Space debris removal

***Abstract*—To allow continued use of the space around the Earth for the benefit of humanity measures have to be taken in order to remove space debris currently in orbit. The natural pace of deorbiting through atmospheric drag and solar wind will not be enough to prevent an exponential growth in debris numbers, meaning spacecraft missions will be required to increase the debris deorbit rate. To examine possible solutions to this problem a feasibility study is performed of a spacecraft devised to use nets and sails to bring down six spent rocket stages within a single year. The results show that such a mission would take 301 days excluding rendezvous maneuvers. Costs would be around $192M without considering research and development. The environmental impact of rocket launches today is negligible compared to the airplane industry but is expected to become a larger problem in the future. Overall the debris removal mission seems feasible with current technology.**

***Keywords*— Space debris removal, active debris removal, low Earth orbit, net capture, drag augmentation.**

***Sammanfattning*— För att mänskligheten ska kunna fortsätta använda den del av rymden som ligger närmast jorden måste åtgärder vidtas för att avlägsna rymdskrot i omloppsbana. Naturliga effekter från atmosfärisk friktion och solvind är inte tillräckligt för att rymdskrotet ska brinna upp i atmosfären innan det inleder en kedjereaktion, och således krävs en rymdfarkost för att påskynda degraderingstakten. För att undersöka möjliga lösningar till detta utförs en genomförbarhetsstudie med en rymdfarkost som med nät och segel ska avlägsna sex använda raketsteg under ett enskilt år. Resultaten visar att det skulle ta 301 dagar att genomföra ett sådant uppdrag om tidsåtgång för relativa banmanövrar försummas. Utan hänsyn till kostnader för utveckling och testning uppskattas uppdraget kosta cirka 192 miljoner USD. Miljöpåverkan från raketuppskjutningar är idag försumbar i jämförelse med flygindustrin, men förväntas öka och bli ett större problem i framtiden. Överlag verkar uppdraget genomförbart med nuvarande teknik.**

List of symbols:

α_g**:** Right ascension of Greenwich
a**:** Semi-major axis
a**:** Acceleration of spacecraft propulsion system
b**:** Semi-minor axis
δ**:** Orbital declination
ϵ**:** Structural ratio
ϵ_1**:** Structural ratio of first rocket stage
ϵ_2**:** Structural ratio of second rocket stage
e_1**:** Eccentricity before orbital maneuver
e_2**:** Eccentricity after orbital maneuver
E**:** Energy consumption
E_1**:** Energy consumption of first rocket stage
E_2**:** Energy consumption of second rocket stage
E_{tot}**:** Total energy consumption of a rocket launch
I_{sp}**:** Specific impulse
Δi**:** Difference in inclination between two orbits
i**:** Orbital inclination
λ_E**:** East Longitude of the launch site
μ**:** Standard gravitational parameter
m_***:** Overall payload mass
m_{01}**:** Initial mass of first rocket stage
m_{02}**:** Initial mass of second rocket stage
m_{03}**:** Initial mass of payload
m_p**:** Overall propellant mass
m_{p1}**:** Propellant mass of first rocket stage
m_{p2}**:** Propellant mass of second rocket stage
m_s**:** Overall structural mass
m_{s1}**:** Structural mass of first rocket stage
m_{s2}**:** Structural mass of second rocket stage
M_p**:** Propellant mass
$M_{\text{RP-1}}$**:** Mass of the RP-1 fuel
$M_{\text{RP-1,1}}$**:** Mass of the RP-1 fuel of first rocket stage
$M_{\text{RP-1,2}}$**:** Mass of the RP-1 fuel of second rocket stage
Ω**:** Right ascension of the ascending node
$\Delta\Omega$**:** Difference in right ascension of the ascending node between two orbits
$\omega_\oplus$**:** Inertial rotation of the Earth
OFR**:** Oxidizer-to-fuel ratio
π_***:** Overall payload ratio
π_1**:** Payload ratio of first rocket stage
π_2**:** Payload ratio of second rocket stage
r_{approx}**:** Circular approximation of debris orbits
r_1**:** Radius before orbital maneuver
r_2**:** Radius after orbital maneuver
SFE**:** Specific fuel energy
Δt**:** Time required for orbital maneuvers
t_0**:** Aimed time of launch
t_1**:** First possible time for launch
t_2**:** Final possible time for launch
ΔV**:** Speed required for orbital maneuvers
V**:** Orbital speed

I. INTRODUCTION

A. Background

IN 2013 it was estimated that there are more than 170 millions of pieces smaller than 1 cm in space, about 670k measuring between 1 and 10 cm and 29k bigger than 10 cm in orbit around Earth. But where does this debris come from? Where are they exactly? How are they a threat? What has been done to avoid this?

Space debris are both natural (meteoroid) and artificial (man-made) particles. Most of the objects in space we consider as debris are man-made. In the beginning of the space race no space agencies cared for the afterlife of their spacecraft. Most satellites that have been launched since this time are staying in orbit but are now non-functional. The Union of Concerned Scientists have listed 902 operational satellites out of over 19,000 known satellites in orbit. Still, satellite related debris account for 12 percent of all the objects in space. A significant part of the debris comes from rockets, either from intact upper stages still in orbit or from explosions. Some upper stages remaining in space have exploded due to the implosion of the fuel tank in which there was still fuel. Others exploded because the battery exploded. The majority of the stuff in space are the results of weapons. During the Cold War both USA and URSS developed weapons that aimed to destroy spy satellites

(ASATs). By 1990, twelve tests of these weapons have created 7 percent of the debris and additional small parts that cannot be tracked. The last US ASAT test destroyed a satellite that weighed a ton, creating thousand of debris larger than 1 cm. Fortunately almost all of the trackable debris had fallen from orbit by 2000. Although most countries stopped developing such weapons China conducted a test in 2007 by launching a missile and destroyed one of their old satellites at an altitude of 863 km creating the biggest space debris incident of history. Now the parts resulting from this explosion are located at altitudes ranging from 175 to 3600 km.
The Kessler syndrome was theorized by Donald Kessler, NASA scientist, in 1978. It is a scenario in which the density of objects in low Earth orbit (LEO) is high enough that collisions between objects could cause a chain reaction which could end in the infeasibility of space activities and use of satellites. Some debris are so small they can not be tracked. But they are travelling at speeds of up to 7800 m/s so they can cause major accidents. That is why tracking debris is a must do for space agencies.
Figure 1 comes from the website stuffin.space [1]. In it we can clearly see why the situation is concerning given that the Earth is covered by debris which means that the LEO is crowded.

