rate, resulting in environmental damage and pollution. Economic growth, environmental protection, and social progress are the pillars of successful sustainability. There, It is crucial to remember that sustainable development requires comprehensive actions to maintain the ecological, social and economic balance.

For years, land-based networks have aimed to provide the same benefits that commercial space operators promise. As a result, the goal of this study is to see how mega-constellations would affect the social and environmental aspects of sustainability. The social dimension will be focused on the influence of satellite internet in providing inclusive healthcare and education digital services. In terms of the environment, this study investigates satellite mega-constellations effect on Earth's resources consumption.

The results reveal covering rural areas, which is not always profitable for telecom operators, is seen as profitable for satellite-based systems. However, coverage is not the essential criterion for inclusion. According to the analysis, there are preconditions for inclusion, such as service affordability, digital skills, and electricity infrastructure. Satellite internet business models, according to literature, are still far from giving affordable prices that can compete with telecom operators' business models where mobile networks are available. Even if commercial space operators could provide coverage at a low cost, digital illiteracy and a lack of infrastructure such as electricity could limit the adoption rate of digital healthcare and education services. On the other hand, the study showed that the environment is not prioritized in many satellite companies' future business plans. Current satellite launches are already ringing alarms regarding fuel consumption and space debris. Satellite mega-constellation will only increase this consumption, and this research showed that mega-constellation also would contribute to resource depletion of vital resources such as the aluminum.

Lastly, the hybrid model of terrestrial systems and satellite systems has been motivated by this study. If both models collaborate, they may offer robustness to urban areas, and fewer satellites will be needed. This hybrid model will pave the way for closing the digital divide and may decrease environmental impacts from mega-constellations.

In conclusion, this study emphasizes the gap between developed and developing countries regarding digital inclusion, and more efforts should be focused on closing these gaps. Also, it highlights how policymakers and business strategists should design the infrastructure to prioritize the environment.

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List of Acronyms

ICT Information Communication Technology
SDG Sustainable Development Goals
UN United Nations
Opex Operating expense
Capex Capital expenditures
LCA Life Cycle Assessment
LEO Low Earth orbiting satellites
MEO Medium Earth orbiting satellites
GEO Geosynchronous Earth orbiting satellites
HAPS High-altitude platform systems
IoT Internet of Things
WHO World Health Organization
ESA European Space Agency
ITU International Telecommunication Union
FCC Federal Communications Commission

1 INTRODUCTION

1.1 Background

During the 1950s and 1960s, the space race was framed as a nationalistic contest between the United States and Russia (Wood, 2020). Satellites always have a pivotal role in navigation, telephone services, weather forecasting, and climate and environmental monitoring (Perks, 2021). However, as private businesses began operating in the commercial space sector, the market structure of government investment dominance in the space industry was disrupted, especially after the satellite communication industry announced the notion of Mega-constellations. Mega-constellations are vast networks of low-cost low-Earth-orbiting satellites (Sánchez & Wolahan, 2017). Several private companies plan to deploy large or mega-constellations with hundreds or thousands of satellites (Pardini & Anselmo, 2020). These satellite mega-constellations aim to provide global internet coverage in response to the growing demand for low-cost broadband, particularly in rural areas (Morgan Stanley, 2020). The 21st century may be characterized as a private interest space race, much as the 1960s was known as a government-funded space race (George, 2019).

The introduction of reusable rockets drove dramatic cost reductions (Baumstarck, 2021). Thus, the cost of getting a satellite into Earth's orbit dropped, and the number of operational satellites in Earth's orbit doubled. This decrease in expenses allowed the commercial space industry to expand and a rising number of new space actors to emerge (ibid). An example of these mega-constellations is SpaceX's plan to send 42,000 satellites into space over the next two decades as part of its Starlink satellite program. The claimed objective is to bring the internet to everyone on the planet (Space.com, 2022). In July 2020, the Federal Communications Commission (FCC) authorized Amazon to install and operate Project Kuiper, a 3,236-satellite internet constellation (Amazon, 2020). Moreover, Samsung already made plans in 2015 to launch 4,600 broadband satellites, but the development since then is unclear (Khan 2015; Horn 2020). Therefore, this race for satellite broadband services and how commercial satellite operators hope to provide worldwide internet drives the recent increase in satellite launches.

The Brundtland Commission Report of 1987 defined sustainable development as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs." (Brundtland Report, 1987). Therefore, the overall environmental, social and economic costs must be less than the corresponding returns of the technology that aimed to push some of the sustainable development goals (Durrieu & Nelson, 2013). Although it is widely accepted that satellite's internet will provide incredible services to a global community of people in sectors such as healthcare and education. However, in her article "The impacts of Mega-Constellations on Astronomy", Megan Perks discusses the threats of satellite launches on the planet. Perks demands the entire scientific community to take notice of the fact that satellites are being launched into orbit at an alarming rate (Perks, 2021). In other words, by the end of this decade, the number of satellites will have increased to 20,000 to cover the Earth with the internet (EU Space Policy, 2019), but this acceleration of satellite launches comes with a hidden cost that can not be neglected.

The motive behind the satellite mega-constellations is to provide global internet that will decrease the digital divide. However, many researchers questioned that these mega-constellations increase the space debris and collision rate among space objects. According to NASA, there are millions of pieces of junk flying in low-Earth orbit (LEO) (NASA, 2022). Moreover, satellites are primarily constructed of aluminum (Wassmer, 2015). Therefore, each mega-constellation will induce aluminum deposition and might produce particles, thereby creating more space debris. To sum up, the operation of mega-constellations might be inconsistent with environmental sustainability.

The present study investigates the sustainability impact of internet satellites, focusing on sustainability's social and environmental aspects. The research is based on scientific literature and qualitative data collected through interviews and questionnaires. This work was supervised by Uppsala University's Department of Media and Informatics and Ericsson Research's sustainability team, with high considerations for research ethics.

1.2 Problem Statement

Satellites are sometimes put forward as embedded components of a future mobile communication system. However, the sustainability aspects of such systems need more attention. For this reason, this study will attempt to explore some of the positive and negative impacts across environmental and social dimensions of sustainability. Brynjolfsson and Sauder (2013), in their book "*Wired for Innovation*", mentioned that in this age, we are in the early phase of an information-driven revolution with a high potential to boost productivity and growth in years to come. We are still far from the limits of what current technology can achieve. Even if technology were to be frozen for the next decade, we might make significant progress simply by employing the presently available resources (Brynjolfsson & Sauders, 2013). However, technology will not be frozen with the ongoing development of communication systems, including the space race and its acceleration. It is predicted that internet access will increase, and more data will be available. As growth is expected to accelerate, an analytical study is helpful to predict which sectors will benefit and who will pay the hidden cost of this growth. Thereby information industry must take advantage of such technologies to increase productivity growth. However, performance and cost are not the only criteria for booming technology; the environment must be prioritized too. Therefore, this study will investigate future satellite-based internet's positive and negative sustainability impacts.

1.3 Research Objectives

This thesis aims to establish a comprehensive summary of satellite internet sustainability impacts. Two objectives were formulated:
O1: Investigate future communication satellites' contributions to the social dimension of sustainability, especially in the healthcare and education sectors.
O2: Investigate the impacts of the future communication satellites on the environmental dimension of sustainability.

1.4 Research Questions

RQ1: In what ways would the satellite mega-constellations and their global internet positively impact the SDG's agenda?

RQ2: In what ways would the satellite mega-constellations negatively impact the SDG's agenda?

1.5 Delimitations

In their 2030 Agenda for Sustainable Development, United Nations has defined 17 Sustainable Development Goals and 169 targets to be achieved (United Nations, 2015). This study is limited to the interaction of four SDGs (health, education, technology infrastructure, and resource consumption) when investigating sustainability impacts due to mega-constellations. It is essential to acknowledge that the researcher is studying how technology is affecting people's lives. Therefore, the study will focus on the effects of the satellite mega-constellations on inclusive healthcare and education services in rural areas in developing countries while considering the environment.

1.6 Structure of the Thesis

The research focuses on satellite mega-constellations and how investments in satellite internet will impact the social and environmental dimensions of the UN development agenda. The study's general format consists of eight chapters, including the results and conclusion. The first part of this thesis provides an overview of satellite foundations and resources employed in the satellite industry, allowing the reader to track the environmental impacts. The third chapter will show how different scholars handled the social as well as the environmental implications of commercial space. The theoretical components of the research are set out in Chapter Four, which introduces the Business Model Themes and SDGs Interactions theoretical frameworks. The methodology for this research is discussed in Chapter Five. The outcomes of the secondary data and the primary data from interviews and questionnaire are presented in Chapter Six. In addition, in Chapter Seven, research findings will be discussed and considered against the theoretical frameworks. Lastly, the research's key conclusion will be illustrated.

2 BACKGROUND ON SATELLITE SYSTEMS

Before delving into the consequences of satellite mega-constellations, it is vital first to grasp what satellites are and what they are consist of. As a result, by explaining the components and materials used in satellites, this chapter is intended to lay a basis for non-specialist readers.

Dan Stillman from NASA answers the question, “What is a Satellite?”. He states that “a satellite is an object that moves around a larger object” (Stillman, 2014). Because the Earth revolves around the Sun, it can be considered a satellite; similarly, the moon revolves around the Earth. However, both the Earth and the Moon are “natural satellites,” and most people think of a “man-made” satellite when they say “satellite.” There, the term satellite refers to spacecraft launched into orbit around the planet or another celestial body (IntelSat, 2022). Dai et al. (2007) explain that communication satellite systems consist of space and ground segments. The space segment consists of the satellites in space, whereas the ground segment consists of user communication devices, ground stations that connect to the terrestrial network, and satellite control and monitoring facilities. Although space segments come in various shapes and sizes, they all have at least two components: an antenna and a power supply. The antenna receives and transmits data, and the power source is either a battery, solar panels that convert sunshine into electricity, or a combination thereof (Stillman, 2014). The following sections will focus on space segment components and resources used in building, operating, and maintaining these components.

2.1 Satellites main components

This section will illustrate the two main components of the space segment and the power system. To begin, a typical communication satellite in the space segment comprises a satellite bus and a communication payload. First, there is the satellite bus or platform, which is the satellite’s basic frame and the components that allow it to operate in space (Dai et al., 2007). As shown in Figure 1, the satellite bus comprises structural, thermal, power, attitude control, propulsion, telemetry, tracking, and command (TT&C) subsystems (ibid).

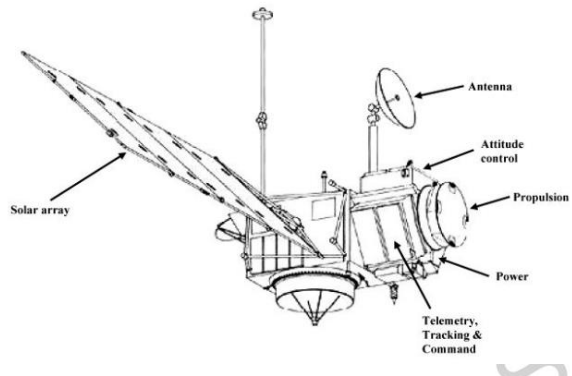

Figure 1 Satellite Subsystems (Dai et al., 2007)

The second component is the communication payload, which establishes connections between communication devices. Antennas, which receive, amplify, and retransmit signals over a defined geographical area, are vital components of a satellite communication payload. The ground control segment monitors and controls these components to complete the satellite mission (Dai et al., 2007).

In addition to the satellite's body, space missions can last decades, and large communications satellites, require tens of kilowatts to operate correctly. Therefore, a stable continuous power supply is critical to the success of the satellite's mission (ESA, 2022). The power system accounts for around 20-30% of the spacecraft's mass and it is mainly utilized for power generating distribution and storage (Baraskar et al., 2022). All of the onboard electronics are powered by two different sources of electricity. The primary source is solar arrays that convert sunlight to electricity. However, the solar panel's energy collection efficiency is diminished during eclipses. For example, when the Earth blocks the Sun or when a spacecraft moves away from the Sun, individual solar cells degrade unpredictably, deteriorating solar arrays (ibid). Therefore, batteries are used to power onboard electronics as a secondary power source. Batteries constitute a large percentage of the total weight of most satellites; typically, they account for more than ~15-20% of the mass (Dai et al., 2007). The following section will talk about the materials used in satellites as well as in launching and operating them.

2.2 Resources used in Satellites

Satellites as machines are made up of various electronic and mechanical components that must resist the vibrations of a rocket launch and then operate in the space environment (IntelSat, 2022). The four materials used in aerospace are metals, non-metallic or polymeric materials, composite materials, and ceramic materials. The most often utilized materials in aerospace systems are metallic materials such as aluminum alloys, titanium alloys, and iron alloys (steels) (Grant & Clyde, 2018). The first element is aluminum, which happened to be the second most often utilized metal in modern society, the following steel. Aluminum is not particularly strong, but it gets significantly stronger when mixed with other metals to form alloys. Aluminum alloys are commonly used in satellites because they are both strong and light (Wassmer, 2015).

The second element is titanium alloys, also known as titanium, which are the ninth most abundant element in the Earth's crust, with a concentration of roughly 0.6 percent. Titanium is the fourth most abundant structural metal after aluminum, iron, and magnesium. In general, the satellite's exterior is often built of a lightweight material such as aluminum or titanium, which provides the satellite with the essential structural support to face challenging conditions in space (Dai et al., 2007).

