Business model for outer space mineral mining missions

Christopher Döring, Pier Antonio Esposito, Tilda Sikström, Xavier de Vaucorbeil, Markus Bernecker
KTH, Royal Institute of Technology, Stockholm, Sweden.

***Abstract*—In this paper, a business model for mineral mining in space is presented. The proposed company's task is to launch a human mission to the asteroid 469219 Kamo'oalewa, that houses a large concentration of valuable platinum group metals (PGM). The humans will set up a mining station that will autonomously mine the asteroid and ship around 40 tons of PGM back to Earth annually. The costs of such a mission will be considered as well as the potential earnings, giving that it will take the company 14 years to start earning more money than the total costs. Legal aspects are considered, where especially national laws that benefit the company have a big impact on the company's location. Environmentally, the company will have lower carbon dioxide emission per ton mined than the industry today, and will also be more sustainable. Several risks and the impact on the company have been considered to ensure that the business model will hold even if some off-nominal scenarios would happen.**

***Index Terms*—469219 Kamo'oalewa, 2016HO3, Platinum Group Metals, space mining, asteroid mining**

CONTENTS

LIST OF SYMBOLS

EVA	Extravehicular Activity
GEO	Geosynchronous equatorial orbit
ISS	International Space Station
LEO	Low Earth orbit
PGM	Platinum group minerals
SLS	Space Launch System

I. INTRODUCTION

Based on known terrestrial reserves, and growing consumption in both developed and developing countries, key elements needed for modern industry could be exhausted on Earth within 50 to 60 years [1].

Additionally, mining today is a dangerous business. Mining is conducted deep underground that poses dangers with falls, explosions and collapse of the mine. In 2019, 19 people in the platinum metal industry died due to these dangers [2]. This is seven more than compared to the previous year. The mining workers also face dangers due to chemicals [3]. Since the demand is rising while the reserves are shrinking, the dangers will only increase as the mining becomes more challenging.

Due to this, alternatives options, such as accessing resources in space, are getting more in focus. Especially the demand for the valuable Platinum Group Metals will stay high in the future. By autonomously mining PGMs in space, the dangers for humans will be lowered while still keeping up with the demand for the metals. Today, several organizations are already trying to design asteroid mining missions [4].

By virtue of this facts, this project work got created. The goal is to design a human asteroid mining mission to an existing asteroid whichs composition is made up but reasonable to get a feasible mission. For this project, 18 students have been divided into 4 different groups: the overall coordination team which created the company and mission framework, the logistics team which mainly evaluated the asteroid mining, the space vehicles team which calculated the orbits and maneuvers and designed the spacecrafts, and the human aspects team which is responsible for the life support system.

The created scenario of the blue team is an example on how a future asteroid mining mission could look like. The following report of the overall coordination team covers a short mission outline, gives an overview about the company's structure, presents a business plan, mentions briefly the legal, social and political aspects and finally provides a risk assessment.

II. Mission Outline

The purpose of the company is to fly to an asteroid called 469219 Kamo'oalewa or 2016HO3, mine valuable materials like platinum and return them back to Earth in order to sell them. The asteroid orbits the sun at distance of 0.9 to 1.1 times the distance of the Earth and the sun with a time of 366 days to compete one orbit [5]. In addition, its orbit is slightly inclined relative to the ecliptic. This leads to the phenomenon that the asteroid is "quasi-orbiting" the Earth and is staying within about 100 Earth-moon distances to the Earth, which makes it easier to reach than other asteroids [5]. It is assumed that 2016HO3 mainly consists of rock material and iron (∼87%) but is rich in rare metals such as platinum (∼10%), palladium (∼2%) and rhodium (∼1%).

The asteroid mining and recovery of the material will be split into three separate initial launches. First, two unmanned missions will be carried out, bringing mining equipment, supplies and a cargo re-entry vehicle to the asteroid. The equipment will be launched with an SLS launcher whereas the empty cargo spacecraft will be launched with a Falcon Heavy rocket. These missions will be launched only a few days apart in the same launch window and will use a trajectory that is optimized for maximum payload mass. After a flight time of around 300 days, both spacecrafts will arrive at the asteroid.

About half a year after the equipment has arrived at the asteroid, a manned mission with three astronauts on board will be launched with an SLS rocket. This time, a trajectory optimized for minimum duration will be used in order to minimize the time the astronauts have to be subjected to the space environment. Their flight time to the asteroid will be around 120 days. The spacecraft will be a new development with an extensive life support system that is capable to support the crew for the whole duration of their mission, which will be a little less than a year.

After the astronauts arrive at the asteroid, they will install the equipment brought by the first mission. In order to extract the useful materials from the asteroid regolith, a foldable cone is anchored on the asteroid's surface to catch the mined material and prevent it from flying away due to the low gravity of the asteroid. The actual mining will be performed by several autonomous small mining robots. On top of the cone, refinement and storage units will be installed by the astronauts. The refinement unit separates the useful material from the rock. It does so by redirecting sunlight with mirrors to melt the mined material and spins it around in a centrifuge afterwards. The metal separates from the rock and can be extracted, cooled and stored.

