# Commodity prices for asteroid mining serving Earth market

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**Abstract**

Mineral resources are available in limited quantities on Earth and will become more difficult to extract in the future. Space mining offers new prospects to extract the necessary resources to serve the needs of Earth's economy. Some near-Earth asteroids (NEA) are believed to contain high value metals with attractive grades compared to Earth's surface. In particular, Platinum which benefits from attractive market price and size, is often seen as one the best cases for asteroid mining. However, most existing studies have not put enough focus on throughput rate of ore processing, which is key to assess the overall viability of the project.

We built a model of a space mission architecture to determine the maximum mass of equipment that can be brought to the asteroid to ensure recovery and transportation of platinum back to Earth. Combined with hypotheses on costs of space missions, this study finds out that a minimum platinum selling price over 70,000 € per kg is required. This is significantly above current and historical market values of platinum, but still in the same order of magnitude. Analyzing this result in the context of likely future decreasing costs of space transportation, asteroid mining could therefore be seen as attractive in a context where platinum market price increases toward its historical heights and above.

However, in-situ processing equipment is limited to 1 ton for 25 tons launched from low Earth orbit. Based on state-of-the-art processing machines used by the mining industry on Earth, this last constraint appears to be unrealistic to obtain in-situ pure platinum from asteroid regolith.

As a result, we take into account a more comprehensive processing equipment and the fact that the output obtained from the in-situ processing is not pure platinum but just a higher concentration aggregate. With these additional constraints, the required platinum wholesale price has to increase by 3 orders of magnitude to around 25 M€ per kg. Given such a price gap, we conclude that a large asteroid mining venture aiming at Earth market is very unlikely, even over a 100-year time horizon.

Keywords: Asteroid mining; NEA; platinum; PGM ; transport costs; economy viability.

## 1. Introduction

### *1.1 The focus on Near Earth Asteroids (NEA) and platinum*

Man has looked at space for a long time with the dream of someday taking possession of its infinite resources. In particular, the idea of exploiting the Moon for its mineral commodities has been a regular theme promoted by many space enthusiasts. However, due to its common origin with Earth, our satellite has a similar abundance of precious metals than Earth. Therefore, given the challenge of mining in the very harsh lunar environment plus the extra cost of shipping back those resources to Earth, it makes moon mining structurally not competitive for serving Earth commodity market.

An alternative to the Moon often considered are near-Earth asteroids (NEA), that are defined as asteroids orbiting the Sun with a perihelion distance less than 1.3 AU (See Appendix).

NEA can be classified, according its emission spectrum, color, and albedo as Carbonaceous (C-type), Siliceous (S-type) or Metallic (M-type). It is the M-types that have triggered interest from asteroid mining perspective, as they are assumed to have a very high concentration of premium minerals.

Given the challenges of asteroid mining, only metals with a very high value on Earth could be of interest. In addition, as suggested in the first paragraph, the concentration found in asteroids should be significantly higher than on Earth in order to offset transportation and operation costs.

In Table 1, we summarize the most valuable minerals on Earth based on their market size and value. We also display the estimates of their concentration in M-type NEAs.

| Commodity | Price Earth[1] (€/kg) | Market Size[2] (tons) | Market Value (MM €) | Grade NEA[3] (ppm) |
|---|---|---|---|---|
| Gold | 27,708 | 3300 | 91.4 | 0.5 |
| PGM | 27,263 | 631 | 17.2 | 89.1 |
| Palladium | 22,461 | 315 | 7.1 | 1.3 |
| Platinum | 30,953 | 243 | 7.5 | 35 |
| Ruthenium | 17,274 | 35 | 0.6 | 13 |
| Rhodium | 60,383 | 31 | 1.9 | 4.8 |
| Iridium | 18,543 | 7 | 0.1 | 35 |

Table 1. Analysis for most valuable commodities on Earth. [1]From http://www.platinum.matthey.com/prices/price-charts, average prices for the 2000-2020 period, historical evolution available in the appendix B [2]From USGS and Platinum Matthey, total demand for 2019, include mining production and recycling [3] From Ross (2001)

From this table, it appears that gold combines the biggest market value (90 MM €) and an attractive market price (27,708 €/kg). Unfortunately, its concentration in NEA is very low (0.5 ppm). On Earth, a low-quality underground gold mine has an average grade of 2.5 ppm (World Gold Council). Therefore, due to its low concentration in NEAs, gold does not seem to be a good candidate for asteroid mining.