Iron alloys (steels) are the third material utilized in satellite. Steels are the most widely used metallic materials in structural applications worldwide due to their high strength and inexpensive cost. One disadvantage of steel, it has a higher density than aluminum and titanium, which causes the mass of satellite systems to increase (Grant & Clyde, 2018).

On the other hand, for the resources used in satellite power systems, Borthomieu (2014) covers the history of batteries in the satellite industry. The article mentioned that thousands of satellites were powered by nickel-cadmium (Ni-Cad) batteries in space as early as the 1960s. Later, weight became an increasingly important characteristic for satellites towards the turn of the century. Thus, the high specific energy provided by Lithium-ion (Li-ion) technology aided the transition. By the end of 2012, more than 200 satellites had been launched worldwide utilizing Li-ion batteries. Also, by 2014 Li-ion batteries were mentioned in more than 99 percent of satellite contracts (Borthomieu, 2014). Table 1 shows the most common materials used in satellites.

Table 1 The most common used materials in satellite

Material	**Proportion**	**References**
Aluminum	**80%**	(Wassmer, 2015)
Titanium	Ti-alloys are used to cover primary and secondary structures of the spacecraft	(SpaceMatDB, 2000)
Stainless Steels	at least **12** %	(SpaceMatDB, 2000)
Lithium in Li-ion batteries	**~15-20%**	(Dai et al., 2007)

Dallas et. al (2020) explained the launch process of rockets and how rockets require a vast number of catalysts to make it out of the Earth’s atmosphere. Typically, they have between 2, and 4 stages, a lift-off stage, an early launch stage, and the upper stages used at high altitudes. As stages 0 and 1 run out of fuel, they detach from the rocket, and the following successive stage fires. This process is repeated until the rocket reaches its desired final orbit.

Moreover, Dallas et al. (2020) illustrated that the most used fuels in Liquid Rocket Engines (LRE) are kerosene (RP-1), and it will be referred to as kerosene, liquid hydrogen (LOx/LH2), and hypergolic propellant. Kerosene is a commonly used fuel for the first stage of a rocket launch due to its high density and ease of handling compared to LOx/LH2 propellant. It is worth noticing that the emission of CO2 from kerosene is an essential environmental consideration as RP-1 has 34% Carbon content (ibid). For instance, launching Falcon 9, a SpaceX rocket into space, consumed 440 tonnes of kerosene (spaceflight101, 2022). Thereby, it can be noted that the environmental effect of satellite mega-constellations cannot be neglected.

The above background provided a quick summary of the above 50 years of the satellite industry. The next chapter will focus on how the new satellite paradigm and its impact on sustainability have been studied and presented in the literature.

3 LITERATURE REVIEW

This chapter focuses on the concept of mega-constellations and the evolvement of the satellite industry to the internet age. The second section of the chapter discusses how the literature linked mega-constellations to sustainable development goals. In general, the majority of mega-constellation investigations have focused on environmental impacts. However, the societal consequences of mega-constellations and how they will affect other sectors have been overlooked in the literature.

3.1 Mega-Constellations and the Commercial Space

To begin, mega satellite constellations aim to provide worldwide internet coverage. This considerable investment is in response to the ever-increasing demand for low-cost broadband capacity, especially in developing countries with limited access to terrestrial networks (Sánchez & Wolahan, 2017). Therefore, many commercial operators plan to launch thousands of satellites in low earth orbit LEO to supply global space-based wi-fi (Pardini & Anselmo, 2020). According to the European Space Agency (ESA), **12,720** satellites have been launched throughout the history of the space industry since 1957, currently **5,200** active satellites as of March 2022 (ESA, 2022). In 2020, **1,283** satellites were launched, which stands as the highest number of satellites launches in a year compared to all the previous history of the satellite industry (Mohanta, 2021). Figure 2 shows a graph from Statista (2022) of the acceleration of satellite launches in recent years.

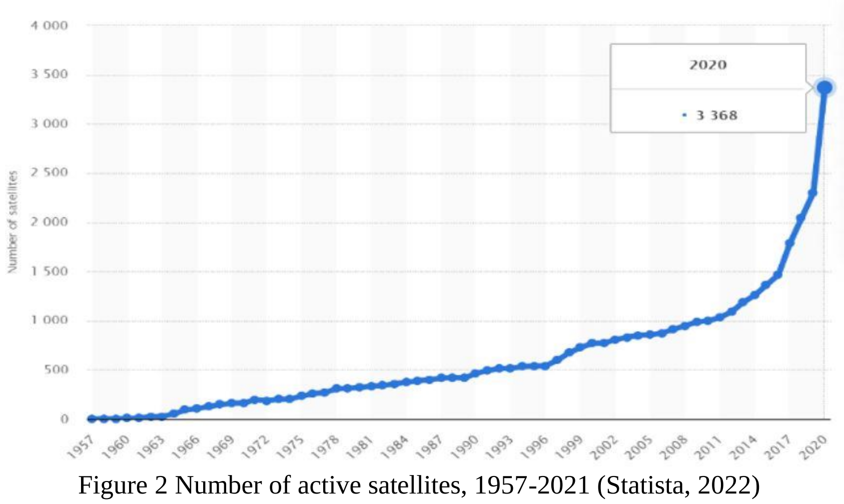

Figure 2 Number of active satellites, 1957-2021 (Statista, 2022)

Note: This statistic illustrates the number of active satellites from 1957 to 2021, broken down by year. In 2021, there was an estimated 4,877 operational satellites orbiting the Earth, an increase from 3,291 active satellites in 2020.

As already discussed in the introduction, the number of satellites is expected to increase significantly within the coming years and decades because of the new actors (e.g., SpaceX's Starlink program and initiatives from Amazon and Samsung). Also, existing satellite companies such as SpaceWork's annual rate of smaller satellites (nanosat and CubeSats with weights below 50kg) is projected to be 3,000 nano/microsatellites (Christensen, 2016). Between 2019 and 2028, more than 9,900 satellites are expected to be launched, roughly four times the number launched in the preceding decade (2009–2018) (Park et al., 2020). As the commercial space sector expands and new actors enter the space sector, this number will continue to rise to 20,000 satellites by the end of the decade (EU Space Policy, 2019).

Furthermore, in her article “Who owns our orbit", Therese Wood discusses the new space race with a comprehensive analysis and forecast of satellite production and launch services. According to the essay, it is estimated that this race will continue to accelerate, with 15,000 satellites in orbit by 2028. Based on the assumption that 990 satellites will be launched annually, compared to 230 satellites on a yearly average in the previous decade (Wood, 2020). Also, different studies predict that mega-constellations will approximately launch 136,000 new communications satellites in the coming decades (Perks, 2021). The main reason for the surge in satellite launches is broadband services. Therefore, the new space race appears to be collaborative and commercialized, unlike the last space race, a nationalistic struggle between Cold War competitors.

What is striking in Figure 2 is the exploding growth of the number of satellites launches in the 2010s. The main reason for this high rate is a reduction in payload costs. The cost of sending payloads to orbit remained so expensive for years until the breakthrough came in the 2010s with the partially reusable Falcon 9 and Falcon Heavy rockets (Baumstarck, 2021). These new types of rockets have driven dramatic cost reductions, and the price to get the payload into Earth’s orbit has fallen, leading to an enormous increase in the number of operational satellites orbiting the Earth (Baumstarck, 2021). Peter Platzer, CEO of Spire Global, confirmed this in an interview about satellites and mega-constellations (Thomsen, 2022). Platzer commented that space-based applications were once developed exclusively by governments, but commercial companies are now leading the way (ibid). There, reusable rockets will not only attain cost savings of satellites launches but also may increase satellite mass production, and satellite technology maturation.

Various studies have assessed the economic impact of mega-constellations. According to a consultancy report from Morgan Stanley, the global space sector might earn $1 trillion or more in income by 2040 (Morgan Stanley, 2020). Additionally, during the 2010s, several countries have increased their space research and development budgets. EU Industry Commissioner Thierry Breton explains why the EU allocates 6 billion Euros to a satellite communication strategy. “Our new connectivity infrastructure will deliver high-speed internet access, serve as a back-up to our current internet infrastructure, increase our resilience and cyber security, and provide connectivity to the whole of Europe and Africa" (Newelectronics, 2022). Furthermore, South Korea’s government has announced an “Industrialization Strategy of Space Technology” to maximize the socio-economic impacts of space technology, as pointed out by Park et al. (2020) when performing an economic analysis of mega-constellations in South Korea. As part of the strategy, there is a plan for transferring satellite technologies from the public to the private domain. Also, in 2019 South Korea’s fundamental space research and development network increased from 60 to 381 organizations with an average annual growth rate of approximately 20.3 percent and a total cost of around 3.8 billion USD (Park et al., 2020).

More economic impacts of the commercial space industry were investigated by Kelly George (George, 2019). By using the input-output analysis industry accounts for 2016 to predict the growth rate. George calculated the average employment change using the 7% growth in the industry during that year, and the result was 36 thousand jobs or a 0.02% increase. For instance, the same year in Florida, where there are launch/landing facilities for satellites, the added employment increased by 973 jobs in real estate sector, 805 in wholesale trade and 716 in hospitals. Therefore, according to George, growth in commercial space industry jobs would positively impact the economy (George, 2019).

Previous research into mega-constellations of satellites has focused on the environmental impacts. Many of these studies agreed that the deployment of mega-constellations in LEO will have a profound and durable overall impact on space activities and operations. Also, many researchers have acknowledged that the potentially damaging effects mega-constellations might have on the LEO debris environment are undeniable. Pardini and Anselmo (2020) predicted that these mega-constellations would increase the current collision rate among satellite objects, which will increase space debris. Similarly, Ian Christensen conducted a literature review study and concluded that space sustainability issues were raised by expanding the commercial space sector. The prominent constellations of small satellites operating in the same orbit significantly increase the number of potential collisions (Christensen, 2016). Also, in other studies, satellite mega-constellation's reliability is identified as a potentially catastrophic impact on the space debris environment if satellites fail to deorbit (Castet et al., 2009; Sánchez & Wolahan, 2017).

According to Megan Perks, a physicist and astronomer, the most beneficial service satellites and maybe especially mega-constellations can provide is global coverage (Perks, 2021). The concept of a global high-speed internet infrastructure that would connect even the world's most remote regions appears quite appealing. Nevertheless, Perks raise the question of "how much would such a system cost, and who would be responsible for paying it?". Perks explained that Starlink, OneWeb, and Amazon Kuiper think that the financial costs of such networks are reasonable, but the rest of the world must pay far more (Perks, 2021). The quantity, value, and mass of satellites will change dramatically in the coming years (Wood, 2020). A significant problem with this kind of acceleration in production is that the resources shipped out into space that we likely can never reuse them.

To sum up, this thesis aims to study the paradox of how a balance can be deviated by some agendas against other agendas or, more specifically, the digital inclusion problem against environmental issues. The following section will reflect the literature on the positive and negative impacts of this acceleration on society and the environment from a sustainability perspective. The concept of sustainability and the UN agenda will be explained. Then data from several studies about how satellite mega-constellations impact selected SDGs will be presented.

3.2 Sustainability and UN Agenda 2030

UNESCO described sustainability as a long-term goal, while sustainable development refers to the many processes and pathways to achieve it (UNESCO, 2021). Back in 2000, the Millennium Development Goals (MDGs) were agreed upon as an essential framework for the development of societies. Although there has been significant progress in several areas, the progress has been uneven, particularly in Africa. Therefore, some MDGs remained off track and therefore new goals were formed (UN General assembly, 2015).

In September 2015, at UN Headquarters in New York, 150 world leaders agreed to new global goals or the Sustainable Development Goals (SDGs) that are even more ambitious than the MDGs (United Nations, 2015). While MDGs helped to halve extreme poverty, this new agenda entitled "Transforming Our World: The 2030 Agenda for Sustainable Development" aims to end it (United Nations, 2015).

In addition, the 2030 Agenda has inclusion at its core with its 17 goals that include 169 targets. Developing the SDGs agenda was proposed by the Open Working Group and continued through a three-year-long transparent, participatory process of different stakeholders and people's voices. Many stakeholders, especially youth, were involved from the beginning on social media and other platforms. More than 8 million votes worldwide, and 75% of participants were under 30 (United Nations, 2015). By the end of this exercise, 193 Member States of the United Nations embarked and pledged a new strategy "No one will be left behind". The ambitious new global development agenda recognizes that development will only be sustainable if it remains inclusive (UN General assembly, 2015).

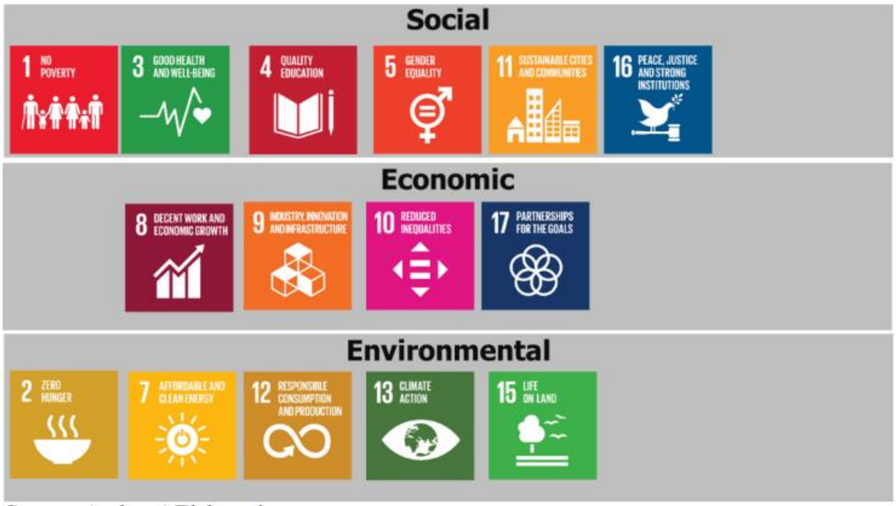

Figure 3 The Aggregation of SDGs into the Three Pillars (Paoli & Addeo, 2019)

Further, the agreement recognizes that ending poverty and other deprivations must go together with strategies that improve healthcare and education, reduce inequality, and spur economic growth. All this while balancing climate change and working to preserve the environment (United Nations, 2015). Figure 3 shows that sustainability has three elements, or what is known as the triple bottom line of economic sustainability, social sustainability, and environmental sustainability (Elkington, 2004). Therefore, according to the UN development agenda, it is crucial to harmonize economic growth, social inclusion and environmental protection. These elements are interconnected, and all are crucial for the well-being of individuals and societies (UN development agenda,2015; UN General assembly, 2015).