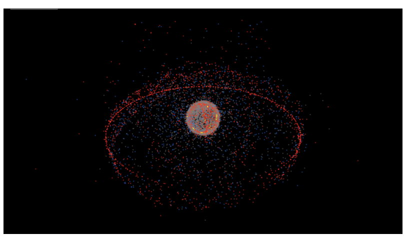
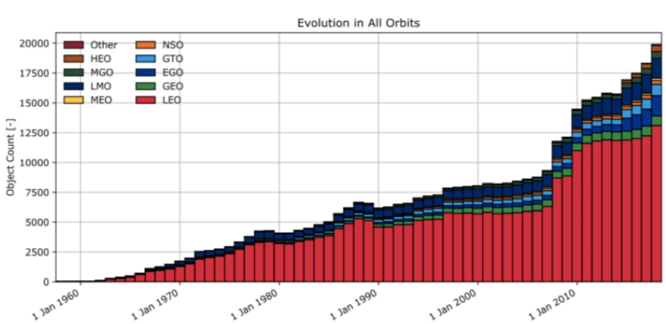


Fig. 1. Picture of all debris around Earth [1].

The following Figure 2 comes from the report of ESA [2] about space debris that was published on May 2018. It clearly shows that the Kessler Syndrome can and will happen if we do not urge ourselves to tackle this issue.



(a) Evolution of number of objects.

Fig. 2. The evolution of number of space debris according to orbits [2].

Nowadays both USA and the European Space Agency launch satellites that have an end-of-life plan for after 25 years of use. At the end of the 25 years the spacecraft have to reenter Earth's atmosphere or, for spacecrafts near or in the geostationary ring, re-orbit to a graveyard orbit, where it is recommended to orbit at around 300 km above the GEO ring.

B. Motivation for the study

The purpose of this paper is to study the feasibility of sending a spacecraft into orbit to take care of six spent rocket stages within a year. The plan is to remove them from their current orbits and send them into the atmosphere. At the end of its mission, the spacecraft will also deorbit.

C. Scope, simplifications and limitations

To make execution of the project as likely and fast as possible focus has been put on using technologies with a high Technology Readiness Level (TRL). The mass of the spacecraft was set to 500 kg without any further details to make calculations simple. The mission duration is only one year and the number of space debris to be removed is six, which is only a small fraction of the total amount of debris in orbit. The low thrust propulsion used also restricts how much the orbital parameters can be varied, which in this case limits the spacecraft to a sun-synchronous orbit.

D. Structure

This paper is divided into 4 sections. First the Method section in which we describe the choice of rocket, debris and launch site. Included here are also details regarding the performance and dynamics of our mission. Then the Result section contains the figures for launch and decay. There is also an estimated cost for the mission and a comparison with a plane flight. After this the results are discussed in the Discussion section in which we talk about environmental impact and the feasibility of our study. Finally the report is concluded by highlighting the future possible work and the work division.

II. Method

A. Assumptions and approximations

- Constant burn rate at launch.
- A perfectly spherical Earth.
- A perfectly cylindrical-shaped rocket.
- Exponential decrease of air density.
- Constant fuel burn rate.
- Rotation of Earth is not considered for launch calculations.
- Constant mass of spacecraft throughout mission.
- The debris orbits are assumed to be circular with a radius of $r_{\text{approx}} = (a + b)/2$.
- The spacecraft is assumed to maintain a circular orbit during the spiral maneuvers.
- Maneuvers affecting one orbital parameter are assumed to have no effect on the other orbital parameters.
- No atmospheric drag on the satellite during the one year mission duration.
- Ejection of capture mechanism does not dramatically affect the motion of the spacecraft.

B. Active debris removal (ADR) techniques

When it comes to active space debris removal one can imagine the best method to be one which can be operated remotely. Laser removal is one of the Earth-based techniques, where powerful lasers on Earth track the debris while continuously firing short pulses at it [3]. Research shows that this method has great potential, but the method needs to be refined further to make sure no additional debris is created in the beaming process.

Approaches with a higher TRL are those involving a spacecraft sent into orbit to remove space debris on site. Once a rendezvous is executed to bring the spacecraft into the debris' proximity, the main alternatives for capture are arms/tentacles, harpoons and nets [3]. The arms and tentacles have the benefit of being easy to test, and as robotic arms are already widely used in industry today the TRL is high. They encounter a problem however when faced with tumbling debris as this would require detumbling before a connection between spacecraft and debris can be established. The success of this mechanism also depends on the geometry of the debris, as the arms or tentacles will need to find something on the debris surface to grab onto. If a harpoon is used to capture the debris the dependency on debris geometry largely disappears. Harpoons also have a greater range, which simplifies the required rendezvous maneuvering by the spacecraft. Just like in the case of lasers however, harpoons are likely to damage the target debris at impact, even to the point where the entire debris could break up into multiple pieces. The last main capture mechanism is using a net with weights in its ends. Although nets are hard to properly test and control on Earth, they have the great advantage of working on all types of space debris. Using a large net significantly larger than the target debris additionally makes accuracy less of a problem.

Once the debris is captured the primary deorbit techniques are drag augmentation, electro-dynamic tethering and contact removal [3]. The first two both involve using the environment to create net force slowing the debris down, the first one using naturally occurring molecules in the atmosphere while the other one utilizes the magnetic field of the Earth to induce a Lorentz force. There is also the possibility to physically push the debris away from orbit by a thruster in the capturing spacecraft. Worth noting is also an entirely second class of deorbit techniques which do not require any capture at all, such as shooting molecules or ions at the debris from a distance. While options like these would be favorable, the TRL is still a bit too low to make them a viable choice.

C. Selected ADR technology

Based on the analysis in the previous section the selected approach is a net capturing mechanism coupled with drag augmentation in the form of deployable sails. The spacecraft will house six tiny packages of nets attached to sails folded to limit the space they occupy. Once the spacecraft gets close enough to a chosen space debris, a spring mechanism will shoot the net to capture its target. Once out of the spacecraft the sail will deploy, which increases the drag experienced by debris, leading to its eventual deorbit. With varying sizes and altitudes of debris, the size of nets and sails can be adapted accordingly.

The main motivation behind the choice was to combine simple technology with a generic area of use. Both nets and sails are well understood by current science, indicating a high TRL for the underlying principles at work, even though all the details regarding the execution are not yet fully understood. The net means that debris of all sizes and shapes are potential targets, while the sail can operate at a wide range of altitudes in LEO.