Platinum group metals (PGM) which are similar in price to gold, are found in much high concentrations in NEA (89 ppm). However, its total market is 5 times smaller than gold's. If we break down the PGM earth market, we notice that despite its high concentrations in NEA (35 ppm), world's annual demand for Iridium is quite small. As a matter of fact, Palladium and Platinum represent more than the 80% of demand for PGM and are on first glance the most attractive commodities among PGM.
However, on further examination of Table 2 below, Palladium concentration in NEA does not seem to be particularly attractive.

| Commodity | Grade NEA[1] (ppm) | Grade Earth [2] (ppm) | Ratio |
|---|---|---|---|
| Platinum | 35 | 3.75 | 9.3 |
| Palladium | 1.3 | 3.75 | 0.3 |

Table 2. Comparison between platinum and palladium in NEA and on Earth. [1]From Ross (2001) [2]From US Geological Survey (2017) for mines exploiting mainly PGM.

Overall, it comes as no surprise that platinum is the focus of most studies on asteroid mining, as it's the only commodity that combines an attractive price per kg, significant annual demand and some much higher grades in NEA than on Earth mines.

### *1.2 Limitations of existing studies*

The idea of exploiting NEA resources has been around since the beginning of space exploration. However, research conducted so far in this area include a number of limitations:

R. Gertsch and L. Gertsch (1997) evaluate how much asteroid material should be mined to get a return of investment (ROI) ranging from 10% to 100%. The study concludes that spatial projects have long payback periods. One possibility to mitigate this drawback is to combine projects. With this approach, Platinum mining is considered as just an add-on for more attractive projects, such as water extraction missions, aiming at life support and in space propellant. The study remains at a high level and concludes that investment in space resource utilization is unlikely to be attractive without extraordinary good preparation from the entrepreneurs managing the venture.

Blair (2000) examines high-value asteroid-derived mineral products from an economic perspective to assess the possible impacts on long-term precious metal supply. He concludes that platinum ore alone is not currently attractive for serving Earth's market. However, he considers that potential for other mineral-based products extracted from asteroid resources is sufficiently good to justify a detailed examination of multi-product economic feasibility. As a result, he believes asteroid platinum-group metal mining has the ability to be attractive. We will see that even when several PGM are combined, the economic challenge remains very high.

Sonter (2001) assessed the technical problem, He added the concept of net present value (NPV), which means taking into account the time value of money. He suggested a generic mission with a lightweight (3 or 4 tons) remote tele-operated regolith miner or drilling rig, recovering products such as water and other volatiles using solar thermal power, and subsequently returning approximately 1000 to 2000 tons to Low Earth Orbit, using solar thermal rocket propulsion. However, the study does not quantify processing constrains for the proposed mission.

Ross (2001) based his study in the technical model from Sonter (2001). He also presents metal concentrations in near Earth asteroids as well as a brief discussion about the possible extraction methods. However, its discussion is more focus in water extraction methods. He states that for a metallic asteroid it is needed a cutting method and the metal have to be melted at high temperatures. No further details about methods are provided.

Zacny et al. (2013) identified water as the commodity most likely to be of value for extraction and use in space. The study considers Platinum as potentially addressing Earth market. For that, the authors introduce two main challenges. First, it is difficult to evaluate the schedule and cost for developing metallurgical processes that will extract any of the PGMs in space. The reason is that, it already is extremely difficult to evaluate cost and schedule for developing of any metallurgical processes on Earth, so for space the uncertainties are just too big. Second, it is difficult to foresee the prices change of any PGMs in the scenario where large additional supply is brought to the market. As a result, the study does not come to a robust conclusion regarding Platinum potential.

Craig et al. (2014) provides a preliminary economic and sensitivity analysis of a possible off-Earth mining business extracting minerals from an existing asteroid. Its model show that in order to get a positive net present value (NPV), a period of more than 40 years is needed. Results change significantly when taking the hypothesis of a space market, but unfortunately this space market does not exist today and it's still unclear how and when it will develop.

Calla et al. (2019) presented a mining architecture that uses a 500 kg spacecraft. Its study concludes that 200 spacecrafts are required to achieve an economically feasible operation within 10 years of operation. His estimations are limited to water extraction.

Hein et al. (2020) modify and expand Sonter's work (2001) by assessing multiple mining mission, taking into account the cost of return to Earth and the transfer time. He concludes that throughput rate and using multiple small spacecrafts are key technical parameters for reaching breakeven quickly. For future work, he states that the estimation of possible throughput rate of known mining and refining processes would merit further investigation.