This research aims to investigate the impact of technology on the SDGs. As it was found that the essential accelerator for the transformation of societies is Information and Communications Technology (ICT). ICT has proven to be the fastest and most global technological adoption in human history since the mobile broadband revolution. ICT and mobile communication technologies have had a more significant impact on the country and society's growth than any other domain. ICT is also a catalyst for better resource management, with sound effects on education, financial inclusion, health, and energy, as well as connecting the disconnected.

As the International Telecommunication Union (ITU) describes, “ICT has the potential to accelerate progress toward achieving the SDGs” (ITU report, 2021; Ericsson & EIC university, 2016). All of this is a solid motivation to investigate the impact of ICT on the United Nations’ 2030 Agenda.

The ITU, as an intergovernmental body responsible for coordinating communications systems, adopted the concept of “leaving no one behind”. ITU unveiled a strategic goal for inclusion called "leaving no one offline" (ITU report, 2021). For instance, COVID-19 has demonstrated that no one is safe until we are all safe; nonetheless, the Internet is used by little over half of the world’s population (GSMA, 2021). There, applications that allowed distance learning or e-health systems were unavailable for all. As a result, it is important to remember that we will not be able to fully realize the potential of ICTs until everyone is online. To ensure that no one is left behind, everyone must have access to the vital digital infrastructure, services, and applications used during the COVID-19 crisis by the developed parts of the world.

When it comes to satellite systems and the UN agenda, the Organization for Economic Cooperation and Development (OECD) with the International Futures Program (IFP) has published several reports related to space during the years 2004 to 2014 (OCED, n.d.). In the “Space Project 2030” by IFP participants forecasted several scenarios for the social role satellites may play in future (OCED, 2004). First, in the healthcare sector, they predicted that satellites would contribute to the vision of the World Health Organization (WHO): “health for all in the 21st century”. This will increase healthcare availability by actively supporting telemedicine in the developing world. Second, in the education sector, they assumed that EducSat will expand as more countries will recognize the merits of the online education (OCED, 2004).

To sum up, any technology’s environmental, social, and economic costs must be lower than its benefits (Durrieu & Nelson, 2013). This indicates that to support communication systems in achieving any of the SDGs, we must guarantee that these systems are as sustainable as possible. This study investigates the potential that the future satellite business may provide in terms of pushing the health and education agenda and the environmental costs that society will incur in the process. Therefore, the next section will reflect from the literature, the influence of satellite mega-constellations (SDG 9) on two social SDGs: health (SDG 3) and education (SDG 4). Furthermore, the impact of mega-constellations (SDG 9) on environmental SDGs represents resource consumption (SDG 12).

3.3 Existing Research on the Impacts of Satellite Systems on the SDGs

3.3.1 Impacts on Industry, Innovation, and Infrastructure (SDG 9)

The GSMA, in their 2021 report, estimated that 450 million people globally do not have access to a fixed or mobile broadband signal. This figure is largely concentrated in underdeveloped countries (GSMA, 2021). Broadband or high-speed internet connectivity is no longer a luxury but a need for both developed and developing countries’ economic and human development (WorldBank, 2016). Internet is a vital tool for delivering critical services like education and healthcare as well as environmental sustainability and contributes to enhance governments performance (ibid).

The challenge is to expand broadband access and close 'digital divides' that exist across regions and countries. Such divides within countries have an unequal impact on poor rural communities. However, in support of SDG 9.c: "strive to provide universal and affordable access to the internet in the least developed countries by 2020", satellite-based systems could be an option to address the digital divide. This is due to the wide coverage capabilities of space-based infrastructure that could accelerate the uptake. Using satellites to close such coverage gaps has been pursued since the early 1990s (Croshier, 2022). However, satellite development and deployment took more time than planned, and costs were too high, which reduced its potential for profitability compared to land-based systems. Meanwhile, terrestrial infrastructure evolved more quickly, and it is predicted that traditional terrestrial infrastructure will continue to have far more capacity, about 2,000 terabytes per second by 2026 (Croshier, 2022). Table 2 compares coverage and delay between different platforms (Ravishankar et al., 2020). As can be noted, satellites can provide huge coverage but can also have long delay times.

Table 2 Coverage and delay comparison between satellites and 4G/5G cells (Ravishankar et al., 2020)

Platform	Typical altitude	Min delay	Edge Coverage	Max delay
GEO satellite	35 786 km	239 ms	41 672 km	278 ms
MEO satellite	~8000 km	53 ms	9423 km	63 ms
LEO satellite	~1200 km	8 ms	1692 km	11 ms
Cell tower	~0.05 km	0.000 33 ms	25 km	0.16 ms

The entry of a strong and diverse private space sector into the satellite industry has affected launch costs. George (2019) studied the impact of commercial businesses entering the space sector and how the market structure of the satellite industry was altered. It is predicted that boosting the role of commercial space enterprises in production and launch operations would lower the cost of satellite services. In June 2017, the economic value of satellite space activities was estimated at $339 billion (George, 2019). Using reusable rocket stages, the cost of launching a satellite has dropped from $200 million to around $60 million, with a potential drop to as low as $5 million (Morgan Stanley, 2020). If these projections are actual, the satellite sector might supply affordable and accessible technology in a few years. Currently communications satellites make up more than 60% of the overall number of satellites. As long as there are investments with the attempt to provide high-speed internet access to every corner of the globe though satellite systems continue, this figure will continue to rise (DEWESoft, 2022).

According to Croshier (2022), the OECD calculated the cost of extending broadband internet to the whole population of Africa using terrestrial infrastructures such as fiber and mobile towers might cost $100 billion in 2020. However, according to Morgan Stanley report, it is expected that with the introduction of satellite internet, the cost of wireless data will be less than 1% of current levels (Morgan Stanley, 2020). Therefore, satellite broadband internet connectivity could provide enormous opportunities for digital inclusion. Hence, launching satellites that offer broadband internet service could help reduce the cost of data when demand for it increases (Morgan Stanley, 2020). Examples of future bandwidth demands include autonomous cars, the Internet of Things (IoT), artificial intelligence, virtual reality, and video, to name a few.

One study by Sedin et al. (2020) discussed the expected capabilities of the 5G core network and how it is expected to be flexible and adaptable. Their vision of 5G is to provide high-speed connectivity to support applications such as the IoT, automotive, and emergency communications. Also, 5G aim to consider future factories, health care, augmented virtual reality, and tactile internet. In response to this high futuristic demand, Non- Terrestrial Network (NTN) technologies are being considered in the 5G standardization process. NTN refers to a network utilizing a space-based platform for communication. Examples of space-based platforms include LEO satellites, medium Earth orbiting (MEO) satellites, and geosynchronous Earth orbiting (GEO) satellites, as well as high-altitude platform systems (HAPS) and air-to-ground networks (Sedin et al., 2020). Satellites can play a significant complementary role to terrestrial networks through this hybrid model. At the same time, this will allow the satellite industry to benefit from the robust interoperability of the mobile ecosystem (Sedin et al., 2020).

Moreover, in their paper, Ravishankar et al. (2020) discussed several scenarios, among them how the IoT market requires worldwide coverage. Therefore, IoT is a crucial use case for satellite-based connectivity. Ravishankar et al. presented end-to-end system architectures and protocol architectures that use mega-constellations as part of an ecosystem based on terrestrial 5G specifications. They concluded that using satellite based as a backhaul will provide affordable tracking antennas that will directly serve consumers in the developed and large communities in developing countries (Ravishankar et al., 2020).

To conclude, mobile networks can extend their coverage through this hybrid model, while satellite services can be provided directly to the users or provide trunking and back-hauling capabilities (Gaudenzi, 2019). With the rising demand for broadband, a new market strategy with a better baseline business case will be developed. This new trend will provide an environment for space-based communications to provide more affordable connectivity to individuals who are currently on the dark side of the digital divide.

3.3.2 Impacts on Good Health and Well-Being (SDG 3)

Moving to the second development goal this research is investigating, SDG 3, which aims to provide good health and well-being. In general, the WHO has adopted the following broad description of telemedicine “The delivery of health care services, where distance is a critical factor, by all health care professionals using information and communication technologies for the exchange of valid information for diagnosis, treatment and prevention of disease and injuries, research and evaluation, and for the continuing education of health care providers, all in the interests of advancing the health of individuals and their communities” (WHO, 2010).

A classic example of the first documented telemedicine telephonic consultation took place in 1879. Thus, telemedicine is not a new concept (Mars, 2013). The terms (telemedicine OR telehealth OR tele-health OR ehealth OR e-health OR mhealth OR m-health) returned 22,947 papers in SCOPUS’s electronic database (Mars, 2013). However, the illness load is enormous, and healthcare services in underdeveloped nations are still in a poor state. As a result, telemedicine has the potential to increase access to scarce specialist care, enhance the quality of care in rural areas, and lessen the need for rural patients to travel for medical treatment. Also, telemedicine is considered a way to support rural doctors, overcome doctor shortages, deliver education, and facilitate research (Mars, 2013).

In 1994 a group proposed a telemedicine technique which enables instantaneous diagnosis from a land-based medical specialist to a moving vehicle far from the location based on mobile satellite communication (Murakami et al., 1994). An image, an audio signal and physiological signals, such as ECG and blood pressure, are obtained from a patient. Transmitted to a satellite, and instructions from the doctor were sent back to the mobile station via satellite (Murakami et al., 1994). However, no evidence was found that this project moved to the pilot phase. Later in 1999, UNISPACE III stated that activities of the United Nations Programme on Space Applications should improve public healthcare services (UNOOSA, 1999). The program should assist developing countries in advancing space-based solutions for telemedicine. Thus, healthcare systems should embrace computer and telecommunications technologies, including satellite communications, to bring medical experts into virtual contact with patients or doctors in remote and rural areas, thus avoiding a costly relocation to hospitals in urban areas (ibid).

Moreover, several practices for the use of space in public healthcare were found in the literature review. Using scoping review methodology, including a literature review for 473 articles and the involvement of stakeholders, Dietrich and his colleagues managed to link satellite applications to the global health domain (Dietrich, 2018). They summarized that satellite communication could be useful in many areas. Firstly, medical expertise or resources are not available on-site, but the patient may be physically present in the health centers. In this case, they are connecting the medical practitioner to the patient. Secondly, medical tele-education, which is providing medical education via distance learning. The third case introduces the concept of health-on-the-go, which covers a large area that may be deprived of traditional communication systems by health care services. Lastly, satellite communication is also valuable in emergencies arising from natural disasters or man-made disasters. For example, Satellites for Epidemiology (SAFE) is a system that combines satellite, radio, wireless networks, and Geographic Information System (GIS) to promptly identify and respond to a disease outbreak, especially if terrestrial networks are not accessible (Dietrich, 2018).

Furthermore, a large and growing body of literature has investigated the evolvement of using satellite applications in telehealth. To begin with, two researchers tracked the evolvement of mobile broadband capabilities in telemedicine from 2010 to 2019 (Saravanan & Sudhakar, 2020). They concluded that in 2010 internet speed for 2G was 256 kbps which was impossible to convey videos and big images like X-Ray to the field or rural areas. In 2013 the speed became 3 Mbps and in 2014 jumped to 10 Mbps, and this continued to accelerate till 2019, when the speed reached 100 Mbps. Although this advancement in transmission speed yet, coverage is limited by the number of internet users and distance from mobile towers, where internet signal propagation becomes weaker. As an experience, the researchers linked a satellite system to set up a dish antenna and made a maximum of 65 Mbps internet to transmit big data with less transmission delay. This supports the transmission of big data like the patients of ECG, EMG, pulse rate, heart rate, respiration signal, temperate, and pressure is monitored on a computer, and mobile phone live with reduced transmission delay at the receiver side (Saravanan & Sudhakar, 2020). Similarly, some other researchers studied ambulance transport between healthcare facilities with medical support via telemedicine (Pedrotti et al., 2021). This study was conducted with a single health center that worked as a reference for satellite emergency departments for one hospital. It was a big step in the use of telehealth in transport that allowed qualified doctors to provide support for several ambulances, which reduced the costs for the healthcare system (Pedrotti et al., 2021).