D. Selection of launch vehicle and payload

We chose Falcon 9 Full Thrust (FT) because most of the parts and systems of this rocket are economical and can be reused repeatedly. The Merlin engine has a high thrust-to-weight ratio of 150 which results in a high acceleration. The interstage is a special feature of the Merlin engine design which allows for operation in the vacuum of space. It is designed to burn for about six minutes but is able to be remotely shut down and restarted numerous times to deliver different payload. All of this in turn helps to make this have the largest engine efficiency of any American-origin liquid oxygen or kerosene engine with its vacuum I_{sp} of 348 seconds [4]. We have chosen such a large vehicle because of its latest technology and due to the fact that we already have a lot of data from the previous Falcon 9 FT launches. Dedicated small launch vehicles such as the Falcon 1 have previously proven to be unsuccessful because of the limited market and the small number of launches, and therefore have not been profitable. Thus, we have selected an already available launch vehicle with proven capabilities overlooking the environmental aspects and the cost involved for purchasing such a huge launch vehicle. The spacecraft of our mission will also be a part of a joint launch together with other payloads, which brings down the costs.

The advantages of an ion drive electric propulsion engine, also called ion thruster, over conventional propulsion mechanisms include lower fuel weight, much higher fuel efficiency, and longer operational life [5]. Electric propulsion has a clear advantage over chemical propulsion since the I_{sp} of a chemical rocket may range anywhere from 100 to 500 seconds while an ion rocket can have an I_{sp} of 10,000 seconds [6].

Falcon 9 FT consists of a two-stage launch vehicle controlled by liquid oxygen (LOx) and rocket-grade kerosene (RP-1). The vehicle is manufactured by SpaceX and can be flown with a fairing or a SpaceX Dragon spacecraft. The major difference between the fairing and the Dragon configurations is that the payload mechanism interfacing changes in the second-stage [7]. Over the years, the rocket has been modified to increase thrust efficiency and the structural components of the spacecraft have been strengthened to provide additional stability.

Launch Vehicle Parameters (Falcon 9 FT) [7]:

- Height: 70 m (Including interstage and fairing)
- Diameter: 3.66 m

- Material: Al-Li skin and domes
- Fuel: LOx / Kerosene (RP-1)
- Tank Type : LOx (monocoque), Fuel Tank (Skin and stringer)
- Engine Type : Liquid, gas generator for both the stages.
- Engine Designation : 9 x Merlin 1D (First stage), MVac (Second stage)

Spacecraft (Payload) Parameters:

- Propellant type: Xenon
- Staging: The first stage consists of LOx tank, LOx transfer tube, fuel tank and Merlin engines while the second stage consists of LOx tank and fuel tank. The payload consists of a spacecraft which has sail and ion thrusters attached to end of the spacecraft for propulsion, along with a control system for maneuvering.
- Propulsion: The first stage consists of 9 Merlin engines. The second stage consists of a single Merlin vacuum engine. Finally, the spacecraft (payload) consists of an ion drive electric propulsion engine.
- Ratios:
  The aim here is to have a rocket with high payload ratios and low structural ratios.
  - Payload Mass:
  m_* = 500 kg
  - Structural Mass:
  m_s = $m_{\mathrm{s}1} + m_{\mathrm{s}2}$ = (25,500 + 4000) kg = 25,900 kg [8]
  - Propellant Mass:
  m_p = $m_{\mathrm{p}1} + m_{\mathrm{p}2}$ = (395,700 + 92,700) kg = 488,400 kg [8]
  - Payload Ratio of First Stage:
  $\pi_1 = \frac{m_{02}}{m_{01}} = m_{\mathrm{p}1} + m_{\mathrm{s}1} + m_*$ = 0.943 [6]
  - Payload Ratio of Second Stage:
  $\pi_2 = \frac{m_{03}}{m_{02}} = m_{\mathrm{p}2} + m_{\mathrm{s}2} + m_*$ = 0.005 [6]
  - Overall Payload Ratio:
  $\pi_* = \pi_2 \cdot \pi_1 = 0.005 \cdot 0.943 = 0.004715$
  - Structural Factor of First Stage:
  $\epsilon_1 = \frac{m_{\mathrm{s}1}}{m_{\mathrm{s}1}+m_{\mathrm{p}1}} = 0.060$ [6]
  - Structural Factor of Second Stage:
  $\epsilon_2 = \frac{m_{\mathrm{s}2}}{m_{\mathrm{s}2}+m_{\mathrm{p}2}} = 0.041$ [6]
  - Overall Structural Factor:
  $\epsilon = \epsilon_1 \cdot \epsilon_2 = 0.060 \cdot 0.041 = 0.00246$

E. Selection of space debris

The space debris were selected from the list in [9]. The criteria for selection were angle of inclination (i), right ascension of the ascending node (Ω) and size, which resulted in the selection shown in Table I below. For i and Ω it was important to select debris with values within a relatively small range to limit the time duration of orbital maneuvers. Debris of small sizes were selected as these were assumed to be easier targets for the capture and deorbit mechanism. The selected debris are all intact spent rocket bodies from the Thor Burner 2 program, a US program between 1966 and 1976 [10].

F. Propulsion

The estimated mass of the satellite is about 500 kg. Using the same NASA NSTAR ion-propulsion system as on the Dawn spacecraft yields a thrust of 90 mN with a burn rate of 8.5 g of xenon per hour [11] [12]. These values together with an assumed constant mass allows the acceleration to be calculated as in (1).

$$\mathrm{a} = \frac{\text{thrust}}{\text{mass}} = \frac{90 \cdot 10^{-3}\ \mathrm{N}}{500\ \mathrm{kg}} = 0.18\ \frac{\mathrm{mm}}{\mathrm{s}^2}. \tag{1}$$

G. Launch

We are going to launch our rocket from Vandenberg Air Force Base (AFB) for different reasons:

- Latitude of Vandenberg is $l = 34.633^\circ$ and smaller than the inclination angle $i = 98^\circ$, so we will have two launch windows.
- Vandenberg AFB is close to the equator, so the rocket will have to counter the Earth's rotational speed since the orbits of the debris are all near polar orbits. The rotation of the Earth slightly counteracts the thrust from the rocket. This effect is however minimal.
- Vandenberg's infrastructures are adapted to a Falcon 9 rocket launch.
- The launch site is close to ocean so if any problem occurs the rocket will not cause damage. The platforms for boosters landing can be on water.