When the equipment is set up, the crew monitors the automatic process to ensure that it is working and then starts its return to Earth after about three weeks on the asteroid. After another 191 days of flight, the astronauts will land back on Earth.

The automatic mining and refining will continue on the asteroid until the the cargo return ship is at its full capacity of 50 tons. The cargo ship will then start its journey back to Earth. For reentry, the ship will split into several smaller vessels that are contained in the cargo ship and are equipped with their own heat shields and parachutes.

To continue the mining on the asteroid, a new cargo ship can be sent to the asteroid and filled up every year. This can be repeated until the mining site is stripped of its resources.

III. Company Structure

The primary goal of the company is to make a profit from asteroid mining as well as proving the feasibility of commercial human spaceflight. This translates into a company structure that is as lean as well as cost- and time efficient as possible in order to account for the costly initial investments and to reach the break-even point as soon as possible.

In the time before the initial launches in the early 2030s, the company will be founded and set-up. The first step will be to establish an Administration department whose responsibilities entail management and financing tasks. A sub-department for Human Resources is needed as well as the company will grow extensively from this point on. At this point in time, a dedicated Public Relations or Outreach Department will be installed, which will start with the acquisition of funding (see section IV) and will establish relations with space agencies and other commercial space enterprises. The latter is important because in order to keep the development cost and time of the spacecraft low, they will be developed using as much existing technology or even complete vehicles as possible.

The launchers themselves will be bought directly and no launcher development will be necessary. For the three spacecraft needed, a Research and Development and an Integration department will be founded, which will work together to construct the spacecraft so that they are ready for testing as soon as possible. The spacecraft for the human mission will consist almost completely on existing, basically "off-the-shelf" modules, such as a Vinci Engine, a SpaceX Dragon 2 capsule or Bigelow Expandable Activity Modules which will help in keeping the development times short. For the life support system, a partially closed loop system approach will be adopted where multiple systems already in use on the ISS will be used. The development of the cargo ship will take the most time and resources, as it will have multiple smaller cargo pods inside that can separate from the main ship for the re-entry in Earth's atmosphere. This is a system that will have to be developed in-house and is therefore a bigger risk for the schedule than the manned spacecraft.

A crew of three astronauts is planned for the manned mission to the asteroid. Their main roles will be commander, pilot and mission engineer, but they will be required to be able to fill any of the other roles as well in case of emergency. Teams of six astronauts will be trained in order to have a backup crew. The training for the astronauts can present a major time factor, which is why the astronauts for the mission should be hired from other space agencies or companies, where they already received basic training. Alternatively, the astronauts can be trained from scratch and the training facilities can be rented. Only specialized training specific to the mission at hand will be done in-house. In order to further reduce training effort, the EVA suits used by the agency or company where the training takes place will be bought and there will be no further EVA suit development.

Before the launches can take place, a Ground Control Center will be needed as well. This will be an in-house department as it will have to be present 24 hours a day to be able to supervise the mission and be in contact with the human crew.

IV. Initial Funding and Revenue

This section covers the revenue once the mining process has been started and the funding needed before this point.

A. Revenue

Around 2035 the mined goods are on Earth and can be sold. As a result of the steady demand and the decreasing supply, the price for platinum, palladium and rhodium is expected to increase until then.

To successfully run the business, the mined goods have to be sold and distributed. Two different approaches are considered. The refining, selling and distribution of the mined goods could be carried out by the company itself. However, the huge amount of know-how, manpower and management, to establish the necessary structures, out weight the benefits. Consequently, the sales of the mined goods will be outsourced for a small fee. It is considered, that one of the members of the London Platinum and Palladium Market will do this. The amount of valuable metals brought back with every cargo is 40 tons, about 80% of the total capacity of the cargo ship due to the imperfections in the separation process taking place on the asteroid. Considering the current costs per gram of the metals and their assumed relative percentage it is possible to have an estimation of the total value of each cargo.

Table I: Value per cargo

	Price [$/g]	Percentage on the asteroid	Mass [tons]	Price [$M]
Platinum	32	10 %	30.8	985.6
Palladium	89	2 %	6.1	542.9
Rhodium	380	1 %	3.1	1178
Total			40	2706.7

Therefore, it is possible to estimate that the total revenue per cargo coming back to Earth is of $2.7 billion. Furthermore, considering that the spacecrafts containing the metals will come back with a period of every year the revenue will be of $2.7 billion per year. It is assumed that in the given time frame the company will be able to fully sell the metals brought back since the quantities are not going to over-saturate the market. For instance, nowadays 190 tons of platinum are mined per year and the missions will bring back 30.8 tons per year.

B. Research

Understanding microgravity and space is an expensive challenge. There are some experiments that can be performed without going to space, as gravity wells and parabolic flights. Sending something to space, either by a sounding rocket or all the way up to the ISS is even harder. Today there are private companies launching rockets and selling ride-along spots aboard these, meaning that there already is an existing market and demand. One example of this is the private company Spaceflight Industries. Spacecraft Industries charge $300 000 for a 3U cubesat to LEO, and $900 000 for GTO [6], that will be used as a baseline for the price aboard the human spacecraft.