Moreover, on the business side of the satellite industry, many satellite players, including Inmarsat, Globalstar, and Eutelsat, have invested in healthcare research to better understand the market. According to the Healthcare Satellite Connectivity research report (2021), the market value in 2020 was US$ 15.1 billion; however, it is anticipated that this market will grow to 17.1 % during the forecast period 2021 to 2030 (Healthcare Satellite Connectivity market research report, 2021). Typically, several satellite operators have started initiatives that support health projects. One example is in Nigeria, the collaboration of Inmarsat with InStrat (health solutions provider) on a project aimed at raising the standard of healthcare outcomes in areas with unreliable or non-existent terrestrial communication networks. The project provided video-based healthcare worker training and improved disease monitoring. Examples of remote video training in action included the resuscitation of newborns and saving women's lives in childbirth. Also, through this project, disease reporting rates in the areas rose from 20% to 65%, with the speed and accuracy of data analysis significantly increased (Inmarsat, 2014).

From the above, it is clear that throughout history, telemedicine has benefited from satellite technology in conveying text messages, images, and videos. However, literature lacked on reflecting how telemedicine will benefit from the revolution in the satellite industry. Already in 2008, Graschew et al. commented that the satellite communication systems have for years complemented damaged terrestrial communications. However, it is expected in the future that the growing adoption of satellite technology and the use of IoT will drive the growth of this segment (Graschew et al., 2008). More recently, Starlink has stated that satellite internet speeds will reach 1 Gbps with a full operation (Reisinger, 2019). Thus, some researchers think that satellite communication may extend its support to e-health by providing not only tele-medicine but also telesurgery services. Telesurgery could mean doctors from Europe can operate on patients in remote corners of Africa using a robotic machine (Froehlich et al., 2021). However, this technology is far too expensive and difficult to obtain, but in future, the cost could perhaps come down so that contemporary internet connections can save many lives in Africa (Froehlich et al., 2021).

As mentioned earlier, in 2004, the OECD Space Project discussed a scenario within a positive political and economic climate that priorities the world's principal social problems exemplified in healthcare and education. This scenario imagined that by 2030 satellites will support the WHO through telemedicine to achieve its goal of "health for all in the 21st century", especially during pandemics (OECD,2004). However, in April 2021, a review session was conducted to appraise the practices of space science and technology for global health by the Peaceful Uses of Outer Space Scientific and Technical Subcommittee (UNOOSA, 2021). Some attendees pointed out some telemedicine and telehealth deficiencies in utilizing satellite technology. The first gap that worth noticing is the necessity to design new health-related emergency systems that actively exploit space-based technologies and improve the existing ones. Second, many participants feel that attaining the full potential of space technology's benefits in the health industry is now impossible (UNOOSA, 2021).

From the above, it can be concluded that space technology and satellite mega-constellations could cover a gap in healthcare systems. However, digital practices that can utilize these capabilities are still way behind.

3.3.3 Impacts on Quality Education (SDG 4)

The lack of academic literature on satellite mega-constellations and SDG 4 has revealed the gap in this area. In 2004 the participants in OECD Space Project at that time anticipated that the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the International Labor Organization (ILO) would promote distance learning (OECD, 2004). It was believed that it would be an effective way to reduce educational inequalities and facilitate the education of the rapidly growing working-age population in developing countries. Membership in EducSat gradually increased as more countries recognized the merits of tele-education (OECD, 2004).

Jumping to the year 2021, several researchers investigated how digital divides and the lack of internet connectivity within Africa could be addressed by new technologies and commitments from terrestrial and space actors (Froehlich et al., 2021). They analyzed the E-Government Development Index (EGDI), which is the readiness and capacity of national institutions to use ICTs to deliver public services. It turns out that Africa exhibits poor e-government readiness levels and the lowest regional averages across all indices. Lack of communication infrastructure is considered the most significant hurdle currently facing e-government adoption within the continents, as Africa internet connectivity remains the most challenging factor in the digital divide. Therefore, space-based internet and communication were provided as a solution as it has the advantage of providing global coverage. This means it can significantly support governance in Africa. However, Froehlich et al. (2021) mentioned two factors that could hinder this technology. The first factor is the affordability, as communication and internet provided by geostationary satellites are expensive; around US$ 150 per month is unattainable for a large number of people on the African continent. The second factor is the illiteracy problem; in 2018, one out of every three people aged over 15 were found to be illiterate (ibid).

From previous sections, large-constellation satellite internet, if offered in decreasing launch costs, may provide more affordable access. Thus, Satellite Internet may allow education opportunities in rural areas through e-education. Yet we must face the illiteracy problem in these areas, and solutions must be tailor-made to address the specific digital divides of each geographic location to ensure inclusivity (Froehlich et al., 2021). In summary, there is a research gap yet to be covered to reflect how the new capabilities of the satellite industry could assist in closing this digital divide.

3.3.4 Impacts on Responsible Consumption and Production (SDG 12)

While there are several environmental impacts resulting from the launch of a space satellite, the impact on the ozone atmosphere from rocket emissions is the most studied. Also, much of the available literature focused on the removal of satellites operating in the low Earth orbit at the end of their lifetime to prevent them from posing collision risks to other missions. However, very little is currently known about the loss of the resources used in these satellites if we never deorbit them. This section will address the gap in the literature on how mega-constellations of thousands of satellites will impact the depletion of vital resources from Earth.

Satellites have played an essential role in various fields, including civil, political, military, and, most recently, commercial. As discussed in section 3.3.1, more computing capacity, data storage and networking technology will be loaded onto satellites to create a space-based internet backbone. But the increase in space traffic due to multiple large satellite constellations worryingly increases the risk of collisions with existing space debris and other satellites, which will create more debris (Croshier, 2022). Scientists predicted in 1978 that an increase in the number of uncontrollable objects in Earth's orbit would eventually lead to cascading collisions and self-perpetuating proliferation of space junk (Kessler & Palais, 1978). Ten years later, Su developed a model to investigate the interaction of constellation satellites with other groups of space objects and predicted that a 2% annual increase in satellite traffic intake would result in a debris runaway situation (Su, 1986; Su, 1997).

A study by Pardini and Anselmo (2020) concluded that approximately one hundred more satellites would be sufficient to increase the current collision rate in LEO by ~10% (Pardini & Anselmo, 2020). A year later, the two researchers declared that the overall mass of artificial objects in orbit around the planet increased by 22% between 2014 and 2020 (Pardini & Anselmo, 2021). Figure 3 displays the acceleration of space debris over decades until it reaches one million for objects between 1 cm and 10 cm (ESA, 2022). Several studies have explored the correlation between the number of satellites in a constellation and the amount of LEO debris. According to Pardini & Anselmo's research, commercial businesses' planned constellations will increase the total LEO collision rate by 20–30% over their lifetime. Furthermore, the researchers are pessimistic about space debris' future (Pardini & Anselmo, 2021). In the next 25 years, if no serious action is taken, the global collision rate in LEO between objects larger than 10 cm will increase by more than 50% (ibid). Thus, the proposed plan of launching many satellites involved in the mega-constellation satellite by commercial satellite operators might have damaging effects on the LEO debris environment that cannot be neglected.

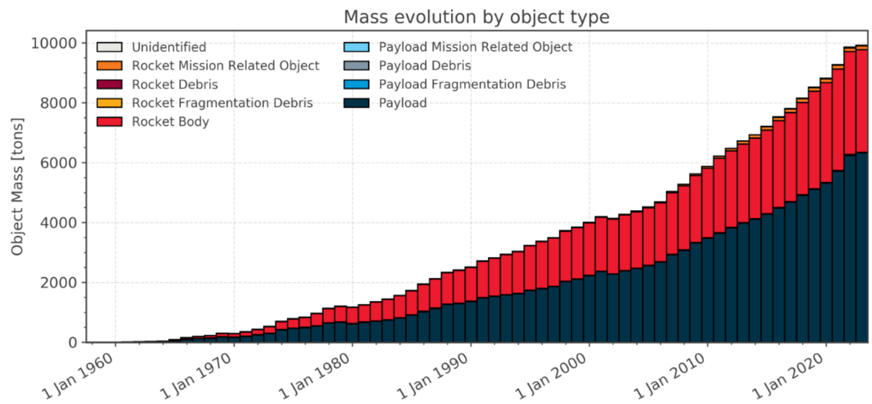

Figure 4 Space Debris over the years (ESA, 2022)

Note: This Space Debris Environment Report issued by ESA's Space Debris Office. Environment Statistics published by Dr. Francesca Letizia April 04, 2022.

Moreover, Maclay et al. (2021) mentioned environmental effects that can change a satellite material property, including thermal cycling, radiation exposure, and atomic oxygen impingement. Such events have previously caused explosions of batteries and fuel tanks in satellites and launch vehicles that were left in orbit after the completion of their missions. This would increase the probability of collision rate and create more debris objects orbiting the Earth.

The literature showed many suggestions for the predicted mega-constellation satellites' consequential risk to the space environment. One suggestion is to increase the post-mission disposal success probability to at least 95%, hopefully to 99% (Pardini & Anselmo, 2020). Others suggested that we should ensure every service from space is also provided independently from the ground (Maclay et al., 2021). However, Sánchez et al. reflected that currently, we do not have enough information to investigate the correlation between mega-constellations and space debris. Firstly, space applications' current reliability prediction process has many inadequacies and limitations. Secondly, the available field data regarding low Earth orbit satellites may not be representative due to the revolutionary design, manufacturing, and testing approach proposed by the mega constellation satellite suppliers (Sánchez et al., 2017). In support of this opinion, in their research about space debris, Durin and his colleagues motivated that a more detailed analysis of the debris model is required (Durin et al., 2022).

Richard Smith, in his book "*Beyond Growth or Beyond Capitalism*" discuss how humans are consuming more resources than the Earth can regenerate (Smith, 2010). When it comes to modern spacecraft, it is typically 80 percent aluminum by weight (Wassmer,2015). Moreover, the energy systems of satellites broadly consist of batteries, power systems, and solar paddles, as explained in section 2.1. The power system takes up about 20-30 % of spacecraft mass and is primarily used for power management generation, distribution, and energy storage. The pack of batteries in the power generation unit stores energy which accounts for more than 10-25 % of the mass of the satellites. Lastly, the solar paddle subsystem accounts for 15-20 % of a satellite's total weight (Baraskar et al., 2022). One of the problems facing the space industry is determining how to deorbit pieces that have been lost in satellite collisions. This analysis shows the massive quantity of resources that will be lost if such spacecraft never return to Earth again due to satellite collisions. This amount is of particular importance to this research to explore the impacts of mega-constellations investment from a resource exhaustion point of view.

From the above, it can be clearly seen that an extended and expanded operation of mega-constellations (SDG 9) would be inconsistent with environmental sustainability (SDG 12). At the same time, the commercial space race may positively impact health and education agendas (SDG 3 and 4); however, studies on the social and environmental balance of mega-constellations are rare. This research attempts to shed light on how changes in technology can impact one sustainable development goal and negatively or positively interact with other goals. The following chapters will illustrate the research process and research findings.

4 THEORETICAL FRAMEWORK

This research will attempt to explore the potential impact of future satellite industry capabilities on the healthcare and education sectors while considering the environmental impact. The dual strategy of merging education and healthcare is justified by the fact that the needs for both sectors are often located together. Furthermore, the fundamental communication needs for educational and healthcare services are extremely similar (Edin et al., 1995). The following sections will explain two theoretical frameworks that have been used during the research process. First, a business model themes theoretical framework will be utilized to compare satellite systems and land-based business models from a value creation perspective for people in remote areas. Second, a framework for understanding SDGs interactions by Nilsson et al. (2016) will be adopted to interlink the SDGs and the satellite systems' impacts.

4.1 Business Model Themes Framework

The first framework that will be used in this study is related to value creation in e-business developed by Amit and Zott (2001). Figure 5 shows the four configurations or designs that drive value creation in business model design: complementarity, efficiency, novelty, and lock-in. First, when the value of the whole surpasses the worth of the parts, complementarity is achieved; for example, selling a bundle of items together may provide greater value than selling a single product. Second, efficiency refers to the management of a company's resources. The lower the cost, the more valuable the company's offers become as transaction efficiency improves (Amitt & Zott, 2001).

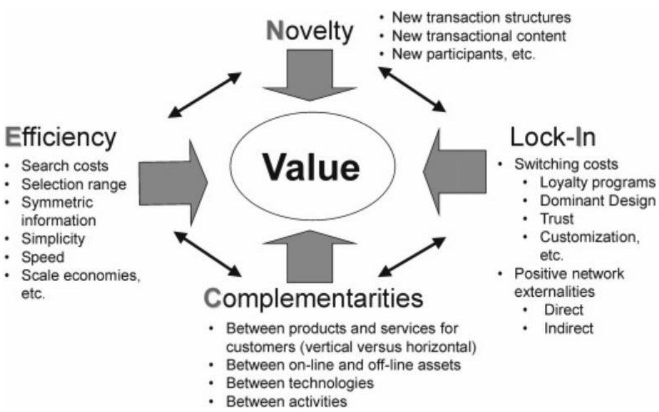

Figure 5 Sources of value creation in e-business (Amit & Zott, 2001)

Third, lock-in encourages customers to make recurrent purchases and avoid switching to competitors. Customers can be locked in through loyalty programs, special benefits, and the development of trusting relationships with personalized products tailored to their specific demands. The model's final configuration is Novelty, which develops the adoption of new business practices (Amitt & Zott, 2001).

Transaction content, structure, and governance are three factors that Amit and Zott included in their business model description. They see a business model as a unified unit of analysis that captures value creation through the use of business opportunities (Amit & Zott, 2001). The scholars inspired theoretical perspectives that inform the study of boundary-spanning organization design. The authors also adopted Miller's design themes, which connect the elements of a business model, such as innovation and efficiency. Although these factors are not mutually exclusive, their use can reflect important alternatives for entrepreneurs to create value in the face of uncertainty. Moreover, the empirical findings of Amit and Zott indicated that businesses could innovate not only by recombining their own resources but also by using the resources of their partners, suppliers, and customers. As a result, this approach connects business model design to entrepreneurial firm performance under a variety of environmental conditions. Finally, the business model themes framework operationalizes and measures the business model construct, demonstrating its impact on value creation empirically (ibid).