The equations (2) and (3) from Spaceflight Dynamics [13] are used to calculate the launch time, giving us

$$t_1 - t_0 = \frac{\Omega + \delta - \alpha_g - \lambda_E}{\omega_\oplus} \tag{2}$$

$$t_2 - t_0 = \frac{\Omega + 180^\circ - \delta - \alpha_g - \lambda_E}{\omega_\oplus} \tag{3}$$

where Ω is the RAAN, δ is the declination, α_g is the right ascension of Greenwich, λ_E is the East longitude of the launch site and $\omega_\oplus$ is the inertial rotation of the Earth.
If we assume we are launching at 12:00 on October 5 we have t_1 = 5h 08m 56s and t_2 = 18h 29m 59s.

H. Adjusting orbital parameters

Moving the spacecraft between different altitudes using low-thrust propulsion is done through a spiral maneuver. The ΔV required in one such maneuver is given through equation (4)

$$\Delta V = \sqrt{\frac{\mu}{r_1}} - \sqrt{\frac{\mu}{r_2}} \tag{4}$$

$$\Delta V = V\sqrt{2 - 2\cos\left(\frac{\pi}{2}\Delta i\right)} \tag{5}$$

$$\Delta V = \frac{\pi}{2}\sqrt{\frac{\mu}{a}}|\Delta\Omega|\sin(i) \tag{6}$$

$$\Delta V = \frac{2}{3}\sqrt{\frac{\mu}{a}}|\sin^{-1}(e_1) - \sin^{-1}(e_2)| \tag{7}$$

where r_1 and r_2 are orbital radii before and after the maneuver. Equivalent equations for changes of the orbital parameters inclination (i), RAAN (Ω) and eccentricity (e) are shown in equations (5), (6) and (7) respectively.

TABLE I
THE SIX SELECTED SPACE DEBRIS WITH CORRESPONDING DATA.

Debris number	Apogee (km)	Perigee (km)	r_{approx} (km)	Eccentricity	Inclination (°)	Ω (°)	Mass (kg)	Area (m^2)
1	787	729	758	0.377	98.38	220.8	65	0.7
2	823	772	798	0.347	98.64	223.5	65	0.7
3	865	826	846	0.297	98.87	224.1	65	0.7
4	829	777	803	0.349	98.43	225.5	65	0.7
5	857	803	830	0.349	98.91	233.9	65	0.7
6	822	792	807	0.268	98.59	235.3	65	0.7

TABLE II
MISSION DATA FOR ALTITUDE MANEUVERS.

Maneuver index	Δr (km)	ΔV (m/s)	Δt (h)
1a	358	195	301
2a	40	21	32
3a	48	25	39
4a	–43	22	34
5a	27	14	22
6a	–23	12	19

TABLE III
MISSION DATA FOR THE INCLINATION MANEUVERS.

Maneuver index	Δi (°)	ΔV (m/s)	Δt (h)
1b	0.26	53	82
2b	0.23	47	73
3b	–0.44	90	139
4b	0.48	98	151
5b	0.32	65	100

I. Cost

In the early conceptual development phase of space (satellite) missions, there are several subsystem requirements needs to be considered to estimate the cost of the spacecraft system. However, for the debris removal mission, there were only a few things that have been determined so far including the launch vehicle, debris capturing mechanism, and the propulsion system of the satellite. Therefore, for the cost analysis, the research cost and testing cost were not included, and it was done based on the previous space missions which gave a rough but reasonable estimation.

- According to Space X, the price of the Falcon 9 to LEO orbit with full payload capacity of 22,800 kg is \$62M. However, due to the fully reusable first stage of a Falcon 9 (Block 5 Falcon 9), SpaceX recently lowered the standard price of a Falcon 9 to \$50M [14]. With lowered price, the cost per payload mass is roughly \$2,300. [15].
- The cost of the satellite bus was calculated based on the SSTL-600 (UK) model as it had the nearest payload mass capacity and mission operational altitude (LEO) [16].
- The price of the Sail-Net system was estimated according to the NASA's Solar Sail Demonstrator ('Sunjammer') led by the industry manufacturer L'Garde Inc (\$20M for the solar sail). Although the material and principle of the solar sail and drag sail are dissimilar, Solar Sail Demonstrator was used for the rough estimation of the cost by comparing the size of the sails (the area of the drag sail was about a fifty-sixth of the solar sail) [17].
- The price of the NSTAR particle thruster was \$40M when it was manufactured in 2007. Therefore, the price of the NSTAR was estimated to be the same or less as the technology readiness level became higher [18].
- The manufacturing cost was estimated through the Dawn mission (\$281.7M for spacecraft development) as the NSTAR particle thruster was used in the mission. However, the value of the antennas and alternative sensors employed in the Dawn satellite was contemplated as the ADR mission is not for interplanetary observation [19].
- The price of the ground operation was estimated based on NASA's FY 2018 Budget [20].
- Research and testing prices are not yet determined.

TABLE IV
MISSION DATA FOR THE RAAN MANEUVERS.

Maneuver index	$\Delta\Omega$ (°)	ΔV (m/s)	Δt (h)
1c	2.7	544	840
2c	0.6	121	187
3c	1.4	281	434
4c	8.4	1694	2614
5c	1.4	281	434

TABLE V
MISSION DATA FOR THE ECCENTRICITY MANEUVERS.

Maneuver index	Δe	ΔV (m/s)	Δt (h)
1d	–0.030	160	247
2d	–0.050	262	404
3d	0.052	272	420
4d	0	0	0
5d	–0.082	422	651

J. Energy consumption per long-haul flight and rocket launch

To conduct an energy comparison between long-haul commercial flight and rocket launch, Korean Air A380-800 from ICN (Incheon International Airport) to JFK (John F. Kennedy International Airport) and Falcon 9 to LEO orbit was compared.

Korean Air's long-haul flight from ICN (Incheon International Airport) to JFK (John F. Kennedy International Airport) is about 11,070 km [21]. According to Korean Air's fleet, Airbus A380-800 can hold up to 407 passengers (seating capacity can differ by airlines) [22]. Using the A380-800's fuel consumption per seat, 3.27 L/100km provided by the Leeham Company (aviation consulting company) [23], fuel consumption per seat of flight from ICN to JFK is 362 L (8). Considering the calorific value of petroleum is 10 kWh/L [24], the energy consumed by each seat is 3620 kWh (9). Multiplying the number of seats and the energy consumed by each seat, the total energy consumed throughout the flight from ICN to JFK becomes 1,473,386 kWh (10).