The human vehicle is designed to have room for 1 ton of research, at a volume of $3.5\,\mathrm{m}^3$. The 3 astronauts on board will have time to perform experiments for 7 hours each day. Out of the 330 days of the mission, 300 of these can be used to do research. There are then 2100 hours for each astronaut, or 6300 total research hours.

The room allocated for research on the human spacecraft is divided into two categories. The first category is the modules that will require no handling. For standardization, these will be required to follow the 3U cubesat convention with dimensions of $10 \cdot 10 \cdot 34\mathrm{cm}^3$ and a maximum weight of $5\,\mathrm{kg}$. Each unit will have a price of $1.5 million, about 50% more than what it costs to send an item to GTO today.

The second category are larger experiments that will require astronaut handling. Each experiment should have a maximum mass of $50\,\mathrm{kg}$ and not require more volume than $0.3\,\mathrm{m}^3$. These numbers agree with the size and weight of experiments currently at ISS. These experiments will have a cost of $10 M each, plus an hourly rate of $23500. The hourly rate is set as slightly higher than what NASA charges for an hour of an astronaut time at the ISS [7].

Table II: Income for research onboard human spacecraft

	3U Cubesat	Larger Experiments	Total
# of units	100	10	
Mass	500 kg	500 kg	1 ton
Volume	$0.5\,\mathrm{m}^3$	$3.0\,\mathrm{m}^3$	$3.5\,\mathrm{m}^3$
Income	$150M	$100M+$148M	$398M

In total, using space and astronaut time will give an extra profit of almost $400 million. Another benefit is that the mental health of the astronauts will benefit of having stimulating tasks during the long mission.

C. Advertisement

While advertising has been done in the past, such as an astronaut drinking Pepsi in space or having a Pizza Hut logo on an aircraft, there are several aspects to consider when deciding if advertising could be a form of revenue for the company.

Comparisons with the cost companies had paid in the past, and after adjusting for inflation, the income would be significantly lower than the revenue from the ores. Instead, there could be grave repercussions for the company image if using advertising as a way to make money. Therefore, this option was discarded in the end.

V. EXPENDITURE

The estimation of the costs has been performed by fist splitting the different aspects of the mission and for each one has been performed a proper study.

The cost associated with the mission are presented in figure 1 where a distinction between one-time costs and recurrent costs has been made.

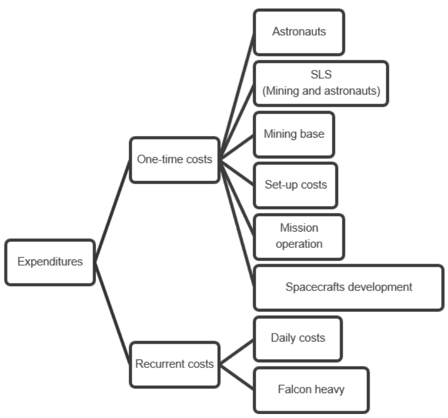

Figure 1: Costs division

A. Astronauts

The cost associated with the astronauts is the more easily predictable since, even if under different circumstances, people have already been trained to perform highly technical operations in space. The training of an astronauts requires costly and highly specific equipment, therefore it has been decided to not train astronauts for the company from zero, but to hire the ones working for NASA. This decision would benefit the costs estimations of the company. Furthermore NASA is expected to be keen to agree on it since the company will propose to pay for part of the costs of the training and the company will offer NASA the possibility to perform scientific experiments during the flight to the asteroid. Given such considerations the cost per astronaut can be estimated to be of about \$10 million [8]. Since the mission will require 3 astronauts and each one of them will have a back-up the total cost will be of about \$60 million.

B. Vehicle: SLS & Falcon heavy

Our company won't take part in the development of the vehicle, neither the one carrying the mining equipment nor the one upon which the astronauts will flight. The rocket SLS developed by NASA will be used for the transportation of the mining equipment and for the astronauts. Its cost per launch is set to \$800 million [9].

According to plan the cost of the SLS will be a one-time one, since humans will only be used to set up the mining base. On the contrary, the Falcon Heavys will be employed for the cargo missions, that will take place every year, will be constitute a recurrent cost. The current cost for each launch is \$90 million [10].

C. Mining base

The mining equipment was the most challenging cost to estimate since nothing similar has ever been done before. The cost for such an operation has therefore been compared to the one of building a base on the Moon whose total cost has been estimated to be of several billions US dollars and then reduced due to the fact that there won't actually be humans living on the asteroid and the technology improvement in the upcoming years. The cost for such a mining base has therefore been set to \$2 billion.

D. Mission operations

The mission will require to have a fully operational ground control center to make sure that the mission proceeds smoothly and communications system such as antennas and satellites. This will be particularly relevant during the manned mission to set-up the mining base due to the higher risk related to the possible loss of human lives. To estimate this cost it has been taken as a reference the cost of the mission operations of the ISS every year. The cost is of \$1 billion per year [11]. The cost can be expected to be lower for our kind of mission due to the technological improvement in the upcoming years and the fact that the actual mission will take place during only a few weeks therefore in the meanwhile the workload of the control center is expected to be much lower. The cost of the mission operations has been estimated to be \$250 million.