For many years, telecom operators have offered internet packages and have quietly evolved through time. However, demand for satellite internet that can adapt dynamically and seamlessly to changing market conditions is expected to grow. For example, geographically distributed traffic requests like autonomous cars may provide value to satellite operators, transforming the satellite telecommunications industry. Also, the new economic model of the satellite business is projected to enable internet access in previously impossible ways. Therefore, this research aims to examine the business models of commercial satellite operators and telecom companies in terms of value creation for people in rural areas. As a result, this theoretical framework will compare and contrast satellite-based futuristic business models with the existing telecom operators' business models. In conclusion, the researcher chose the value creation model by Amit and Zott to analyze these two business models' performances to a specific segment.

4.2 SDGs Interactions Framework

Despite widespread acknowledgement of health and education as essential aspects of a sustainable society, significant gaps in education and health care services persist. Many people either have limited access to primary education or health care or may not have access at all. Predicted population growth, especially in the most afflicted areas, would place even greater burden on education and health-care efforts. Complex economic, political, social, and cultural considerations sometimes limit access to education and health care services (OECD, 2004). One technological solution cannot hope to resolve such vast and complex shortcomings. However, it has been shown that technology can help to improve the issue. Modern telecommunications technology, in particular, has the potential to play a significant role in this situation. In densely populated locations, it was found that terrestrial communications infrastructures offer a greater capacity of people at a low cost. However, they may not be cost-effective in isolated areas with low population density. As a result, it was proposed in 1995 that satellite systems could be an effective way of delivering the essential communication links in the absence of terrestrial networks (Edin et al., 1995).

Further, the space sector is growing, and satellite utilization is expected to increase due to the mega-constellations lately supported by space companies. Satellite commercial operators plan to launch a massive number of satellites as part of these mega-constellations to establish a high-speed worldwide internet system. These constellations may fill a gap in digital inclusion for the healthcare and education sectors, however satellites constellations may also increase the environmental issues. There, it is crucial to study the impacts of this huge investment on sustainability as well as the changes that satellite internet will bring to the SDGs. Therefore, this study utilizes the SDGs interactions framework developed by Nilsson et al. (2016) to explore the critical interlinkages within and between SDG goals and associated targets. These interactions could support more strategic and integrated implementations.

Table 3 Seven types of interactions between SDG targets (Nilsson et al., 2016)

Interaction label	Meaning
+3 Indivisible	Progress on one target automatically delivers progress on another
+2 Reinforcing	Progress on one target makes it easier to make progress on another
+1 Enabling	Progress on one target creates conditions that enable progress on another
±0 Consistent	There is no significant link between two targets' progress
−1 Constraining	Progress on one target constrains the options for how to deliver on another
−2 Counteracting	Progress on one target makes it more difficult to make progress on another
−3 Cancelling	Progress on one target automatically leads to a negative impact on another

Table 3 shows that the SDGs interactions framework characterizes the range of positive and negative interactions between the various SDGs. Nilsson et al. (2016) have chosen {-3, -2, -1, 0, +1, +2, +3} as the scale range of the interactions. If a relation between two goals had a negative value, progress in one goal would cancel the second goal. In contrast, the positive values indicate that changes in one goal enable or reinforce the other. Typically, zero value means that the two goals' progress or hinders will not affect each other's. As a result, the magnitude of the score reveals the impact of one SDG or target on another in any direction (Nilsson et al., 2016). This approach will be applied to reflect how changes in one sustainable goal may affect positively or negatively other goals. This study, in particular, will investigate how SDG 9: Industry, Innovation, and Infrastructure can interact with: SDG 3: Good Health and Well-Being, SDG 4: Quality Education, and SDG 12: Responsible Consumption and Production.

According to Nilsson et al. (2018), the SDGs interaction paradigm will allow systematic thinking of the interactions across the SDGs. This could explain how changes in SDG 9 due to mega-constellations of satellites from firms like SpaceX would affect other goals, particularly resources consumptions under SDG 12. On the other hand, Climent and Haftor (2021) argue that the BMT framework explains the introduction of new actors to an industry may motivate potential rewards in value creation. They believe that emergence of a new industry and the provision of new service offerings reflect new types of technology with a wide variety of potential applications that could fill a latent market need (ibid). Overall, this study attempts to provide a helicopter view of what satellites commercial operators would bring to the internet as a service. Also, how would the new paradigm of satellite internet as a byproduct of satellite mega-constellations impact the entire ecosystem, including the social and the environmental. There, the study utilized both frameworks to achieve this goal.

5 METHODOLOGY

5.1 Research Approach and Research Strategy

A comprehensive study may have multiple purposes, but it must have a primary goal. Therefore, the primary goal of this research is to determine how the satellite industry's new paradigm should be conceived in light of the UN 2030 Agenda. The investigation will illustrate whether changes in SDG 9 by the introduction of mega-constellations and commercial space will impact health (SDG 3) and education (SDG 4) systems. Also, how these changes can overlook the effects on SDG 12 considering the existing offerings from the land-based systems.

Quantitative research based on a positivistic method typically assumes that hypotheses are drawn from some theory or hypothetical construct, making it deductive in nature and referred to as theory testing. A qualitative or constructivist method of research, on the other hand, can be considered inductive because the goal is to produce theory and explanations of phenomena rather than verify them (Newman, 2000). Researchers in the social sciences frequently employ qualitative research to understand better human behavior in diverse relational, organizational, and virtual contexts (Tracy, 2019). In this study, a qualitative approach was used to build a dynamic approach to the research as the use of follow-up and generating valuable conversation was vital during data collection.

In general, in deduction research, a theory and hypothesis (or hypotheses) are developed, and a research strategy is designed to test the hypothesis. With induction research, data are collected, and a theory is created as a result of the data analysis (Saunders et al., 2009). In the case of this research, the researcher is not framing a hypothesis about satellite internet but rather investigating its impact. Moreover, there is a gap in the literature in covering the balance between environmental and social impacts of mega-constellations in the satellite industry. Thus, this research is mostly conducting an inductive approach. However, according to Saunders et al., "Not only is it perfectly possible to combine deduction and induction within the same piece of research but also in our experience, it is often advantageous to do so." (Saunders et al., 2009). Therefore, the research deduced themes related to the environmental impacts of the commercial space movement based on previous research on mega-constellations of satellites.

On the other hand, the researcher's empathetic attitude toward social and environmental challenges is the driving force for this study's research strategy. This corresponds to the interpretivism theory, which requires the researcher to comprehend others' social roles through their own meanings (Saunders et al., 2009). Usually, survey strategy is mainly associated with the philosophical paradigm of positivism since it looks for patterns and generalizations, but it can also be used with interpretive and critical research (Oates, 2006). Since the topic is related to global internet coverage by satellite systems, a survey was the most convenient strategy. It will assist in obtaining data from a large group of people in a standardized and systematic way. Many people assume that if a survey strategy is chosen, then a questionnaire will be used for its data generation method. However, surveys are also possible through other data generation methods such as interviews, observations, and documents (Oates, 2006). Therefore, this survey research strategy will use interviews and questionnaires as data collection tools.

In addition, the main goal of this study is to consider the ecosystem of the communication industry when investigating the effect of the new business model on the industry. To study the paradox of supporting inclusive healthcare and education systems while considering the impact on the environment. This is because a research gap was found in balancing the social and the environmental when promoting space internet. Thus, the process started with the literature to understand what is there and how other researchers from different backgrounds investigated mega-constellations or commercial space. Then primary data were collected through questionnaires and interviews to grasp detailed insights. Later, themes and patterns were generated when the data were prepared, cleansed, and segmented. Lastly, all data were presented against the SDG interactions and the BMT frameworks from the previous chapter, and conclusions were reached. Figure 6 shows the research process, and the following sections will further illustrate the details of the data collection and analysis phases.

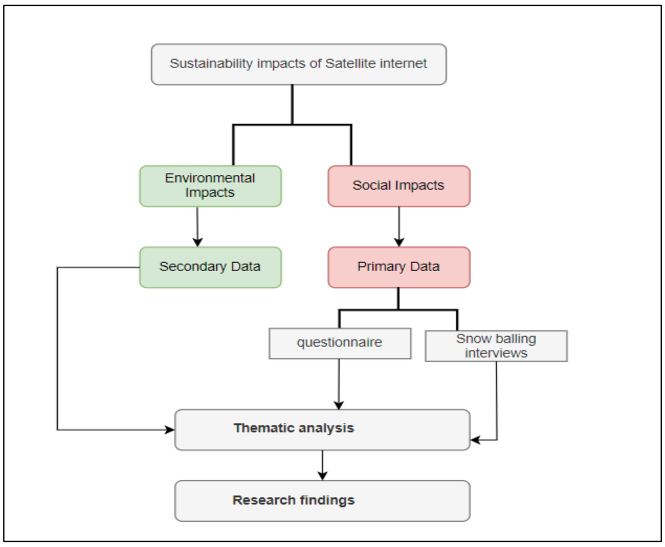

Figure 6 The Research Process

5.2 Data Collection Methodologies

According to Oates (2006), the researcher must decide what data they want to collect before starting to collect it. In this scenario, qualitative data are collected because the researcher is more interested in understanding why something is occurring rather than in being able to describe what is happening. The general aim of this research project is to investigate the environmental and social impacts of satellite internet on sustainability. Therefore, data about the satellite's fundamental components and life cycle were gathered from literature and analyzed accordingly. Also, the published literature needed to be investigated to understand the environmental impacts. However, primary data were collected for the social impacts to understand different stakeholders' opinions about the satellite mega-constellations and satellite internet. The study used questionnaires to collect data from different stakeholders' who could impact or be impacted by these mega-constellations. Later, interviews were used to generate data to understand specific stakeholders' angles. The next sections will explain how primary and secondary data were collected.

5.2.1 Secondary Data

The Literature Review Phase:

To begin, many comprehensive databases were employed as literature sources to gather relevant scientific papers from journals and conference proceedings to review for this study. This includes Google Scholar, ScienceDirect, Scopus, and the Uppsala library. Furthermore, relevant reports and documents were found and used as an additional source of information for this study. This contains reports from experts and the government, as well as websites and policy documents. The terms: (Sustainable Development Goals; SDGs; UN agenda; 2030 Agenda) and (Satellite; Satellite communication; contribution; interaction; Satellite impact on the environment; health and Satellite; Satellite and telemedicine; Satellite and telehealth; Education and Satellite; Teleducation with Satellite; EduSat) were used as search keywords.

Following the establishment of a list of references, the process was carried out by examining the content of each publication and reading the keywords, abstracts, and conclusions to see whether they were relevant to the proposed study. Furthermore, by selecting the most recent papers, the study addressed this new topic while simultaneously finding new research opportunities. Finally, linkages were built between various extracted sources. Each logical and persuasive argument was assessed for the research's usefulness and necessity using a matrix, and then similarities, contrasts, and gaps in the literature were identified as a result.

5.2.2 Primary Data

To fully understand the process of survey strategy, six different activities were conducted that can be broken down into: data requirements, data generation method, sampling frame, sampling technique, response rate, and non-responses, sample size (Oates, 2006). Data were gathered in multiple phases at various time points during the survey process. In the first phase questionnaire was used to collect as many opinions as possible. Then set of interviews followed this questionnaire to understand specific views more thoroughly. The next paragraphs will illustrate how this process was conducted within each phase.

The Questionnaire Phase:

Questionnaires are commonly connected with survey research and are widely used in research. This is an excellent tool for situations where a researcher has to gather data from many people yet merely needs to obtain brief, uncontroversial information. A questionnaire is a set of questions arranged in a particular order. Respondents must answer the questions for the researcher to assess and interpret the data (Oates, 2006). Typically, there are two sorts of questionnaires: one with open questions, in which the respondent is free to choose an answer, and the other with closed questions that force the respondent to choose from a range of predefined answers (ibid). Moreover, in survey strategies using questionnaires, the researcher needs to increase the response rate and sample size (ibid).

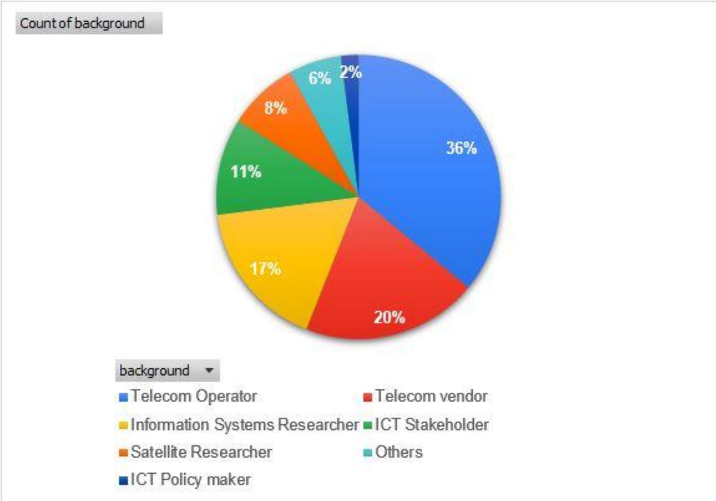

Figure 7 Questionnaire Respondents based on sector

In this research, a questionnaire called 'Sustainability impacts of Satellite internet' was created, and there were several iterations before both supervisors approved it. The last version had four questions, and it was published in many forums, professional networks, and social media posts to increase the reach of both the telecommunication and information industry. The response rate was prolonged in the first few days of launching the link. Later, the researcher added examples to each question and used an attractive promotion message to increase the response rate. Then the response increased significantly to the degree the researcher decided to close the link for the questionnaire. In total, 100 responses were collected from different sectors, and Figure 7 shows the distribution of each sector's participation. However, the target groups of workers in the satellite industry was very hard to attract. Please refer to Appendix 1 for the questionnaire questions.