Throughput rate parameter is indeed key and has to be considered carefully to assess the economic viability of asteroid mining operations. After setting up a standard model, this study discusses throughput rate parameter in more details than previous studies, aiming at hopefully getting to a more robust conclusion regarding the overall attractivity of asteroid mining.

## 2. Method

We present a basic asteroid mining mission from which we will develop a techno-economic model. First, from the technical part, we will obtain the relationship between the mass launched, the required processing equipment and the maximum platinum recovered. Then, after some economic considerations, we will estimate the minimum platinum price that meets our hypothesis. Finally, sensitivity analysis are performed for the platinum price.

### *2.1. Mission description*

The project will consist on the following phases:

1) Launch: Sending the spacecraft to orbit (LEO).
2) Outbound: The spacecraft go out from LEO to the asteroid orbit.
3) Mining and processing
4) Inbound: Return to Earth

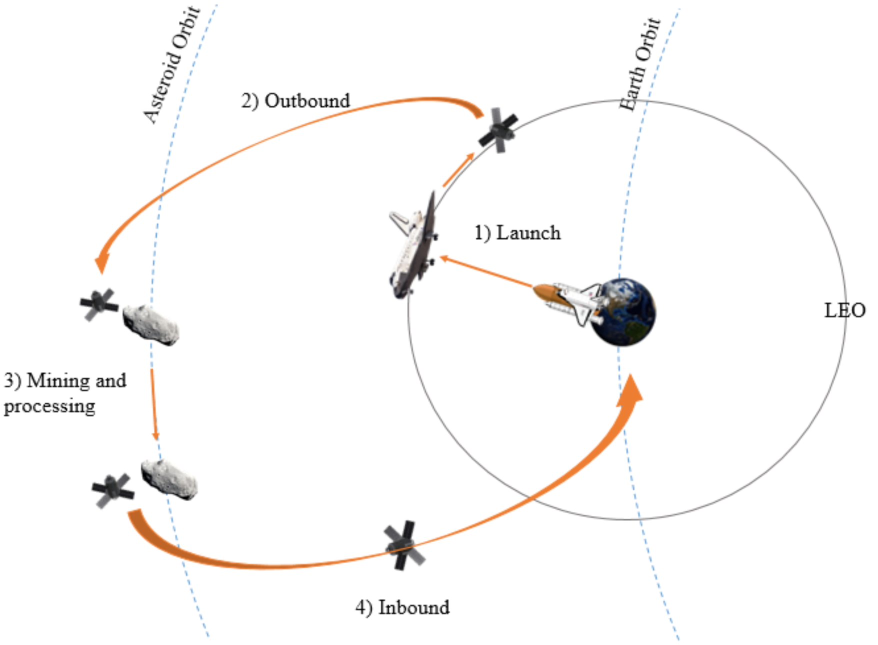



Fig.1 Mission description

### *2.2. Preliminary considerations*

The ratio platinum recovered to processing equipment can be express as:

$$R = \frac{Platinum(\%)}{Equipment(\%)} = \frac{t\ x\ f\ x\ g}{10^6}$$

Where *t* is mining duration in days, *f* is throughput rate in kg of ore per kg of equipment per day and *g* is platinum grade in ppm.

Our assumptions are therefore summarized in Table 3 below.

| Hypothesis | |
|---|---|
| Mining duration (days) | 360 |
| Throughput rate (kg/day/kg) | 400[1] |
| Grade (ppm) | 35 |

| | |
|---|---|
| R = Ratio Pt/E | 5.0 |

Table 3. Geology and equipment hypothesis. [1]Value taken from a Falcon SB750 concentrator.

Therefore, for each kilo of processing equipment sent to space, we can return, at most, 5 kilos of platinum.

In space, the parameter which determines is the energy required to deliver a mass from one point to another, is not distance, but the required velocity change, Delta-V or Δv, needed to perform the transfer.

For our Delta-V budget, we refer to Sonter (1997) who estimates that getting from LEO to a NEA requires a delta-v of 5.5 km/s and the return trip requires a delta-v of 2 km/s.

| Other variables (Rocket Equation) | | |
|---|---|---|
| Delta-V-inbound | 5.5 | km/s |
| Delta-V-return | 2 | km/s |
| Exhausting Velocity | 4.4 | km/s |
| Fuel mass ratio inbound (FMRi) | 71% | |
| Fuel mass ratio return (FMRr) | 37% | |

Table 4. Variables used in rocket equation

Then, From Tsiolkovsky rocket equation, the fuel mass ratio is defined as:

$$Fuel\ mass\ ratio = FMR = \left(1 - e^{-\frac{\Delta Vo}{V_e}}\right)$$

Therefore, from the total mass launched, the 71% will be fuel and from the total mass that can be return to Earth, 37% will be fuel.