E. Maintenance

Due to the complexity of the mission and the fact that this will be the first time that such a technology will be used, maintenance operations will be be required. It is not possible to estimate the cost of such operations since they will depend on the incidents and the parts to fix. Although, it is expected that the equipment design will be robust enough to keep working at least until the break-even point is reached. Enough profit would be made until then and the expenses of another human mission to the asteroid will be covered.

F. Spacecraft development

The company will be responsible for the development of the spacecrafts that will contain the mining equipment and the astronauts. The estimation of its cost has been based on the cost for the development of the Orion spacecraft currently under development by NASA with the purpose of bringing humans to Mars. NASA reported that the Orion development costed \$18,138 million (adjusting to 2018 dollars) [12]. Taking into account that the spacecraft needed for our mission will have lower requirements that an interplanetary capsule, and that part of the knowledge, and technologies developed for the capsule Orion could be used into the development of ours, an expected cost of \$1.5 billion seems to be reasonable.

G. Company: set-up & daily costs

The costs for the company will also be related to management and administration. These costs include the salary of the employees, the rent for the offices, legal expenses and taxes. These kind of costs are highly uncertain since they depend on the the state where the legal offices of the company will be located. Therefore, it was decided to set such costs to a value of $0.1 million per day plus an initial set up cost of $500 million. These cost maybe an over-estimation of the real ones, but at least it grants us to be on the safe-side in case our previsions were to be false.

H. Break-even point

Finally, once the estimation of the earnings and of the costs is done it is possible to compute when the break-even point will be reached in time. These are presented in table III and table IV respectively.

Table III: Cost

Cost	Million $
SLS	800
SLS	800
Mining base	2000
Astronauts	60
Company set-up	500
Daily cost	0.1
Bank interests	135
Spacecraft development	1500
Mission operations	250

Table IV: Earning

Earning	Million $
Mining	2700
Research	400

As can be noticed the main costs are associated with the SLS launchers and with the development of the mining equipment and the spacecrafts. Luckily, these are one-time costs and therefore sustained only during the set-up and development phase.

Consequentially the break-even point will be the one shown in figure 2.

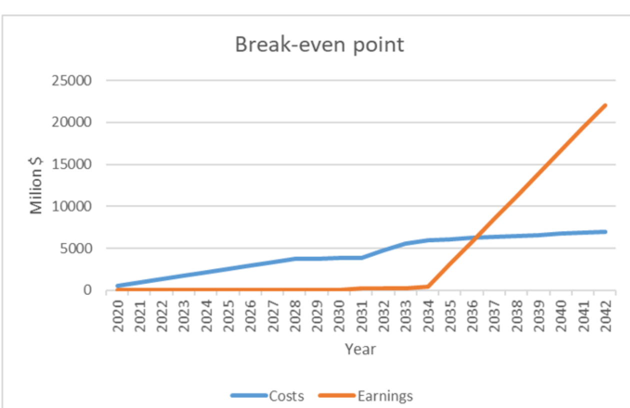

Figure 2: Break-even point

The graph highlights that the break-even point will be reached in 2036. Before then it is necessary therefore to find a capital of about $5.5 billion to cover the initial expenses.

I. Funding

The private company's structure implies that the funding during the start up phase will mainly be based on loans from banks or private investments funding. This choice would make quickly available the large capital needed in order to set up the required infrastructure for the mission that will take place in only ten years from when the company begins. Although the amount of money required for initiating a space company is high, the investors may be keen to place their money on the company due to the high expected value of the space industry. In the upcoming 30 years (year 2040) it is expected to have be worth $3 trillion according to Bank of America (respect to the $300 billion in 2016) [13].

The current interest rates are around 4-5%, although they are not too high due to the large amount of money needed to start up a space company the total value of the interests has to be taken into account when drafting the business plan. The earning from the research contributions can be added to the funding since they will be paid before the first cargo returns to Earth and therefore before the company has reached its steady business plan. Finally, another source of money will be the selling of shares through the stock market to private investors. This is commonly done by companies that need to increase their capital: private investors can buy shares of the company and then sell them again when the value of the options bought is increased. At the same time the company through the selling of the shares increases its liquid assets.

The estimation of the costs to cover before the first re-entry of the capsule containing the metals is $5.5 billion and they will be covered according to the following division:

- Loans: $4.125 billion
- Private donations: $165 million
- Shares' selling: $825 million
- Research: $400 millon

The percentage breakdown of the cost are also presented in figure 3.

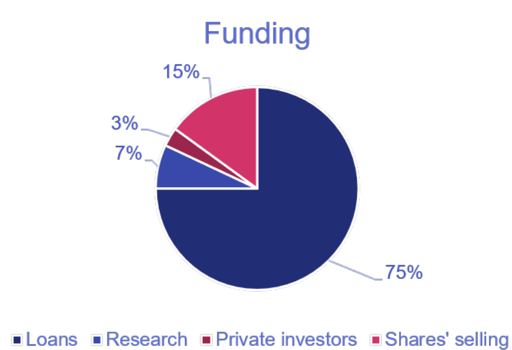

Figure 3: Funding distribution

J. Loans

As can be noticed from the previous figure, the main part of the initial budget is relied to rise from loans. Banks are expected to be more keen in investing money into our business, although the high uncertainty related to the fact that it is the first time that something similar is carried out, because they will receive a solid profit from the interests rate even in case the profit will be lower then expected.