Fuel consumption per seat from ICN to JFK:

$$\frac{3.27 \text{ L}}{100 \text{ km}} \cdot 11,070 \text{ km} = 362 \text{ L} \tag{8}$$

Energy consumption per seat from ICN to JFK:

$$362 \text{ L} \cdot \frac{10 \text{ kWh}}{1 \text{ L}} = 3620 \text{ kWh} \tag{9}$$

Total energy consumption of all passengers from ICN to JFK:

$$3620 \text{ kWh} \cdot 407 = 1.47 \cdot 10^6 \text{ kWh} \tag{10}$$

Falcon 9 is powered by the Merlin engines for both first and second stages using liquid oxygen (LOX) and rocket grade kerosene (RP-1), with oxidizer-to-fuel ratio (OFR) of 2.56. The first stage uses nine Merlin 1D engines producing thrust of 7,607 kN (at sea level) with 162 seconds of burn time, which is five times greater than the Boeing 747 at full power, while the second stage uses one Merlin vacuum engine producing 934 N (in vacuum) with 397 seconds of burn time. The propellant mass of the first stage is 395,700 kg and 92,670 kg for the second stage [15].

To estimate the LOX RP-1 energy consumption of the Falcon 9, specific energy of the jet fuel (kerosene) is used as it is similar to the RP-1 fuel. The specific energy of the jet fuel (SFE) is 11.90 kWh/kg [25]. By multiplying the specific energy value with the amount of RP-1 fuel of the propellant mass for each stage gives the amount of energy consumed by the rocket launch.

Fuel mass of the propellant:

$$M_{\text{RP-1}} = \frac{M_p}{OFR + 1} \tag{11}$$

Fuel energy consumption:

$$E = SFE \cdot M_{\text{RP-1}} \tag{12}$$

The amount of RP-1 fuel in the propellant mass of the first and second stage are calculated using (11) and given in (13) and (14).
First stage:

$$M_{\text{RP-1,1}} = \frac{395,700 \text{ kg}}{2.56 + 1} = 111,152 \text{ kg} \tag{13}$$

Second stage:

$$M_{\text{RP-1,2}} = \frac{92,670 \text{ kg}}{2.56 + 1} = 26,031 \text{ kg} \tag{14}$$

Energy consumed by the first and second stage are calculated using (12).
First stage:

$$E_1 = 11.90 \text{ kWh/kg} \cdot 111,152 \text{ kg} = 1.32 \cdot 10^6 \text{ kWh} \tag{15}$$

Second stage:

$$E_2 = 11.90 \text{ kWh/kg} \cdot 26,031 \text{ kg} = 309,769 \text{ kWh} \tag{16}$$

Total energy consumed during the Falcon 9 rocket launch was calculated in (17) by adding the energy consumption of each stage, which in turn was calculated in (15) and (16).

$$\begin{aligned} E_{\text{tot}} &= E_1 + E_2 \\ &= 1.32 \cdot 10^6 \text{ kWh} + 309,769 \text{ kWh} \\ &= 1.63 \cdot 10^6 \text{ kWh} \end{aligned} \tag{17}$$

III. RESULTS

A. Cost

Table VI shows the results from the performed cost analysis.

TABLE VI
COST BREAKDOWN FOR THE MISSION.

Component	Cost (USD)
Launch Vehicle	1.15M
Satellite Bus	30M
Sail-Net System	12M
NSTAR	40M
Manufacturing	100M
Operation	8M per year
Research	TBD
Testing	TBD
Total = 192M	

B. Energy consumption

Table VII shows the results of the energy consumption of long-haul flight and rocket launch.

TABLE VII
ENERGY CONSUMPTION OF A380-800 FROM ICN TO JFK (11,070 KM) AND FALCON 9 TO LEO (ENERGY CONSUMPTION WAS CONVERTED INTO AVERAGE SWEDEN HOUSEHOLD'S ELECTRICITY PRICE (0.22 USD PER KWH [26]))

Vehicle	Energy (kWh)	Electricity Price (USD)
A380-800	1.47M	0.32M
Falcon 9	1.63M	0.36M
Diff	0.16M	35,200

C. Time schedule

The orbital maneuvers will be carried out in the following order, with indices, ΔV and time requirements Δt defined in Tables II, III, IV and V.

$$\begin{aligned} &&&&\text{1a} &\rightarrow \text{Debris 1 (301 h)} \\ \text{2a} &\rightarrow \text{1b} &\rightarrow \text{1c} &\rightarrow &\text{1d} &\rightarrow \text{Debris 2 (1201 h)} \\ \text{3a} &\rightarrow \text{2b} &\rightarrow \text{2c} &\rightarrow &\text{2d} &\rightarrow \text{Debris 3 (703 h)} \\ \text{4a} &\rightarrow \text{3b} &\rightarrow \text{3c} &\rightarrow &\text{3d} &\rightarrow \text{Debris 4 (1027 h)} \\ \text{5a} &\rightarrow \text{4b} &\rightarrow \text{4c} &\rightarrow &\text{4d} &\rightarrow \text{Debris 5 (2787 h)} \\ \text{6a} &\rightarrow \text{5b} &\rightarrow \text{5c} &\rightarrow &\text{5d} &\rightarrow \text{Debris 6 (1204 h)} \end{aligned}$$

The ΔV from the tables mentioned above and a constant acceleration according to (1) was used to calculate the durations for the mission through (18).

$$\Delta t = \frac{\Delta V}{a} \tag{18}$$

Summing the number of hours above brings the total mission time to 7223 h, or approximately 301 days, excluding catch up maneuvers.

D. Trajectories

The launch trajectory for the Falcon 9 FT carrying a single 500 kg payload to 400 km is shown in Figure 3. For the simulated launch of the Falcon 9 FT a payload mass of 20 tons is used. The spacecraft proposed in this article is only 500 kg but since we want to utilize the re-usability of the Falcon 9 a joint launch is proposed. With a payload mass of 20 tons and rocket performance characteristics from the Falcon 9 FT an apogee of 376 km and perigee of 324 km is reached.

The anticipated rate of descent for the debris and spacecraft using the deployable sail method is shown in Figure 4. The mass of a sail-net package was estimated to about 35 kg, giving a total mass of 100 kg for each captured debris. During its mission lifetime the spacecraft will eject six packages weighing a total of 210 kg, while the fuel used will have a mass of approximately 60 kg. This means the total mass of the spacecraft at the end of the mission will be 230 kg.

IV. Discussion

A. Rocket performance and dynamics

The launch plots show that it is possible to launch a total payload of at least 20 tons into LEO. The rocket performance data is taken from the Falcon 9 with some adjustments to account for inconsistencies in publicly available data and some rough interpolation of the thrust and I_{sp} values, primarily for the first stage. The plots do not entirely reflect the reality of the launch since the launch has been simplified into a gravity turn without a flight control system to better control the final orbit parameters.