*2.3. Technical Analysis*

The objective of this part is to establish relationships between the masses of all the components. It can be broken down as follow:

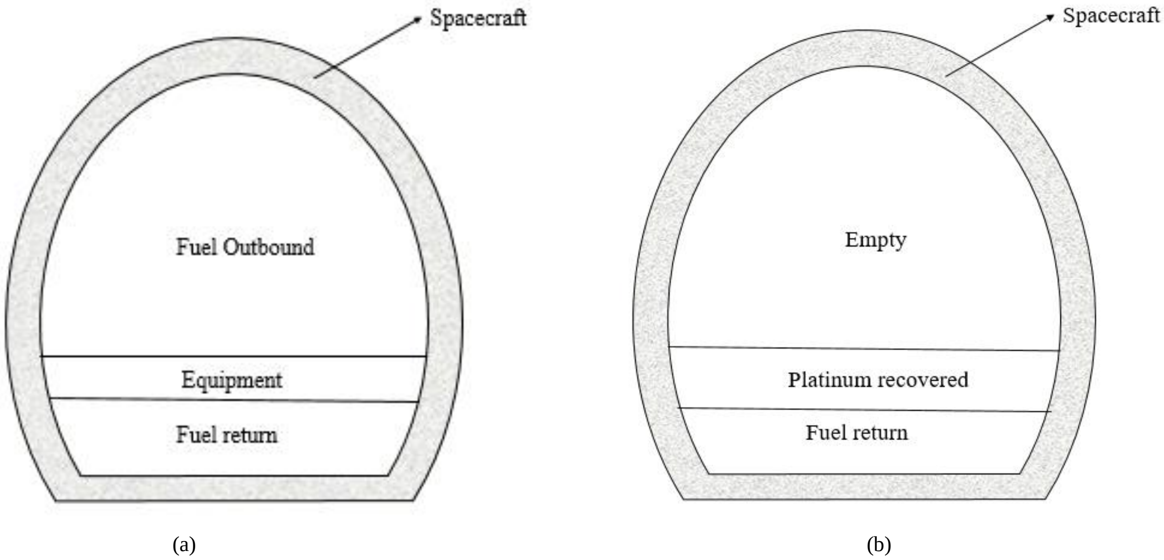



Fig.2 Mass break down for (a) outbound and (b) return

In order to obtain the relationship between all the masses, we will express all of the masses as a percentage of the total launched mass.

Equipment plus fuel return is equal to (See Fig. 2 (a)):

$$Equipment\ (\%) + Fuel\ return\ (\%) = 100\% - spacecraft\ (\%) - fuel\ outbound(\%) \quad (1)$$

In addition, the quantity of platinum recovered is related to the necessary equipment:

$$Equipment(\%) = Platinum\ (\%)/R \quad (2)$$

Replacing (2) in (1)

$$\frac{Platinum(\%)}{r} + Fuel\ return\ (\%) = 100\% - spacecraft\ (\%) - fuel\ outbound\ (\%)$$

For a given quantity of fuel, total transport mass is limited by the rocket equation:

$$Total\ mass\ return\ (\%) = fuel\ return(\%)/(FMRr)$$

Then, we can express the platinum recovered in terms of fuel return (See Fig.2 (b))

$$Platinum\ (\%) = Total\ mass\ return\ (\%) - fuel\ return(\%) - spacecraft\ (\%) \quad (3)$$

Finally, solving for fuel return:

$$Fuel\ return\ (\%) = \frac{((100\% - FMRi - spacecraft(\%)) * R * FMRr + FMRr\ x\ spacecraft(\%))}{FMRr * r + 1 - FMRr} \quad (4)$$