K. Private investors

Potential investors can be identified in two main categories: professional investors who base their investments on reliable data and wealthy enthusiastic of the space exploration.

The first category is the more reliable one since, once evaluated the advantages and the risks in investing in our operation, they would provide a solid source of founding through out the start up phase even if they would not receive any immediate profit. Being their decision based on their experience and expertise they would know that a business in order to start requires high initial expenses, especially in the space field were the technology used has a high cost due to reliability requirements, they are therefore expected to be less keen to retract the decision to support the company. Nevertheless, on our side it is required to be convincing in providing a convincing business plan and high expected profits since as stated before the investors would be professionals in the venture capital business.

The second category could represent a good source of funding with low effort required since it already happened that wealthy enthusiastic about space missions and exploration would invest large amount of money into them even for a low (or none at all) economical return.

The two most notable case are those of Yusaku Maezawa, a Japanese billionaire and founder of Zozotown, Japan's largest online clothing retailer, who paid the private company SpaceX to be sent on a flight around the Moon [14] and that of Dennis Tito who visited the ISS for seven days in April–May 2001, becoming the world's first "fee-paying" space tourist. Tito paid a reported $20 million for his trip [15].

These kind of investors, even if could contribute in part to the budget of the company, cannot be considered a reliable source of incomes due to the low number of similar cases in the past and the high oscillations that a similar phenomena may have. For instance an accident during the flight of one of these investors would cause the drop of the demand while a series of successful launches and an increased fascination for the space exploration in the society would raise the demand.

L. Share's selling

About 15% of the initial funding is expect to come from the stock option market. This hypothesis is backed by the fact that many companies with long-term plans, that made the first profit many years after they have started, often have a strong support by investors even during the first years. This is due to the fact that, even if the risk of not having an economical return for a long time is high, a disruptive technology or new business model, if successful, brings an enormous amount of wealth to those who were the firsts to invest in it.

VI. Legal & Political Aspects

A. Legal

There are five international space treaties, and the use of asteroid is covered by the international treaty "Outer Space Treaty" but in some countries, it is also covered by national statutory laws.

1) International treaties: Space mining involving the extraction and removal of natural resources from their natural location is allowable under the Outer Space Treaty [16]. According to the space treaty, there is a difference between extracting space resources, even by private companies for profit and owning territories and outer space objects.

2) National laws: In some countries, some laws facilitate the development of asteroid mining programs. The Space Act of 2015 allows US Citizens to own, to use and to sell asteroids. According to the article 51303 of the law : A United States citizen engaged in commercial recovery of an asteroid resource can possess, own, transport, use, and sell the asteroid resource in accordance with applicable laws, including the international obligations of the United States [17].
Furthermore, some countries, to facilitate the development of asteroid mining programs, decided to invest themselves in companies. For instance Luxembourg announced they would invest $200 million [18] and they have similar law to the US about the ownership of extracted space resources.

B. Political aspects

The company will be settle in the US, because most of the technologies that are planned to be used come from the US itself and moreover, their laws and legislation are favorable to the start up of private companies and to the use of asteroids. The company is not planned to be part of an international cooperations since these cooperations are slow to act. Furthermore, being ours a private company the main goal is to maximize the profit of the mining and this is not usually compatible with international cooperations. Most of the mining takes place in emerging countries, this new way of mining could reduce their exploitation by developed countries that extract most of their resources without building real infrastructures. Moreover, this new way could be a solution to corruption, wars, and pollution that are connected to mining in emerging countries. Being the first company to mine an asteroid might not revive the Space Race, however Russia is the second producer of PGM (Platinium Group Metal). And with this new way of mining, the US will be independent from Russia, because the cargo will bring back on Earth twice the quantity that is produced in Russia per year. Therefore, if the company succeeds, it might stimulate other countries to develop space mining programs too, in order to do not become dependent of other countries.

C. Impact on society

All knowledge and science gained from research and operations during the program's missions will be publicly available. To have more impact, astronauts will do educational tasks as in the ISS. The objective after the first asteroid mining is to mine more asteroids but also to share the technology that has been developed.

D. Social

Space exploration has had a big impact on culture and society. Seeing earth as a tiny object in space made a lot of people focus more on how to protect our home planet, igniting the environmental movement. Space exploration also inspired people to study aeronautics, engineering, and physics. Therefore, the mission should drive this spirit further, inspire and show humankind what they can achieve. To drive this spirit, research will be done during the mission and social media platforms will be used.

The benefit of asteroid mining should be shown so to get the support of governments and national agencies. Nowadays, rare metal mining is limited due to resources and can be dangerous when connected to corruption, wars, and pollution in developing countries. Therefore, a new way of getting raw material could be seen as a solution for these issues. However, it has to be considered that making available more material on the market could lead to more competition and to an increase of corruption.