B. Debris and spacecraft deorbit

The spacecraft and the 6 pieces of debris are all decelerated using drag sails. Conceptually it is possible to scale this technology to bring down debris of any size. The question remaining is what technical limitations are imposed on the size of the sails, how large they can be manufactured and at what size it is no longer feasible to carry them to orbit. Assuming the sails can be made any arbitrary size, it is without question that the deorbit can be carried out within the specified mission duration of 25 years.

C. Environmental impact

Over the past 10 years, 740 rockets have been launched. Although the number of rocket launches compared to commercial aircrafts is small, the environmental impact of a rocket launch is not negligible. For Falcon 9, roughly 147 tons of kerosene is in RP-1 fuel and 34 percent of it is carbon contents [27]. In other words, every time the Falcon 9 launches, 50 tons of carbon is dropped into the ocean. Compared to the global carbon emission (International Energy Agency reported that carbon emissions reached 32.5 gigatons in 2017 [28]) the amount of carbon emitted from a Falcon 9 is tiny, but the amount of carbon emitted by rockets will increase considerably. This assumes a continued growth in the demand for launch services in the future.

The issue of rocket combustion emissions is not confined to the surface of the Earth (near the launch site affecting the air quality in the lowermost troposphere), but it delivers gases and particles directly into the middle and upper atmosphere. Martin Ross, a senior project engineer for civil and commercial launch projects at The Aerospace Corporation in El Segundo, California, said, rocket soot accumulates in the upper stratosphere, where the particles absorb sunlight, and this accumulation heats the upper stratosphere, resulting change in chemical reaction rates and possibly leading to ozone loss [29].

Figure 5 shows the approximate emission of four main propellant types given as mass fraction of each components. According to the table, solid rocket propellant emits relatively more ozone depleting gases and particles compared to the liquid rocket propellant. Another interesting point to stress out from the table is that both solid and liquid rocket engines emit water vapor (H2O), which depletes the ozone.

	Inert N_2	Inert CO_2+CO	OH source H_2O+H_2	Radicals ClOx, HOx, NOx	Radical reservoirs HCl	Particles Alumina soot
NH_4ClO_4/Al (solid)	0.08	0.27	0.48	0.1	0.15	0.33
LOX/H_2O (cryogenic)	—	—	1.24	0.02	—	—
LOX/RP-1 (kerosene)	—	0.88	0.30	0.02	—	0.05
UDMH/N_2O_4 (hypergolic)	0.29	0.63	0.25	0.02	—	Trace

Note: The Total Mass Fraction Exceeds Unity because of the assumption that air mixed into the plume oxidizes CO and H_2.

Fig. 5. Approximate emission for the four main propellant types given as mass fraction for each component [30].

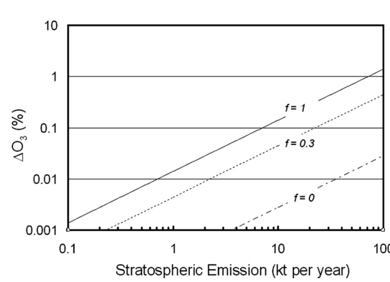


Fig. 6. Global ozone loss ΔO3(%) as a function of annual rocket emission into the stratosphere (kt per year) for different values of f (f, fraction of total stratospheric emissions from solid rocket motors) [30].

In Figure 6, the current global ozone loss for the next decade is expected to be less than 0.03%, which is less than the threshold of small ozone loss, 0.2%. However, assuming the numbers of rocket launches will increase, the global ozone loss is expected

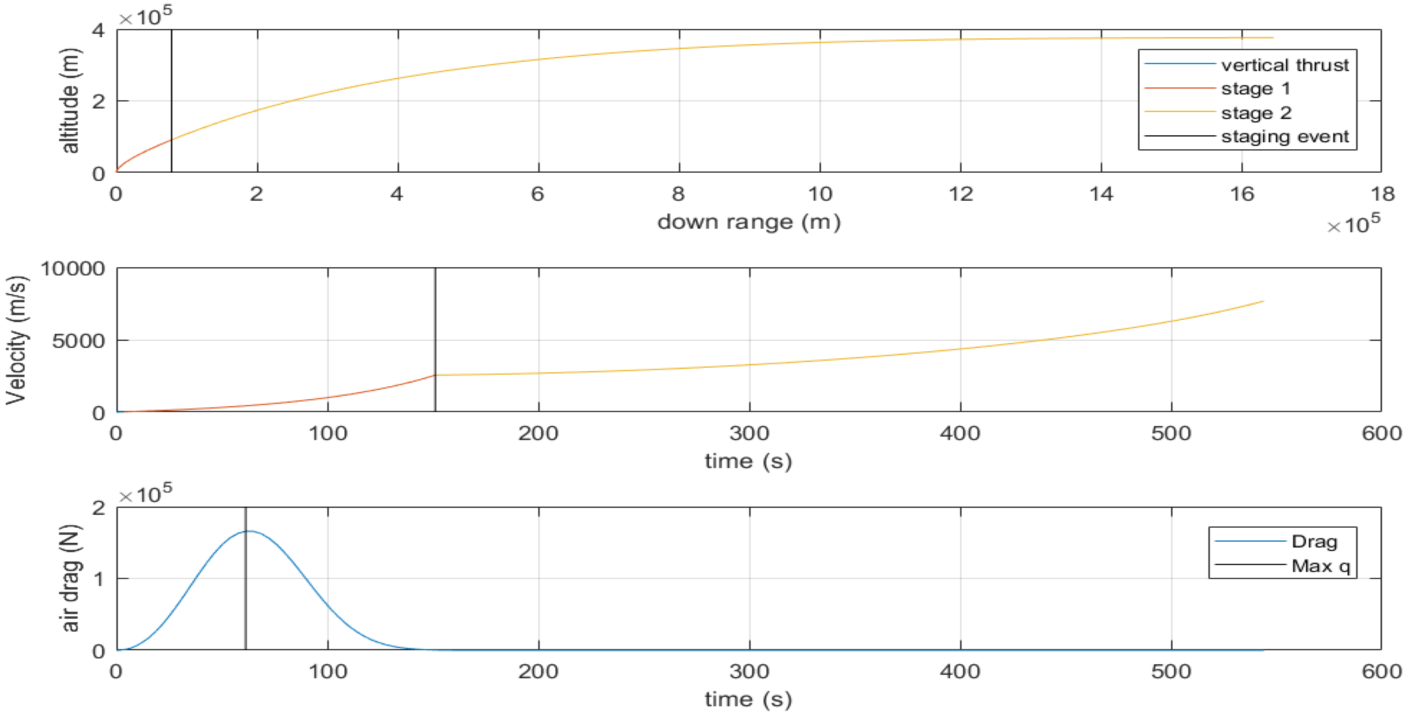


Fig. 3. The above plots show, in order, the launch trajectory, the velocity as function of time and the air drag as function of time.