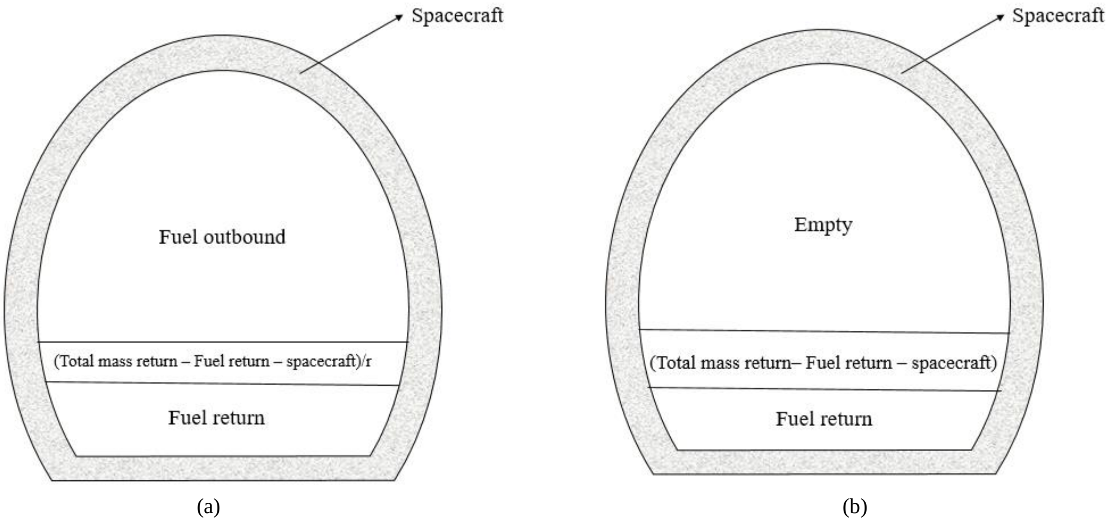



Fig.3 Mass break down for (a) outbound and (b) return expressed as a percentage of the total launched mass.

For our calculation, we will take a spacecraft mass of 8% of total launching mass. This is quite optimistic as most existing rockets have a mass ratio of 10% or more, but we want to consider the most favorable scenario for asteroid mining. We will also assume a total launching mass of 25 tons which is quite typical (based on SpaceX Falcon 9).

*2.4. Economic Analysis*

In order to estimate total costs, we will assume an operation cost (on top of hardware costs) and a margin. Finally, we will estimate the platinum market price that meets our economic hypothesis.

$$Total\ \ cost = Transport\ cost + Hardware\ cost + Operating\ cost$$

We introduce k, as our operating markup:

$$Operating\ cost = k * (Hardware\ cost + Transport\ cost)$$

Then,

$$Total\ \ cost = (1 + k) * \ (Transport\ cost + Hardware\ cost)$$

Where:

$$Transport\ Cost = Total\ mass\ launched\ x\ transport\ cost\ per\ kilo$$

And

$$Hardware\ cost = (Equipment\ mass + spacecraft\ mass\ ) * \ Equipment\ cost\ per\ kilo$$

Our commercial margin m is defined as,

$$Total\ revenue = (1 + m) * \ Total\ Cost$$

Finally,

$$Mininimum\ platinum\ selling\ price\ \ = \frac{Total\ revenue}{Platinum\ recovered}$$

For our calculation, we will take the following standard assumptions:

| | |
|---|---|
| Operation Markup (k) | 30% |
| Commercial Margin (m) | 30% |

Table 5. Operation margin from Schiller (2008) and margin from current values for the gold mining industry on earth (Anglo American annual report 2019)

## 3. Results

### *3.3 Technical analysis*

For our assumptions in the Method section, we obtain:

| Total Mass Launched | 25000 | 100% |
|---|---|---|
| Small Spacecraft | 2000 | 8% |
| Fuel inbound | 17837 | 71% |
| Equipment & Fuel return | 5163 | 21% |
| **Max Equipment** | **1029** | 4% |
| Fuel Return | 4134 | 17% |
| | | |
| Total Mass Return | 11318 | 45% |
| Small Spacecraft | 2000 | 8% |
| Fuel Return | 4134 | 17% |
| **Max Mass Platinum** | **5184** | 21% |

Table 6. Total Mass breakdown

The above table can be graphic as follow:

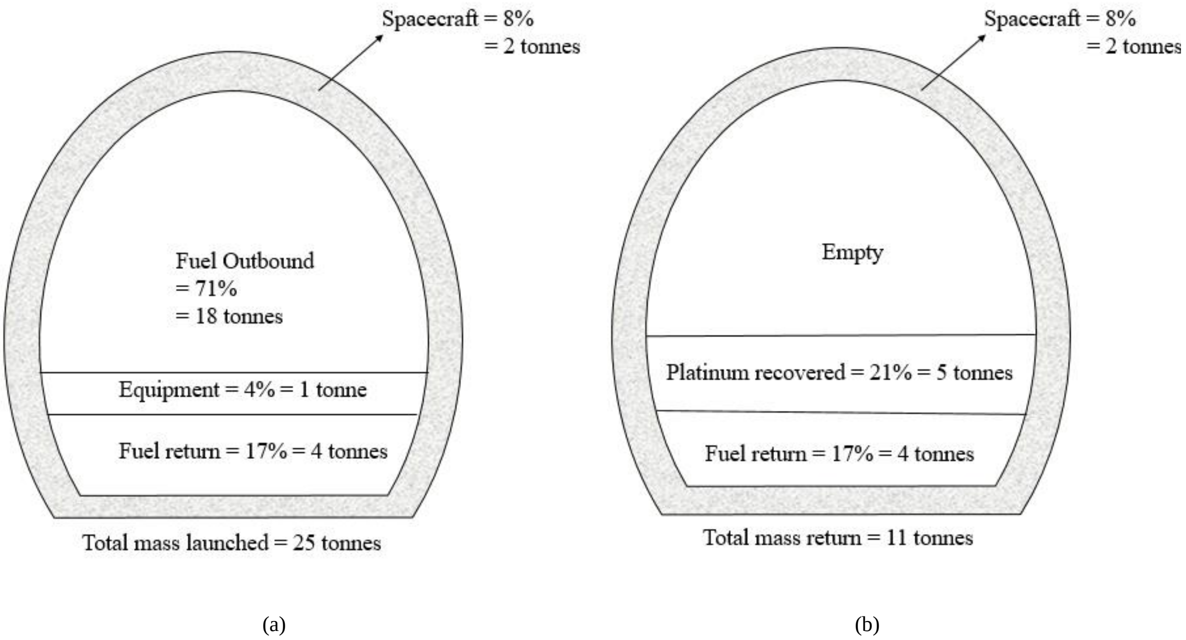



Fig.4 Mass break down for (a) outbound and (b) return expressed as a percentage of the total launched mass and in tonnes.

To summarize the above results, we conclude that equipment and platinum recovered are related to total mass launched in the following relationship.

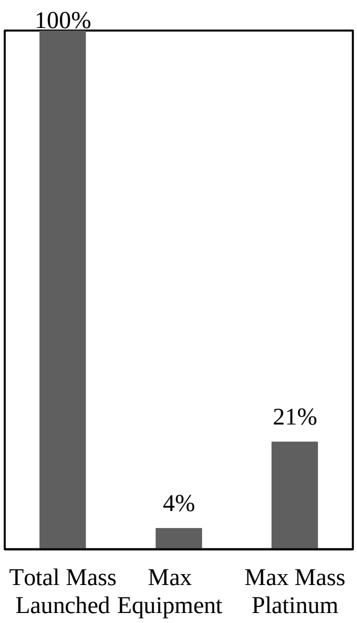



Fig. 5. Relationship between total mass launched, maximum equipment that can be launched et maximum mass of platinum that can be return to Earth.

*3.4 Economic analysis*

From current economic values:

| | |
|---|---|
| Cost transport to LEO (€/kg) | 2700 |
| Cost Equipment (€/kg) | 50000 |

Table 7. Transport cost to LEO from SpaceX Falcon 9 (2019), equipment costs taken as a conservative value from Schiller (2008)

We obtain the following cost break down and the minimum platinum selling price in M€:

| | | |
|---|---|---|
| Cost Transport | 68 | 24% |
| Cost Hardware (Equipment + SC) | 151 | 53% |
| Costs Operation | 66 | 23% |
| Total Costs (M€) | 285 | 100% |
| Total Revenues (M€) | 370 | 130% |

| | |
|---|---|
| Min Platinum Market Price (€/kg) | 71,372 |

Table 8. Costs break down, expressed in M€ and minimum platinum selling price

To evaluate these results, we will compare it to the historical platinum price.


Fig.6 Platinum selling price from the last 20 years (Source: Matthey.com, see Appendix B) and minimum platinum selling price

*3.5 Sensitivity analysis*

Thanks to improvement in rocketry (in particular reusability), transport cost to LEO is expected to go down in the future. We can therefore calculate the impact of cheaper Earth-to-LEO transportation on asteroid platinum market price.