Another important part, of the social aspects, is what society thinks about the asteroid mining mission. In memory of the event, where a asteroid with a supposed diameter of around 15 kilometers was the reason for a mass extinction on Earth, humankind could be afraid of something similar could happen again, this time caused by men itself [19]. Therefore, it must be shown, that the risk for such an event is almost zero.

Finally, the company should be seen as a solution for the limited resources issue on Earth and should have a corruption-free and environmental-friendly image. It shall be seen as a revolutionary and high tech organization that inspires humankind to grow together and push the limits. -

VII. Environmental Impact and Sustainability

The environmental impact of rocket launches has in the past not been seen as an important issue, since the number of launches have been relatively low. However, with the growing interest and industry this is rapidly increasing. In a couple of years there could be thousands of launches each year [20]. One environmental concern is the CO_2 emissions. The emissions from space travel (a few kilotons per year) compared to the aviation emissions (several hundred kilotons per year) shows that space travel could increase a lot before reaching the aviation emission levels [21]. Furthermore, aviation is only responsible for about 2% of the total CO_2 emitted each year [22]. Therefore, the carbon dioxide emissions of space flight is not the highest concern. There is another aspect of the environmental impact of rockets that needs examination - the emission of black carbon or soot. When rockets travel up to space they emit black carbon that ends up in the stratosphere. The stratosphere is also where the ozone layer is, and the chemical reactions of the soot will reduce the ozone layer [23]. The reduction of ozone is an important aspect to address, since the ozone layer plays an important role in protecting the human population from dangerous radiation from the sun. In conclusion, there are factors that needs to be considered if space mining would begin to launch multiple rockets a day. On the time scale that this mission covers, with about one launch per year, the environmental impacts is relatively low.

A. Mining of platinum group minerals

The rare minerals the mission will mainly focus on is most often called the platinum group minerals (PGM). There are several environmental issues with mining metals on Earth. First, the process requires quite a lot of water to separate the wanted minerals from other materials such as rocks. For example in Africa, water is scarce so the usage greatly impacts the total water available in a region. The same argument is applicable for electricity. The greenhouse gas impact is also high when mining on Earth, approximately 1.6 ton of CO_2 is generated for every ton of PGM mined [24]. Compared to one cargo trip to the asteroid that will emit about 0.33 ton CO_2 to bring back 40 ton of PGM, the carbon imprint is greatly reduced by mining in space. Waste materials such as solid wastes and chemicals, that are a great danger to wildlife, nature, humans and societies [25]. In conlusion, while space mining missions will not replace mining done on Earth, they will be a mining source which has lower environmental impact than those on Earth and does not exploit areas or humans.

VIII. Off-nominal scenario and risk analysis

This section discusses a probable but solvable Off-nominal scenario. Additionally, the mission is divided into two parts, before the first launch and after the first launch, and the most probable risks are stated and rated.

A. Off-nominal scenario

An off-nominal scenario could be the mining equipment breaking down, after the humans left. Depending on when this happens in the mission schedule there are three different scenarios.

The first scenario would be the mining equipment breaking directly after it got set up and the humans left. If no counteraction is performed, the mission would be a financial disaster. A second manned mission must be performed to repair the equipment and make the mission profitable again. It would cause an estimated additional cost of $4 billion including a second launch, building a new spacecraft, training the astronauts and other expenses. The final consequence of this scenario would be a mission delay of about one and a half years. This time period includes the 330 days mission duration, additional preparation time for crew and equipment, and the waiting time for a suitable launch window. Moreover, the overall risk of the mission would rise with another human crew far away in space again. Also, the costs would rise. Therefore, the break-even point would be delayed of about two and a half years due to the additional mission time, plus about an additional year to pay off the additional costs.

The second scenario would be the mining equipment breaking down close to the break-even point. Regarding the company's goal to make money, a human repair mission would also be

required. The consequences of the scenario would be the same as in the first one.
The last scenario would be the mining equipment breaking down way after the break-even point. Depending on the material demand on Earth and the resources left on the asteroid, the value of a repair mission must be strongly investigated. It might be, that the additional costs and the risks of a repair mission out weight the benefits.
In conclusion, the first scenario is the most threatening. No earnings can be expected and the costs rise strongly. Also, the time, where revenue is expected, gets delayed by over two and a half years. It should be considered to have enough assets on the side for such a case.

B. Risk analysis

In the following section, the overall financial risks of the mission are examined. The mission is therefore divided into two parts. Before the mission start (before the launch) and after the launch, but before the break-even point. The risk analysis is carried out as a qualitative/quantitative risk analysis [26].

The most likely risks before the launch are shown in table V. The risks include unexpected expenses, not enough loans, not enough investors and a delay of the mission. Nevertheless, the risks are not considered critical because of the high revenue of the mission. Enough investors should be found because of the high earnings and the prestige. Nevertheless, the investors must be informed in advance, that the initial costs might exceed the first calculations and the time until the break-even point is reached, might get delayed for some years.