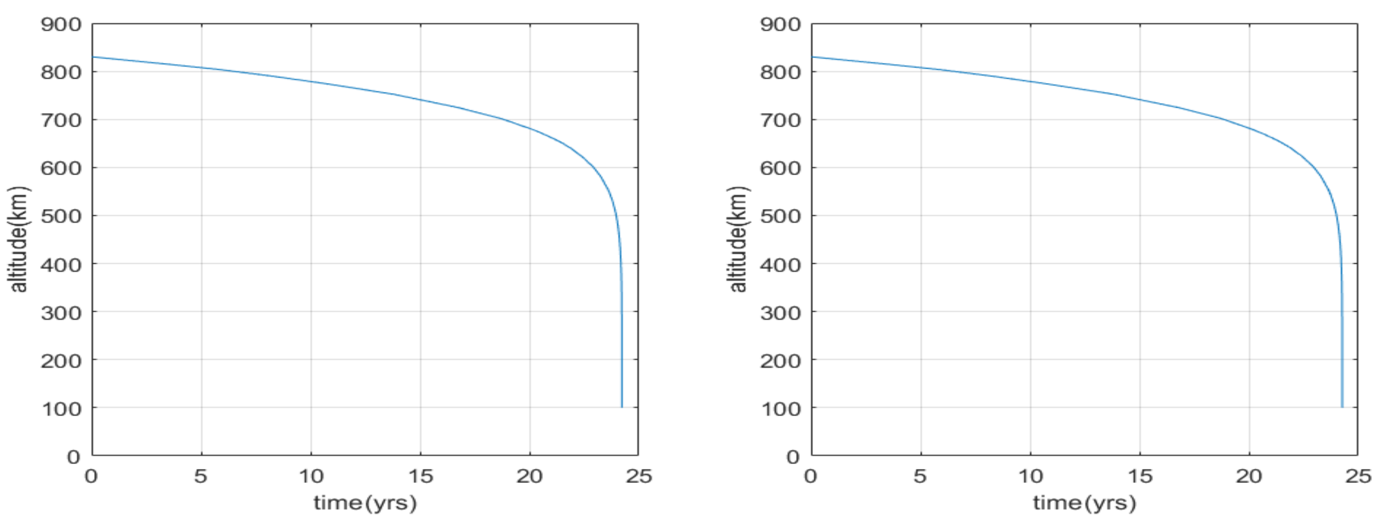


Fig. 4. The altitude of the target debris number 6 (left) and the spacecraft (right) during deorbit using a 5.6×5.6 m^2 and 8.5×8.5 m^2 sail respectively.

to excess the small ozone loss limit varying from 0.2% to 1% as shown in Figure 7.

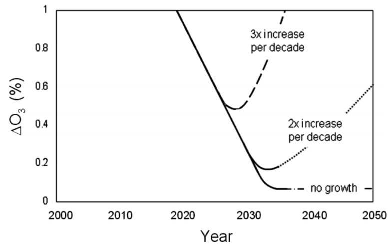


Fig. 7. Global ozone loss from 2005–2050 for different launch growth scenarios. The solid line is decreasing as the global ozone depletion substance (ODS) emission is expected to decrease in the future. The dash-dot, dot, and dashed lines show increasing or stabilizing ozone loss from launch emissions for the cases of no growth, doubling per decade, and tripling per decade, respectively [30].

The Quadrennial Ozone Assessment (in support of The Montreal Protocol on Substances That Deplete the Ozone Layer (and subsequent amendments)) addressed that ozone depletion by rocket emissions is determined to be small [30].However, it was discussed previously that this is not true. In future, the numbers of rocket launches will increase more, and the rocket combustion emissions affecting the lowermost troposphere and stratosphere (ozone layer) will no longer be negligible. Therefore, regulations of the rocket emission and its fuel compositions need to be reinforced, furthermore included in the The Montreal Protocol on Substances That Deplete the Ozone Layer.

D. Comparison of the energy consumption per long distance flight and rocket launch

Every year, the number of flights are increasing. Statista (an online statistic, market research and business intelligence portal) reported 36.8 million flights performed by the global airline industries in 2017 [31]. Not as much as flight, but the number of orbital launches are also increasing every year (most of them are unmanned satellite missions). Last year, 2017, there were 91 orbital launches and 83 of them were successful.

Table VII shows energy consumption of two different vehicles. Falcon 9 launch to LEO orbit consumes more energy than the long-haul flight of A380-800 from ICN to JFK. Although energy consumption per rocket launch is greater (about 160,000 kWh greater) than that of the long-haul flight, Falcon 9 is neither the most fuel-efficient rocket, nor the smallest rocket. The result can also vary with the distance of the long-haul flight, payload of the rocket, and the number of rocket launches and long-haul flights per year. Therefore, therefore the global energy consumption impact of rocket launches requires further discussion.

E. Cost

The total cost of the mission was estimated to be \$192M excluding the research and testing cost, and this seems reasonable as other space satellite missions cost from \$50M to \$500M. However, the complexity of manufacturing the sail-net system is unknown, and thus can change the total cost. Another element that can contribute to cost change is the capturing maneuver. As the details of the debris capturing maneuver are left undecided, there can be a huge increase in the price subject to the change in the number of thrusters, which can also result in an increase of payload. In addition, if the debris decaying time has to be reduced, this can increase the cost as the sails need to be scaled up.

V. CONCLUSIONS

- Space debris is an urgent issue that needs to be tackled as soon as possible, as otherwise humanity will not be able to go to or send objects into space. This means actions need to be taken soon, rather than waiting too long for a more optimized solution.
- This study is a preliminary study that aims to present solutions for this problem. Our spacecraft will remove six intact Thor Burner 2 stages in one year.
- The spacecraft will use a net to capture the selected debris. It is using an ion-propulsion system which has a high I_{sp}. They both have a high TRL, as the propulsion system is flight proven while the net capture mechanism has been successfully demonstrated in a space environment. This took place during an ESA mission in September of 2018.
- An estimated time for the spacecraft to capture all six debris is 301 days. This does not include rendezvous maneuvers.
- The debris will take 25 years to go from their current orbits to atmosphere with a 5.6×5.6 m^2 sail and a combined mass of 100 kg.
- The total cost of the mission is \$192M excluding the research and testing mission. As the mission is in the early conceptual phase, this can vary according the technology readiness level and time limitation of the mission.
- The energy consumption of a typical rocket launch to LEO orbit can be greater than that of a long-distance flight. However, compared to the vast number of flights taking place every day, the energy consumption for a rocket is currently negligible compared to the flights. This is however expected to change as the demand for launch services continues to increase in the future.
- As the debris has been chosen to minimize the time duration of travel for the spacecraft, for debris with a larger separation the mission will be longer.
- The high TRL of involved technologies and the margins in the time durations for the mission stages make the mission seem feasible.
- Continued testing of the net and other debris capturing mechanisms performed by major actors in the space industry will continue in the next years. Improvements such as more net-sail packages on the spacecraft along with larger nets and sails can allow for capture of a high amount of debris of various sizes.
- Sustainability within the space industry will continue being a problem but increases in yearly launches could

be compensated by a focus on reusable launch vehicles, new fuels and smaller, lighter payloads.