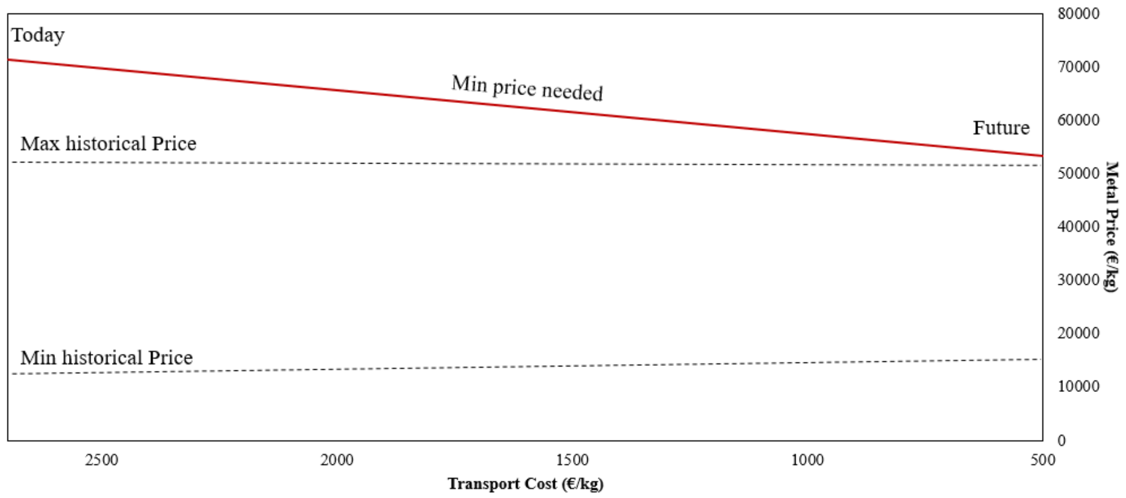



Fig.7 Platinum selling price variation when transport costs to LEO fall down.

Taking recommendations from Hein et al. (2020), we show what would the effect of a higher grade or a higher throughput rate (equivalent to a higher platinum to equipment ratio) on the asteroid platinum selling price.

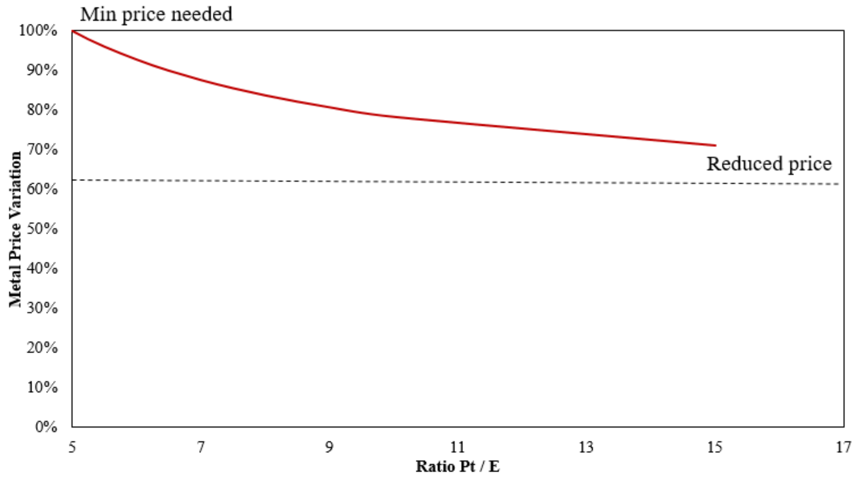



Fig.8 Platinum selling price variation when increasing the ratio Pt/E.

Even assuming an ideal case with an equipment ratio that has infinite productivity, the maximum price reduction that can be expected is less than 40%.

Combining transportation cost reduction and higher throughput rate, the selling price for asteroid platinum can be represented as follow:

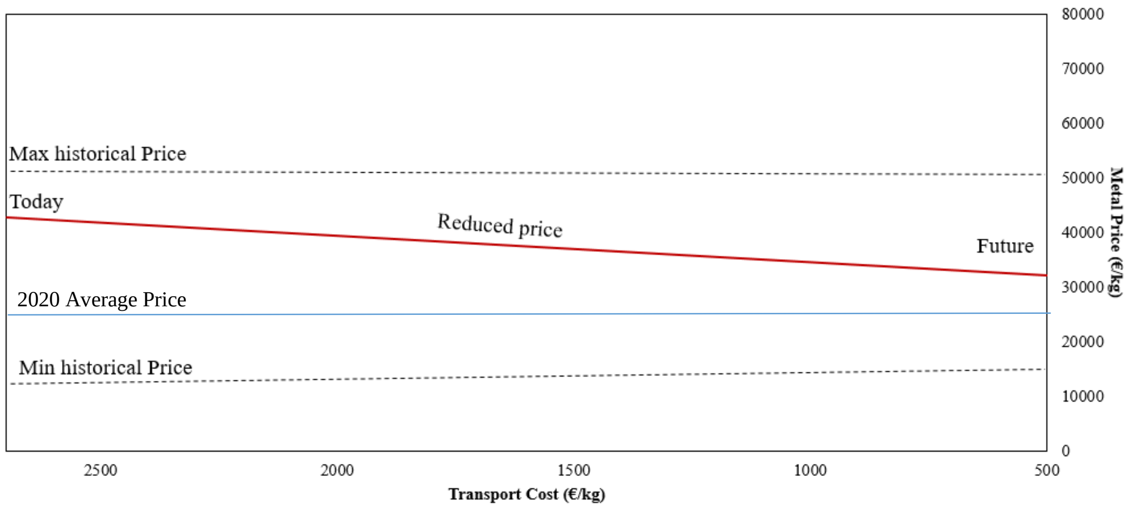



Fig.9 Reduced minimum platinum selling price, values range from 45 000 to 32 000 €/kg.