Table V: Risk before the launch

Event	Probability	Impact	Value
Unexpected costs	4	2	8
Competitors mining the asteroid first	1	5	5
Development delay of spacecrafts	4	1	4
Not enough investors	1	4	4
No permit from the government	1	4	4

The second section shows the risks from launch until the break even point is reached. The most relevant risks are shown in table VI. The biggest financial risk is the failure of the mission. This could happen if multiple of the risky cases, or other unexpected failures occur. Finally they would prevent us from mining the asteroid and bankruptcy would be inevitable. The probability for such an event is expected quite high, since such a mission never has been accomplished before. One of the probable risks, is the mining equipment breaking, as described before. Failure of a spacecraft, cargo loss during reentry and the death of an astronaut would also have an big financial and image impact for the company. Although, they would not necessarily cause failure of the whole mission. They could delay the timeline and have a financial impact. Although, if a lot of these smaller risks accumulate, the mission could fail.

Table VI: Risk before break even point

Event	Probability	Impact	Value
Mission failing	3	5	15
Mining equipment breaking	3	4	12
Astronaut death	2	5	10
Failing of spacecraft	2	5	10
Cargo loss during reentry	2	3	6
Takeoff explosion	1	5	5
Asteroid destroying the Earth	1	5	5
Minerals dropping in value	1	4	4
Astronaut illness	4	1	4
Few minerals on asteroid	1	4	4

After the break even-point is reached, there is no financial risk left. All in all the mission is very risky with a big probability of failure and loss of investment. Nevertheless, the high probable outcome justifies the risk.

IX. Conclusion

The asteroid mining mission would be the next step for human kind to make space more accessible. As consequence of the resources on Earth being exhausted in long term, this kind of mission will get a future leading objective in space industry.

The proposed asteroid mining mission is from the perspective of a commercial operating company aiming to earn money. Due to this fact, the most important objective is to maximize revenue and mine as much as possible. Therefore, the company structure is more focused on management and if possible the responsibilities get outsourced. However, political, social and environmental aspects are not neglected. The company wants to have a positive impact on society and how they think about commercializing space. Also, the mission should be legal, not tense the political situation and do not have a more negative impact on the environment than usual mining. All in all, the mission is quite risky but also a really profitable business.

The suggested mission to 469219 Kamo'oalewa, in this report, could give an example for a lucrative asteroid mining mission. However, such a mission has never been accomplished and it is therefore new terrain with yet unknown challenges and yet untested technology. This would lead to a lot of adjustments to decrease the risks, if such a mission would be attempted in real life. Another limiting factor would be the amount of ores found on a asteroid. Since the asteroid analyzed in this report is full of ores, money are not a problem but this could be a real challenge for a real life mission.

References

[1] David Cohen. Earths natural wealth: an audit. Australien Academy of science. 2007.
[2] Mining fatalities in South Africa at record low. https://www.mining-technology.com/mining-safety/south-africa-mining-fatalities, 2020. Accessed 2020-02-24.
[3] G. Nelson and J. Murray. Silicosis at autopsy in platinum mine workers. *Occupational Medicine*, 63(3):196–202, 02 2013.
[4] Asteroid mining. https://en.wikipedia.org/wiki/Asteroid_mining#cite_note-3. Accessed 2020-02-23.
[5] Wikipedia. 469219 Kamo'oalewa. https://en.wikipedia.org/wiki/469219_Kamo'oalewa, 2020. Accessed 2020-02-13.
[6] Spaceflight Industries Pricing Information. https://spaceflight.com/schedule-pricing/#pricing. Accessed 2020-02-17.
[7] Commercial and Marketing Pricing Policy. https://www.nasa.gov/leo-economy/commercial-use/pricing-policy. Accessed 2020-02-17.