VI. Division of work

Jeongmyeong Bae:
Environmental impact, cost analysis.
Alexis Dorange:
Space debris research and launch site calculations.
Dhruv Haldar:
Rocket performance, PowerPoint slides.
Anton Kåbjörn:
Rocket dynamics, deorbiting, trajectory graphs.
Jesper Larsson:
Mission time and ΔV calculations, WBS and concept sheet design, abstracts, ADR methods, assumptions, project scope.

References

[1] stuffin.space. (2018) Stuff in space. [Online]. Available: http://stuffin.space

[2] ESA. (2018, May) Esa report on space debris. [Online]. Available: https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

[3] S. Minghe, G. Jian, and E. Gill, "Review and comparison of active space debris capturing and removal methods," *Progress in Aerospace Sciences*, 2015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0376042115300221

[4] Questn. (2018, January) What makes falcon 9 of spacex so special? [Online]. Available: https://www.youtube.com/watch?v=apKOg2XLCCc

[5] C. Shelner, "Ion propulsion: Exploring space in the 21st century," *Illumin - University of Southern Califonia, Volume V Issue V*, 2004. [Online]. Available: http://illumin.usc.edu/169/ion-propulsion-exploring-space-in-the-21st-century/

[6] G. Tibert. (2018, September) Rocket performance. [Online]. Available: https://kth.instructure.com/files/1235524

[7] Space Exploration Technologies Corp. (2015, October) Falcon 9 user's guide. [Online]. Available: https://www.spacex.com/sites/spacex/files/falcon_9_users_guide_rev_2.0.pdf

[8] M. Deep. (2013, September) Falcon 9. [Online]. Available: http://www.spaceflightinsider.com/hangar/falcon-9/

[9] M. M. Castronuovo, "Active space debris removal—a preliminary mission analysis and design," *Acta Astronautica*, 2011. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0094576511001287

[10] J. Heyman. (2008) Douglas slv-2 thor / boeing (mcdonnell douglas) sb-3 delta. [Online]. Available: http://www.designation-systems.net/dusrm/app3/b-3.html

[11] NASA Jet Propulsion Laboratory. Ion propulsion. [Online]. Available: https://dawn.jpl.nasa.gov/mission/ion_prop.html

[12] DLR. (2012, February) The ion propulsion system. [Online]. Available: https://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10559/966_read-2028/#/gallery/3906

[13] W. E. Wiesel, *"Spaceflight Dynamics, Third Edition"*. Beavercreek, Ohio, USA: Aphelion Press, 2010.

[14] M. Bylor. (2018, May) With block 5, spacex to increase launch cadence and lower prices. [Online]. Available: https://www.nasaspaceflight.com/2018/05/block-5-spacex-increase-launch-cadence-lower-prices/

[15] Falcon 9. [Online]. Available: https://www.spacex.com/falcon9

[16] S. S. T. US. Nasa rapid iii sstl-600. [Online]. Available: http://www.sst-us.com/shop/satellite-platforms/nasa-rapid-iii-sstl-600-200kg-400w

[17] C. Stephan. (2011, August) Nasa pursues tests of solar sail, laser communications. [Online]. Available: https://spaceflightnow.com/news/n1108/22technology/

[18] M. David, "Low cost electric propulsion thruster for deep space robotic missions," 2007. [Online]. Available: https://esto.nasa.gov/conferences/nstc2007/papers/Manzella_David_D10P2_NSTC-07-0116.pdf

[19] NASA. (2007) Dawn launch mission to vesta and ceres. [Online]. Available: https://www.jpl.nasa.gov/news/press_kits/dawn-launch.pdf

[20] ——. (2018) Fy 2018 budget estimates. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/fy_2018_budget_estimates.pdf

[21] Route map. [Online]. Available: https://www.koreanair.com/global/en/routemap.html

[22] Fleet information. [Online]. Available: https://www.koreanair.com/global/en/routemap.html

[23] (2014, February) A380v777v747-8 economics. [Online]. Available: https://leehamnews.com/wp-content/uploads/2014/02/slide1.jpg

[24] D. J. C. MacKay, *"Sustainable Energy — without the hot air"*. Cambridge, England: UIT Cambridge Ltd, 2009.

[25] E. Gofman. (2003) Energy density of aviation fuel. [Online]. Available: https://hypertextbook.com/facts/2003/EvelynGofman.shtml

[26] (2018) Electricity prices for households in sweden from 2010 to 2017, semi-annually (in euro cents per kilowatt-hour). [Online]. Available: https://www.statista.com/statistics/418124/electricity-prices-for-households-in-sweden/

[27] I. Whittaker. (2018, February) What is the environmental impact of the SpaceX Falcon Heavy launch? [Online]. Available: https://www.sciencefocus.com/space/what-is-the-environmental-impact-of-the-spacex-falcon-heavy-launch/

[28] I. E. Agency. (2018, March) Global energy demand grew by 2.1% in 2017, and carbon emissions rose for the first time since 2014. [Online]. Available: https://www.iea.org/newsroom/news/2018/march/global-energy-demand-grew-by-21-in-2017-and-carbon-emissions-rose-for-the-firs.html

[29] L. David. (2017, November) Spaceflight pollution: How do rocket launches and space junk affect earth's atmosphere? [Online]. Available: https://www.space.com/38884-rocket-exhaust-space-junk-pollution.html

[30] M. Ross, D. Toohey, M. Peinemann, and P. Ross, "Limits on the Space Launch Market Related to Stratospheric Ozone Depletion," *The International Journal of Space Politics & Policy*, 2009. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/14777620902768867

[31] (2018) Number of flights performed by the global airline industry from 2004 to 2018 (in millions). [Online]. Available: https://www.statista.com/statistics/564769/airline-industry-number-of-flights/