The Interviews Phase:

An interview is a form of communication that occurs between two people. In most cases, one person conducts the interview in order to obtain information from the other(s) (Oates, 2006). It is an open meeting with an agreement between the researcher and the interviewees to produce information for research objectives that the interviewee understands and accepts. In this study, interviews are utilized to obtain more information about specific questionnaire responses and elicit themes. Types of interviews are structured interviews, semi-structured interviews, and unstructured interviews. The type used here was a semi-structured interview where the researcher was prepared to change the order of questions based on the flow of the conversation and may ask additional questions if the interviewee raised new issues (ibid).

Next, the researcher must decide who will be interviewed and, thereby, participants in the research, and this can be done using a sampling technique. Oates (2006) discusses two types of sampling: probability and non-probability sampling. When researchers believe they can select a representative sample, they use probability sampling. However, if a researcher decides that a representative sample is not feasible or necessary, non-probabilistic sampling is used. Because the time and costs of obtaining a representative sample were too great, a non-probabilistic sampling was used in this study. One of the techniques that can be used to obtain a non-probabilistic sample is called snowball sampling, when one person from the target population is asked about additional people who might be relevant to interview for the intended research topic. This strategy proves useful when the researcher does not know how to access the target group (Oates, 2006).

When it comes to the sampling frame, a massive population can be included in the research from different sectors. To name a few: satellite operators, satellite researchers, telecom industry actors from operators, vendors, and subscribers. Also, information systems researchers, environmental researchers, and stakeholders from the education and healthcare sectors. The researcher has got some assistance from the supervisors and their professional network in finding appropriate subject matter experts. Eight interviewees were conducted in this thesis, and the following was the final list of interviewees: three of the interviewees were from the satellite sector, three came from the telecom industry, one was an information systems researcher, and the last participant was a telecom energy efficiency researcher. Table 4 shows the background/role of the eight interviewees.

Table 4 List of interviews participants groups

Group	Group Code	Respondents	Organization	Role
Telecom	R-Tel	R5, R6, R7	Ericsson	- Environment expert - Hardware designer - Telecom expert
Satellite	R-Sat	R2, R3, R8	MorganSpace, SudaSat	- Satellite Internet expert - CEO of a satellite service provider - Satellite engineer
Researchers	R-Res	R1, R4	Dotenergy consultancy, Norwegian University of Science and Technology (NTNU)	- Information Systems Researcher - Energy Efficiency Researcher

The interviews were one-to-one conversations that took up to 30 minutes. Each interview was recorded, and later approvals for the transcripts were sent via email to ensure consent. Also, the sequence of questions was divided into three sections. The first section was the introduction, greeting, description of the research, and reciting their rights. If they approved, the researcher moved to the second section, where general questions about communication infrastructure roles in healthcare and education and the current role of ICT infrastructure in these sectors. The last section was specifically about the role of satellite internet and its sustainability impacts. Please refer to Appendix 2 for the interview guide. The next section will explain how the above data were analyzed.

5.3 Data Analysis Methodologies

Prior to the analysis, data must be prepared and cleansed, and all resources must be in the same format. Because the interviews were recorded, they were transcribed. The data might then be segmented, and themes and patterns identified for further analysis. Typically, the researcher can use a deductive technique and commit to the theoretical frameworks of choice or an inductive approach by selecting themes that were seen in the data to categorize the data into segments. (Oates, 2006). The next section will illustrate the researcher's choice.

5.3.1 Thematic Analysis

Thematic analysis is a method for systematically finding, categorizing, and offering insight into patterns of meaning (themes) across a data set (Braun & Clarke, 2006). In this research, thematic analysis was conducted to analyze and connect primary materials to previous research and to the chosen theoretical frameworks.

The information gathered during the semi-structured interviews and the questionnaire was examined in light of the above goal. The researcher worked on transcribing interview records and cleansing all segments that were not related to the study. Then the researcher worked on formatting the materials to be in a similar format. The next step started by reading through the raw data to generate a general impression and identify key themes. A general theme labelled each segment of data that seemed significant. A data analysis approach that incorporates both deductive and inductive analysis provides a more organized, rigorous, and analytically sound qualitative study (Bingham & Witkowsky, 2022). Therefore, some of these themes were related to the SDG interactions and the BMT analysis framework (deductive approach). However, most of the final themes were observed in the data while conducting the analysis, such as coverage and inclusion themes that will be presented in the analysis chapter (an inductive approach).

After recognizing general themes, the researcher used a table to look at the different stakeholder's views and how they were grouped according to the different angles and concerns. Then some patterns were spotted, like the different criteria used by different people for deciding whether an internet satellite is promising or not. Finally, each pattern was examined against the conceptual frameworks and tested to answer research questions.

5.4 Research Quality

Many procedures were taken to assure the study's quality in terms of reliability and validity. To begin, the empirical data were gathered through a questionnaire and interviews. To eliminate bias and conflict of interest, the researcher made sure that participants in both techniques came from a multitude of sectors who had a stake in the internet as a service; this brought different perspectives to the study. In addition, to analyze patterns and contrasts, all interviews were conducted using identical interview guide, available in Appendix 2. Secondly, inductive reasoning was used to find patterns and generate generalizations and themes from the data. Moreover, during the process of assessing the acquired data, the literature study and existing research were considered, and some of the conclusions were supported by the collected secondary data.

5.5 Research Ethics

Each step of this study was conducted in accordance with research ethics. Firstly, the questionnaire message was clear that no personal questions would be asked, and it was completely anonymous. Secondly, before each interview, participants were informed that the interview would be audio-recorded and transcribed, and the researcher might quote them in the text. Then the researcher read them several rights, to name a few: they have the right not to answer any question they are uncomfortable with and at any point, they have the right to withdraw from the interview without any hesitation. Also, they were informed that their identity would be anonymized, and data would be stored and processed according to the GDPR guidelines. Lastly, each interviewee received an email with the interview transcripts to ensure consent.

5.6 Limitations

The research aimed to investigate how satellite internet will impact the environment and the social dimension of sustainability. Therefore, this research tapped broadly into satellite fundamentals, satellite energy systems, and the satellite's entire life cycle from launch to the end of the satellite's missions. Further, this research attempted to understand the materials that different satellite operators and organizations have published, for example, NASA, ITU, and ESA. Also, for the social dimension, the study broadly looked at the health and education sectors precisely because of their direct effects on people's life.

However, some participants were missing during primary data collection, such as satellite operators in the questionnaire process; also, not many knowledgeable people about environmental sustainability were interviewed. Also, the researcher aimed to conduct a more comprehensive analysis of the full social and environmental dimensions of both land-based and satellite systems models. However, some significant gaps can be found in this analysis. Hopefully, these gaps can be filled by collaboration efforts from the above sectors to answer the research questions thoroughly.

From the above, data were collected from the literature, questionnaires were distributed and followed by semi structured interviews. Then, these data were analyzed using thematic analysis before SDG interactions and BMT frameworks were utilized to explain the research findings. All this is to determine in what ways the satellite industry's new paradigm will impact the UN 2030 Agenda. The following chapter will walk the reader through the results and how it was analyzed.

6 RESULTS

The previous chapter focused on how data were collected and how it will be analyzed. This chapter will present the results from the primary and secondary data sources. These results will be discussed in the next chapter and in the light of the theoretical frameworks from chapter 4. The first section summarizes findings from the literature about the environmental impacts of mega-constellations on the Earth's resources. The second section presents the results of the questionnaire and the interviews.

6.1 Secondary Data

Literature was reviewed from different sources to understand the used resources in spacecraft. From satellite fundamentals and satellite energy systems to studying the entire life cycle of the satellite from launch to the end of life. Also, documents were studied from different satellite operators' reports, for example, SpaceX and Intelsat; see references in section 2.2. All these sources concluded that the most commonly used material in building spacecraft mentioned in these various sources was aluminum. Therefore, it was very convenient to calculate roughly the amount of aluminum that will be lost due to the mega-constellation or commercial space for satellite internet.

According to the Aluminum Association (2021), aluminum can be recycled, and statistics showed that 75% of all aluminum produced is still in use (The Aluminum Association, 2021). Yet, the main concern in this study is the aluminum sent into space cannot be recycled. Boley and Byers (2021) had the same concern, "Satellite mega-constellations create risks in Low Earth Orbit, the atmosphere and on Earth." According to their research, each mega-constellation's particles may outnumber high-altitude atmospheric aluminum deposition (Boley & Byers, 2021). Moreover, McDowell (2020) calculated that the dry mass of Starlink satellites is around 260 kg per satellite. Since nearly 80% of modern spacecraft are made up of aluminum (Wassmer,2015), thus, if SpaceX plans to launch 12,000 satellites (Boley & Byers, 2021), the total mass will be around 3100 tonnes.

As mentioned previously, much literature focused on how rocket launches affect the atmosphere. Several studies have cautioned about the dangers of black carbon produced by rockets fueled by kerosene, such as SpaceX's Falcon 9. Also, many other studies' main concentration is on how the mega-constellation would increase space debris and the probability of collision rate between LEO satellites (Pardini & Anselmo; 2020). However, a research gap was found on how these launches will impact Earth's natural resources exhaustion and the number of lost resources that will be hard to regain due to satellite mega-constellations. The following section will reflect the social impacts of the commercial space.

6.2 Primary Data

The above section reflected on how the literature discusses the topic of satellite mega-constellations and their significant impact on the environment. This section aims to investigate the social impact of these mega-constellations and how different interest groups perceived these activities.

As previously mentioned, questionnaire and interview data collection methods were used for this stage. The collected data from the questionnaire and the interviews were analyzed using thematic analysis. As shown in Figure 8, patterns were identified, and four general themes were created: Value creation, Coverage, Inclusion, and Environment. In the following few paragraphs, each theme will be illustrated. As per Table 4, the list of interviewees was divided into three groups: Satellite group {R2, R3, R8}, Telecom group {R5, R6, R7}and Researchers group {R1, R4}. Therefore, the interviewees' answers will be referred to as R-Sat for respondents from the satellite group, R-Tel for respondents from the telecom group, and R-Res for the last group covering Information Systems and energy efficiency researchers.

Theme 1 Value creation	Theme 3 Inclusion
Theme 2 Coverage	Theme 4 Environment

Figure 8 Data themes created from identified patterns in the collected data

Theme 1: Satellite internet's Value creation

The majority of the interviewees mentioned that broadband operators are incentivized by profit regardless of background. One of the R-Tel group respondents highlighted the risk of a widened digital divide between urban and rural areas due to the current model of mobile companies. He explained that when a mobile operator decides to cover a small community in Africa, multiple cables from the nearest big city are needed, and many base stations need to be established. Since few users live in the villages, connecting these areas will not be economically viable as there will be no return on investment to the telecom company. However, the entire R-Sat group believes that satellite internet will create value for this exact reason. R3, for instance, mentioned his country Sudan as an example of an African country that suffers from the digital divide. He explained that Sudan is a big country with above 40 million; where more than 12 million people live in the capital, and the rest are distributed all around the countryside. It is typical to find a village with less than 1000 people with very low internet demand. Also, from an investment point of view, it is very costly to find a source of power to operate telecom sites in such areas. Therefore, remote areas require huge investment and operational expenses (OPEX) from the mobile operators, and typically they will probably fail to find a return on their investment. As R3 says: "*Here comes the value of satellite services to cover this gap*".

Figure 9 shows answers to the questionnaire's question "regarding evaluation health and education information systems for rural areas, to what extent are the following criteria important in communication infrastructure?". It can be seen that 40% selected affordability as an extremely important criterion. Also, R1 from the R-Res group pointed out that the current satellite services business model has its own concerns. R1 explained that satellite services are costly, and its current capabilities are not the most attractive to the end-user in terms of speed. When R-Sat was asked about this comment, an expert in satellite internet services explained the satellite internet business model. "*Because the service provider rents or leases satellite capacity from the satellite operators, a profit margin must be added to the service pricing, causing the service provider to sell data packages to end-users at a premium price. As a result, satellite internet costs ten times as much as conventional internet providers.*". The respondent acknowledged that these services are pretty expensive and not affordable for these attended regions to bridge the digital divide. However, if there is no terrestrial network internet coverage, the end-user is left with no other option but satellite internet.

Moreover, there was a general agreement on the cost of the future satellite internet from commercial space operators, and, likely, it will not be economically viable for everyone. One respondent from the R-Tel group explains that existing constellations from companies such as SpaceX consume a huge budget. There, he does not believe that future satellite internet will be economical. Further in this point of view, purchasing a Starlink subscription for a typical customer residing in a city is pointless. However, for those who travel or live in the jungle, such as the Amazon Forest or some African areas, where there is no terrestrial service, Starlink Wi-Fi may make sense. Moreover, R8 from the satellite group compared the current satellite service providers and SpaceX's futuristic model. He expects that the latter prices will be more affordable. However, he also believes the cost will be high for average users.