[8] StackExchange. https://space.stackexchange.com/questions/35431/how-much-does-it-cost-to-train-an-astronaut. Accessed 2020-02-20.
[9] Wikipedia. Space Launch System. https://en.wikipedia.org/wiki/Space_Launch_System, 2020. Accessed 2020-02-13.
[10] QUARTZ. https://qz.com/1439557/spacex-is-building-a-market-for-falcon-heavy/. Accessed 2020-02-21.
[11] StackExchange. https://www.nasa.gov/sites/default/files/atoms/files/fy19_nasa_budget_estimates.pdf. Accessed 2020-02-20.
[12] Wikipedia. Orion (spacecraft). https://en.wikipedia.org/wiki/Orion_(spacecraft)#Funding_history_and_planning, 2020. Accessed 2020-02-13.
[13] CNBC. https://www.cnbc.com/2017/10/31/the-space-industry-will-be-worth-nearly-3-trillion-in-30-years-bank-of-america-predicts.html. Accessed 2020-02-21.
[14] TheVerge. https://www.theverge.com/2018/9/17/17869990/elon-musk-spacex-lunar-mission-ticket-moon-passenger-bfr-falcon-yusaku-maezawa. Accessed 2020-02-21.
[15] Wikipedia. Space tourism . https://en.wikipedia.org/wiki/Space_tourism, 2020. Accessed 2020-02-13.
[16] The treaty on principles governing the activities of states in the exploration and use of outer space, including the moon and other celestial bodies.
[17] Fabio Tronchetti. Title iv space resource exploration and utilization of the us commercial space launch competitiveness act: A legal and political assessment. *Air and Space Law*, 41(2), 2015.
[18] Peter B. de Selding. Luxembourg to invest in space-based asteroid mining. https://spacenews.com/luxembourg-to-invest-in-space-based-asteroid-mining/. Accessed 2020-02-25.
[19] Wikipedia. Cretaceous–Paleogene extinction event. https://en.wikipedia.org/wiki/Cretaceous%E2%80%93Paleogene_extinction_event, 2020. Accessed 2020-02-13.
[20] Michael Sheetz. The space industry will be worth nearly $3 trillion in 30 years, Bank of America predicts. https://cnb.cx/2B3Zrjy. Accessed 2020-02-17.
[21] Penner J.E, Lister D.H, Griggs D.J, Dokken D.J, and McFarland M. Aviation and the Global Stratosphere. *Cambridge University Press*, 1999.
[22] Air Transport Action Group. Facts and Figures. https://www.atag.org/facts-figures.html. Accessed on 2020-02-17.
[23] Martin Ross, Michael Mills, and Darin Toohey. Potential climate impact of black carbon emitted by rockets. *Geophysical Research Letters*, 37(24), 2010.
[24] Gavin M. Mudd. Sustainability reporting and the platinum group metals: A global mining industry leader? *Platinum Metals Review*, 56(1):2–19, 2012.
[25] M. Junior Mabiza and Charles Mbohwa. Quantifying co 2-eq emissions of ore-based pgm concentration process in south africa and identification of immediate environmental impacts. *Proceedings of the World Congress on Engineering*, II, 2015.
[26] Qualitative vs. Quantitative Risk Analysis. https://www.project-risk-manager.com/blog/qualitative-and-quantitative-risk-analysis/, 2017. Accessed 2020-02-24.

APPENDIX
TIMELINE OF MISSIONS TO THE ASTEROID

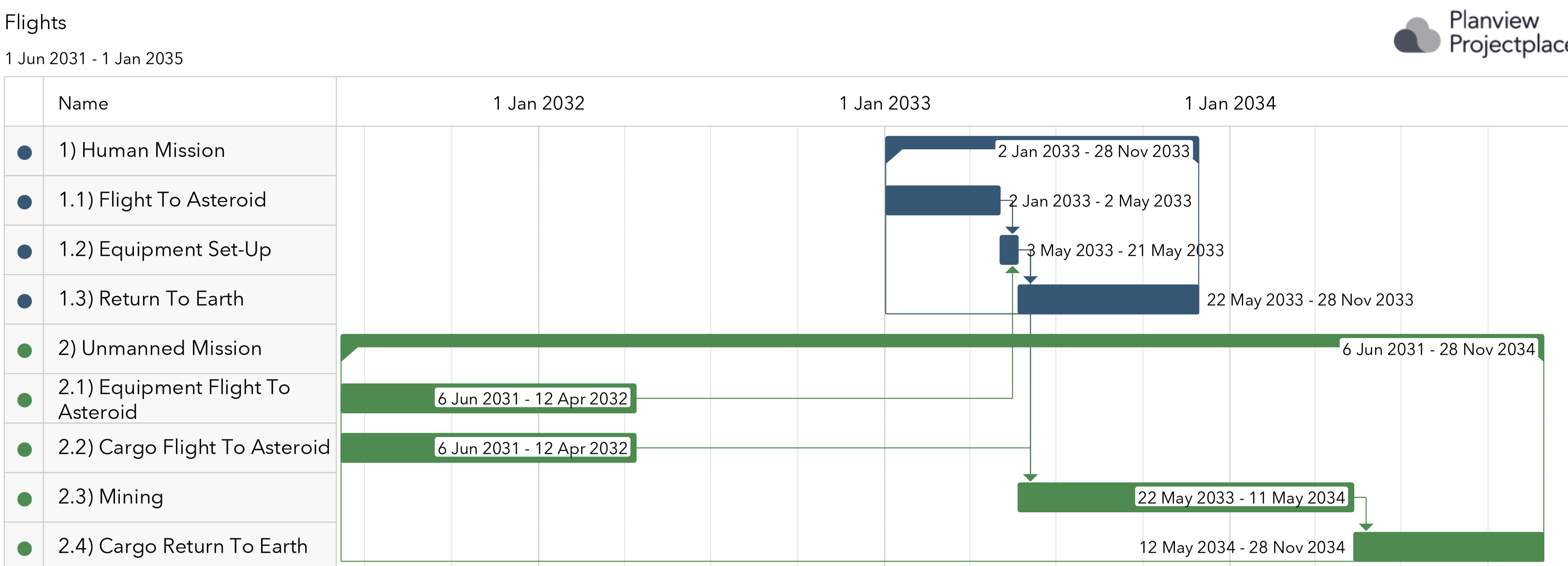

Figure 4: Timeline of the planned initial flights to the asteroid