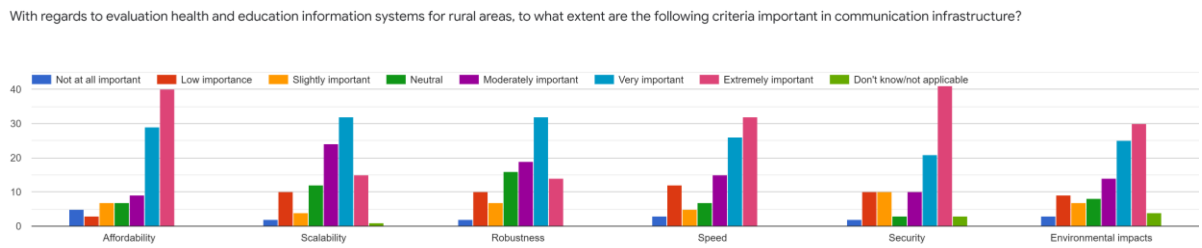

Figure 9 Important criteria in communication infrastructure

Lastly, R4 from the R-Res group raised a critical point when asked about satellite internet. He said: "*The most important question is whether satellite communication can provide internet service at affordable prices and with enough bandwidth because this is the key designing parameter in provisioning digital health and education services*."

It can be concluded that affordability is the most preferred criterion in communication infrastructure, and satellite internet might not satisfy this criterion any time soon.

Theme 2: Coverage as a condition for inclusion

"*The terrestrial network emphasizes discrepancy of broadband access*", as R4 from the R-Res group described it. The operator's network, particularly in Sudan, is built on a radial structure of the terrestrial network, which uses a microwave to cover rural areas with very limited bandwidth coverage. As a result, rural areas that are not serviced by mobile networks lack the necessary capacity to conduct online education or take advantage of telemedicine services that demand large amounts of bandwidth. Moreover, R4 gave two examples from Sudan that demonstrate the impact of network design on people in the countryside. Firstly, the Ministry of Health established an information system to collect statistics data from each locality. However, this system fails outside of the capital city due to the poor quality of internet connections. The second example R4 mentioned was that the Ministry of Education and Google collaborate to provide access to education content. Yet, due to the inequality profile, no one in the remote areas can access all the information available in the urban area. Similarly, R1 from the R-Res group discussed that broadband services must be fully democratized, connected to his research about digital equity. He said, "*everyone should be included in these services, and then we need to look into how to sustain these services*."

Typically, all the R-Sat group agreed that satellite internet would provide the necessary coverage to increase inclusion. R2 mentioned that connectivity is the most important criterion, and through satellite, rural areas can be covered with the most convenient services to fulfil their needs. Also, R3 supported his thesis by reports from Sudan's Telecommunications and Post Regulatory Authority (TPRA). He said: "*According to TPRA's reports, a high percentage of the Sudanese people have no access to the internet. Therefore, satellite internet services are aiming to cover this gap*.". Lastly, one statement from R8 gave a brief story about the time when Sudasat entered the internet mining areas; the social dynamics in those areas had completely changed. R8 explained that before Sudasat offered its services, it was hard to communicate with the outer world, and some people in the area could go for years without making a single phone call to their families. Also, there was no way of sending money except manually, which was very dangerous due to the lack of security in these locations.

When it comes to the R-Tel group, there are various opinions on which criteria are the most important in communication infrastructure. For instance, one respondent mentioned availability as the highest important criteria for digital inclusion, but he thinks that "in *recent years to build up a mobile network is not a problem*". He backed up his claim by identifying two developing regions: India and Africa. "*Almost everyone in India uses mobile networks, and the level of penetration or subscriptions in Africa is quite high.*" The other two respondents were aligned with utilizing satellite internet to cover remote areas. One of them mentioned how studies have shown that satellite constellations cannot compete with terrestrial networks in large cities or metropolitan settings with dense base station deployment. However, he sees the satellite as more helpful in servicing rural areas where the terrestrial network has no coverage. "*It can work like additional coverage to the terrestrial network rather than a replacement.*" Also, it was mentioned that current studies are looking at integrating Non-terrestrial Networks (NTN) into mobile networks. "*This will enable coverage everywhere as we can use the second link if one of the two fails.*"

Similarly, the last respondent in the R-Tel group mentioned three primary use cases where it is beneficial for companies like SpaceX's massive satellite constellations to cover the Earth. One use case could be in a remote place where no fixed connection or mobile network connections is feasible to deploy. The second use case is to have very fast internet on ships, or moving objects, like when travelling on planes or cars. The last use case mentioned was scenarios including the emergence of autonomous or self-driving cars.

To sum up, this theme concludes that a satellite internet through commercial space should be supported to achieve global communication network coverage.

Theme 3: Inclusive health and education systems through satellite internet

This theme highly depends on the previous theme, as here, the study aimed to find how the respondents think about RQ1. The questionnaire, for instance, asked directly whether satellite internet will bring a significant positive effect to the global health and education agenda in rural areas services, and 33 % strongly agreed. Moreover, the same question was asked in the interviews, and the answers were controversial. For instance, the CEO of a satellite service provider said: "*In my opinion, if satellite internet systems were regulated and launched, this will cover 90% of the current gaps in digital inclusion.*"

On the other hand, the R-Res group had a different opinion. First, R1 agrees that any communication structure will help push these services and ensure everyone's inclusion. However, R1 is pessimistic about the new model of satellite internet. "*Investment in coverage systems cannot be enough without including the user side in the equation…*". He argues that considerable efforts must be made to invest in end-users in order to improve the inclusion of these services.

Secondly, R4 expressed a similar viewpoint as he believes that coverage, particularly data coverage, is critical. However, while we now have a high percentage of geographic coverage, adoption is a significant issue. R4 thesis is that "*according to reports from Sudan, the adoption rate in places with internet access is not higher than 40%".* Moreover, R4 mentioned three key areas that must be prioritized to improve adoption other than coverage. First, the priority should be to provide digital education for elementary and secondary school students since this will enhance internet and broadband communication adoption. The second area mentioned was that services should be affordable, both in terms of the service itself and the cost of equipment such as smartphones or even computers. The third comment was that neither education nor digital healthcare services would be possible without supporting infrastructure, particularly the availability of electrical energy.

From the above, it can be concluded that coverage does not guarantee improved inclusion and use of education and healthcare information systems.

Theme 4: Environment impacts of satellite internet

In the questionnaire, as shown in Figure 9, the answers related to the environmental impacts of satellite internet fluctuated between low importance and extremely important. Similarly, this was also evident in the interviews, where a wide range of replies on this topic was given. The majority agreed that these impacts exist, but not everyone agreed on how to address them.

To begin with the R-Sat group, R3 mentioned that in this sector, the ITU and FCC authorize each piece of equipment before launching by accurate checking for the environmental hazards. R3 commented: "*As an investor, I trust these committees and their approval process will keep us safe*." Moreover, R3's and R8's opinions agreed that these issues exist but addressing them should not be a top priority right now. R3 claim that on-ground commercial space businesses plan to exploit existing radio frequencies and resources rather than create or build new ones. However, when it comes to space and where satellites orbit, there will be a lot of satellite equipment spinning around the Earth throughout time. However, the Earth's long-term sustainability impact will be decades away.

On the other hand, two respondents from the R-Tel group highlighted severe red flags regarding these constellations in terms of sustainability. R5 talked about how satellites consume a lot of energy when sending them into space and keep them running. Besides, each satellite requires numerous solar panels and, in the sequence, must have an excess of batteries and commented, "*I prefer these solar panels to be on the ground rather than in space*". Then, R5 explained that future investments must be cautious; for example, telecom operators have already established numerous plans to expand networks that will keep energy costs at least constant, if not lower. There, strategies for supporting new or different internet solutions must be better than the old. Similarly, a second opinion by R7 agrees that we are approaching a historical point where the environmental impact will be the essential factor. Therefore, we must consider the environmental consequences of every decision we make. R5 further stated that terrestrial systems aim to strengthen their power consumption by transferring as much as feasible to renewable energy. In addition, he mentioned that "*terrestrial systems have a closed loop that recycles products and returns materials to the system that could be very difficult to be applied in satellite systems*."

Finally, within the R-Res group, R1 brought up the concept of circularity and how some businesses deal with sustainability from the user side. For example, by offering devices that are recyclable from recycled materials or providing resources that consume less energy. However, he commented that: "*This could be manageable if the target users are aware enough of the sustainability impacts and they are willing to collaborate. However, satellite internet is targeting to cover areas that are still considered a high consumer of waste and still not aware of the impacts on the environments*." As a result, satellite communication providers may have some difficulties ensuring sustainability. R4 raised the opinion that, it is very important to balance sustainability efforts. However, most remote areas currently use petrol generators as a power source rather than using solar batteries to provide electricity to telecom base stations. He says, "*if we use life cycle assessment studies to compare petrol generators and satellites, I think satellites will have fewer effects on the environment*". Lastly, there was one opinion from the satellite engineer in the R-Sat group; questioned these impacts in the first place, as he thinks research about these risks might be biased or overestimating the consequences on the environment.

In conclusion, the majority acknowledged that the environmental impacts of the mega-constellations are authentic. However, not all opinions are aligned on the actions towards them.

The following discussion chapter will analyze the above results in a broader context.

7 ANALYSIS AND DISCUSSION

The results chapter displays the findings of this study and sets the ground for further discussions about the role of satellite internet on sustainability. From the secondary data, it can be seen that large satellites orbiting the Earth can significantly impact the environment. Also, for the primary data, the questionnaire showed that affordability is a critical aspect of digital inclusion.

On the other hand, for the interviews, to begin with, the satellite group (R-Sat) typically were quite enthusiastic about the satellite mega-constellations. Except, these new business model in the satellite industry may threaten their role as service providers. Due to commercial space, businesses plan to eliminate any intermediary between satellite operators and end-users. Furthermore, this group decided to disregard environmental sustainability. The second group, which is the telecom (R-Tel), was more concerned about the environmental consequences of these constellations. However, it was noticed that the majority of this group acknowledged the gap in terrestrial networks in covering rural areas. Also, some of them proposed a hybrid business model combining satellite and mobile networks to cover these areas. Lastly, the researchers' group (R-Res) was a bit diplomatic on the environmental issues. However, they questioned the practicality of satellite internet to increase inclusion rates.

Following the summary mentioned above of the findings, the following sections will use the analyzed data and literature to answer RQ1 and RQ2. These answers will also be addressed utilizing theories from Chapter 4, as seen in Figure 10. The BMT framework compares the satellite internet from mega-constellations with the land-based business models in rural areas and what satellite commercial operators would bring to the internet as a service. At the same time, the SDGs interactions framework is used to illustrate how mega-constellations might affect the environment and sectors like healthcare and education.

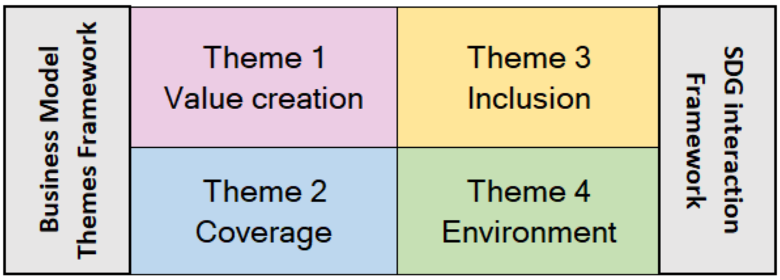

Figure 10 Themes within the theoretical framework

7.1 Business Model Themes Framework Analysis

To answer RQ1: "*In what ways would the satellite mega-constellations and their global internet positively impact the SDG's agenda?*", arrows were used as follows to describe the degree of value creation satellite internet would bring to the digital internet divide.

Table 5 Arrows symbols

Description	Output
Will bring	⟶
Might bring	---------
Cannot bring	. . . .

In general, data revealed four patterns that were explained by the BMT framework:

1. *Theme 1 implies that satellite internet might bring some Novelty*

Novelty can be achieved “when new participants or new transactions are added to the business,” according to Amit and Zott’s (2001) approach. According to R8 from the R-Sat group, when they use the internet to penetrate a new location, the social dynamics change because no internet services existed before. Similarly, the rest of the satellite group, R2 and R3, believe that these new satellites can add significant value to rural areas where mobile operators provide no coverage. Nonetheless, there was a slight agreement with this viewpoint from R-Tel group. As a result of the study’s findings, satellite internet can operate as a first mover in remote areas where terrestrial networks are unavailable, and therefore theme 1 suggests some novelty.

Figure 11 Mega-constellations might bring some Novelty to the internet services

2. *Theme 1 implies that satellite internet might bring some Efficiency*

Efficiency is defined as “reducing information asymmetries between buyers and sellers” (Amit & Zott, 2001). One of the ideas behind mega-constellations is that satellite operators would like to offer services directly to end-users without the need for a middleman or service provider. Such a concept aims to improve the satellite internet pricing model and make the service more affordable. In her research “Preparing for Affordable Space-Based Telecommunication”, Rose Croshier discusses the impact of mega-constellations on satellite internet prices. Croshier concluded that satellite pricing could drop to around $30 per Mbps per month. However, these prices are beyond the means of many individual households (Croshier, 2022). Therefore, if the end user’s cost decreases to the level that is offered by current telecom operators or lower, then theme 1 could indicate efficiency.

Figure 12 Mega-constellations might bring some Efficiency to the internet services

3. *From Theme 2, satellite internet Lock-in cannot be guaranteed*

Lock-in is the extent to which clients are motivated to engage in repeat transactions that improve the possibility for value creation, according to Amit & Zott (2001). The R-Tel group believes that satellite internet cannot compete with land-based systems. Particularly in a huge metropolitan or urban area with a dense deployment of base stations, a satellite constellation is unlikely to compete with the rest of the networks. Also, because mobile operators are the first to enter the market, users will be less likely to switch to other service providers. However, satellites can compete in rural areas where may be no coverage from the terrestrial network.

The R-Sat group claim that their present model has achieved lock-in with the population in remote places. Not only because of the absence of terrestrial networks in some areas but also because satellite internet is not controlled by government laws, which is a preference for some people. However, the general analysis of the data shows that the sole reason for using satellite internet is the absence of a terrestrial network, therefore, mega-constellations cannot guarantee Lock-in.

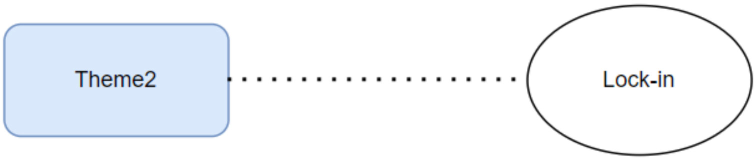

Figure 13 Mega-constellations cannot bring Lock-in

4. *Theme 2 implies that satellite internet and land-based systems will bring Complementarity*

Complementarities, in the BMT model, are present whenever having a bundle of goods which together provides more value than the total value of having each of the goods separately (Amit & Zott, 2001). The analysis has shown that rural areas with very few users might not be connected to the internet because of telecom operators' business models. Therefore, one opinion suggests that we can depend totally on satellites to cover these areas, because "*when satellites are launched into orbit, it does not matter if it covers a big city or the middle of the Sahara Desert*". This opinion is consistent with the literature in section 3.3.1. Literature has shown that many researchers are currently studying the possibility of using NTN and satellites to design 5G networks as backhauling to guarantee data links everywhere (Sedin et al., 2020; Gaudenzi, 2019).

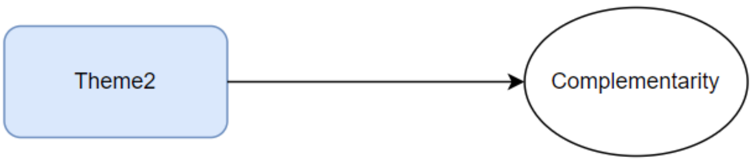

Figure 14 Mega-constellations will bring a Complementarity to mobile networks

To conclude, the business model theme components in studying mega-constellations' internet as a tool for digital inclusion may not be fully fulfilled. However, satellite mega-constellations and terrestrial communication networks can collaborate to support social agendas as a unified business model.

7.2 SDGs Interactions Framework Analysis

To answer RQ1 and RQ2, the framework proposed by Nilsson et al. (2016) was used to grade the SDG interactions and identify SDG connections between SDGs 3, 4, and 12 to SDG 9.

1. *SDG 9 can enable SDG 3 and SDG 4 (+1 Enabling)*

From the analysis, coverage investments alone will not solve digital gaps; instead, efforts must be made to consider the users' perspective. Also, data analysis showed that the availability of communication networks, regardless of their type, is likely to positively impact the availability and use of healthcare and education services, as long as it is affordable. Therefore, theme 3 concluded that coverage is not a sole condition for inclusion. As a result, to answer RQ1: "*In what ways would the satellite mega-constellations and their global internet positively impact the SDG's agenda?*". Changes in SDG 9 with global internet from satellites through large constellations can enable inclusive healthcare and education, but it is not an enforcement tool for it. This was confirmed by a GSMA report that showed although many areas were covered with mobile broadband; however, 3.4 billion people did not actually adopt it (GSMA, 2021).

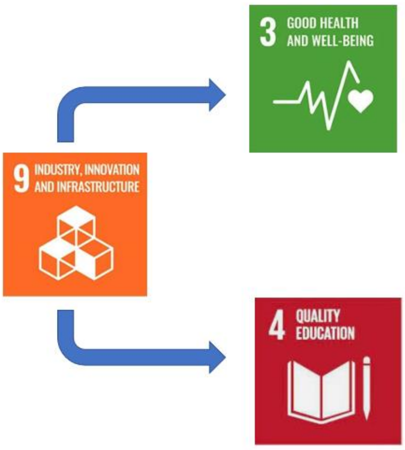

Figure 15 Mega-constellations interaction with Healthcare and Education sectors

2. *SDG 9 can counteract SDG 12 (-2 Counteracting)*

Many studies looked at space debris exposure and the impact of a potential spacecraft break up on the orbit environment. Also, many other studies were concerned about how debris collisions could harm other spacecraft or prevent newly planned satellites from achieving their mission. Satellite sustainability, on the other hand, could incorporate a variety of other environmental concerns, such as resource depletion for materials like aluminum. This responds to RQ2: "*In what ways would the satellite mega-constellations negatively impact the SDG's agenda?*". The environment expert in the R-Tel group reflected that mega-constellation effects on the environment are undeniable because launching and operating them will consume a lot of energy. Also, the analysis of the secondary data proves that the planet loses a large amount of aluminum per mega-constellation.

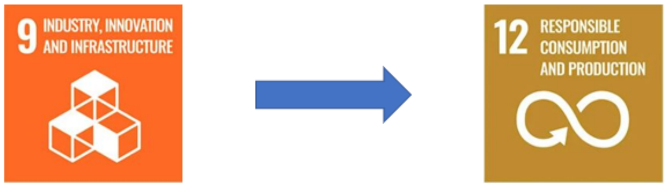

Figure 16 Mega-constellations interaction with the environment

From the above, it can be concluded that the satellite mega-constellations and the commercial space might bring some *Novelty* and *Efficiency* to the internet services for some communities. Also, *Complementarity* is supported through the hybrid architecture, which will bring the best of satellite mega-constellations and terrestrial communication networks to *Enable* the digital divide in rural areas to be closed with consideration to the environment. Lastly, sending thousands of satellites into space to bring the global internet is *Counteracting* responsible resource consumption and production.

7.3 Discussion

The thesis's primary goal was to investigate the dilemma of how the balance between the triple bottom line parts of sustainability can deviate. The current analysis supports previous research that satellite mega-constellations would harm the ecosystem and deplete natural resources. However, according to the findings, under certain circumstances, satellite internet from commercial space firms would move the world closer to "leaving no one offline".

The findings regarding the environmental impacts confirm that satellite mega-constellations have negative implications for the environment, as already many studies focused on how rocket launches affect the atmosphere through the emissions of the kerosene-fueled rockets. Also, several other studies' main concentration was on how the mega-constellations would increase space debris and the probability of collision rate between LEO satellites. This research studied that the Earth would lose a great amount of aluminum per mega-constellation.

Regarding the social role of satellite mega-constellations in improving digital inclusion for healthcare and education services, the results suggest that satellite internet can enable inclusion under certain conditions. For instance, the primary data showed that there was an overall agreement that affordability is the most preferred criterion in communication infrastructure. However, satellite internet might not satisfy this criterion any time soon. Moreover, satellite internet could be the most convenient solution in the absence of a terrestrial network. However, it is worth noticing that any communication infrastructure internet coverage does not guarantee inclusion on its own.

Moreover, some opinions regarding the environmental implications of mega-constellations versus the social impacts were interesting. One opinion suggests that if mega-constellations are promoted, this will push some agendas, like education. As a result, in a few years, we will have an educated generation that can find solutions to the environmental impact. In summary, this opinion acknowledges that satellite mega-constellations have ecological implications, but it does not agree that these impacts should be a reason to halt commercial space investments.

Although the digital divide is a legitimate cause, and the analysis showed that providing internet to rural areas by satellites would support this cause. However, this viewpoint was noticed by those who stand to profit financially from satellite internet; a conflict of interest taints this viewpoint.

To sum up, in order for these results to be meaningful, we need to consider the big picture. The environmental consequences of these massive constellations cannot be neglected. However, considerable attention should be paid to the social implications of the global internet and how it will benefit some communities. Thus, one unanticipated finding of this study can be used to attain balancing elements between sustainability aspects. This finding suggests that a hybrid model of terrestrial and satellite systems would pave the way for bridging the digital divide while also reducing the environmental implications of mega-constellations. There, policymakers and business strategists should design the infrastructure to prioritize the environment, and further studies, which take all these variables into account, will need to be undertaken.

8 CONCLUSION

This thesis has examined the social and environmental impacts of internet satellites. Besides a literature review of the environmental impacts, the author investigated the social impact of mega-constellations on digital inclusion and the availability of health care and education systems. The following research questions have been formulated to answer the objective(s) of this study.

> *RQ1: In what ways would the satellite mega-constellations and their global internet positively impact the SDG's agenda?*

Due to terrestrial network design, remote areas are marginalized from quality broadband. Therefore, if the satellite mega-constellations offered affordable internet connections for rural people, SDG 3 and SDG 4 will be positively impacted as internet services are crucial for healthcare and education information systems.

> *RQ2*: In what ways would the satellite mega-constellations negatively impact the SDG's agenda?

The SDG interaction between SDG 9 and SDG 12 is classified as counteracting on the seven-point scale (-2). The massive increase in satellite production linked to mega-constellation plans will have a detrimental influence on responsible resource consumption, as the Earth will lose a significant amount of aluminum with every mega-constellation.

Finally, in light of the above, this master thesis attempts to study the balance between the social and environmental impacts of technology. This study motivates to ignite the complementarity value that satellites would bring to the land-based systems through the hybrid architecture as robustness can be offered easily when the terrestrial and satellite networks work together. Moreover, fewer satellites will be a good idea to cover areas like the oceans, the high mountains, or rural areas with zero coverage. This may decrease mega-constellations environmental effects and, at the same time, will utilize satellite capabilities to bring us closer to covering the digital divide.

8.1 Future Research

Satellite mega-constellations as a new trend in the satellite industry have mainly been discussed by communication engineering researchers. Such a concept will impact many sectors from different layers; therefore, a deep investigation of the social and economic impact of satellite mega-constellations needs to be covered by research in the future. Moreover, efforts toward improving digital inclusion should be supported to achieve sustainable development goals. However, a balance between the three dimensions of sustainability is important. This study attempted to scratch the surface of this upcoming model that the community may not be prepared for yet. Further, future investigations are needed that can offer a full life cycle assessment to compare the satellite-based system and terrestrial network models from an environmental perspective. Lastly, discussions at the top level and among grassroots level actors are needed to move digital inclusion and environmental issues forward.

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APPENDICES

Appendix 1: Online Survey Questionnaires

Q1: Which of the following best describes your current role/background?

Satellite Researcher (If you are student or researcher in subject related to Satellites)
Satellite Operator (If you are affiliated to satellite operator like SpaceX, OneWeb…)
Telecom Operator (If you are affiliated to telecom operator like Telia, Tele2…)
Telecom vendor (If you are affiliated to companies like Ericsson, Huawei…)
Information Systems Researcher (If you are student or researcher in subject related to IS, IT, HCI…)
Other (please specify)

Q2: What is your overall opinion about satellite internet?

- Very negative - Negative - Somewhat Negative – Neutral - Somewhat Positive – Positive - Very positive - Don't know/not applicable

Q3: To what extent do you agree with the following statements?

Satellite internet is a cost-effective solution to achieve global coverage.
Satellite internet is a resource-effective solution to achieve global coverage.
Satellite internet is an environmentally sustainable solution to achieve global coverage.
Satellite internet will bring significant positive effects to the global health and education agendas in rural areas in developing countries.
Land based telecommunication will bring significant positive effects to the global health and education agendas in rural areas in developing countries.

- Strongly disagree – Disagree - Somewhat disagree - Neither agree nor disagree - Somewhat agree - Agree - Strongly agree - Don't know/not applicable

Q4: With regards to evaluation health and education information systems for rural areas, to what extent are the following criteria important?

Affordability
Scalability
Robustness
Speed
Security
Environmental impacts

-Not at all important - Low importance - Slightly important – Neutral - Moderately important - Very important - Extremely important - Don't know/not applicable

Appendix 2: Interview Guide

Demographic Information

1. Can you please tell me a little bit about your role/background?
   - ◆ If you are a student, what level of education have you attained?
   - ◆ If you are employed, what is the Company that you work for producing? For how long have you being working in the field?

Communication Infrastructure for health and education Systems

1. Have you ever thought about gaps in health and education needs in rural areas of developing countries?
   - ◆ What are your motivation criteria for communication infrastructures to cover these gaps?
     - ◦ Were these criteria important to you? (**Affordability**, **Scalability, Robustness, Speed, Security)** How would you rank each of these criteria?
   - ◆ Which of the criteria that you mentioned do you think is/are the most important? Why?
2. To what extent has the information industry benefited from existing communication infrastructures (terrestrial systems) to cover gaps in health and education needs in rural areas of developing countries?
   - ◆ Base your answer on your understanding of what has already been achieved.
   - ◆ Also, what is needed to push forward global health and education agendas in rural areas of developing countries?

Satellite internet

3. What is your overall opinion about satellite internet?
   - ◆ How do you perceive global internet access through mega-constellations?

4. To what extent will the information industry benefit from the future capabilities of satellite systems to cover gaps in health and education needs in rural areas of developing countries?
   - Where Internet from satellite will contribute the most? (**Affordability**, **Scalability, Robustness, Speed, Security)**
   - So, which of the criteria that you mentioned do you think is/are the most important? Why?
5. If the potential environmental charge of the mega-constellations was included in the cost, would this influence your answer?
   - What influenced your answer when it comes to health and education information systems?