## 4. Discussion

Assuming the most favorable platinum to equipment ratio and a sharp decline in Earth-to-LEO transportation cost, results show that asteroid platinum selling price would be around 20% above the average historical market price. The difference does not look that big and maximum historical market prices for Platinum has been higher than this threshold.

Given the increasing ecological constraints and potential increased in Platinum demand from the car industry, it is a reasonable scenario to consider market price for Platinum to rise significantly in the coming decades (even if past forecasting studies of the last decades have almost all been predicting price rise of Platinum which did not materialized so far). In this scenario of price steady increase, asteroid mining might soon become a credible option.

However, this study uses the hypothesis that we will obtain pure platinum metal using only one perfect "processing equipment". In the model, one simple concentrator (flotation machine) was set as the "processing equipment". While it is not the objective of this study to get into deeper details for the mining or processing methods it is worth to discuss if that is somewhat realistic.

To clarify the above, we present one basic operational flow chart of a platinum mine in South Africa:

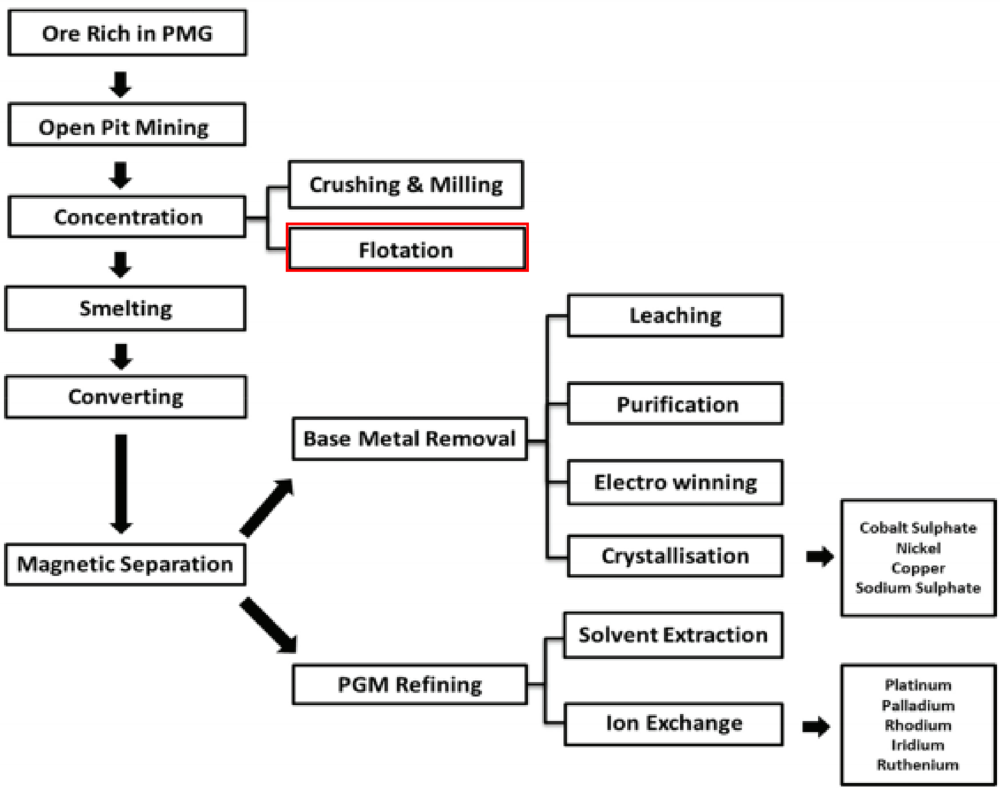
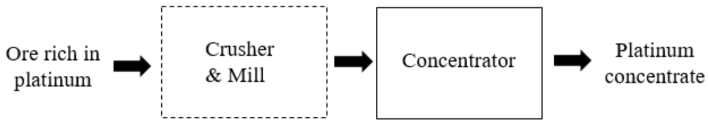
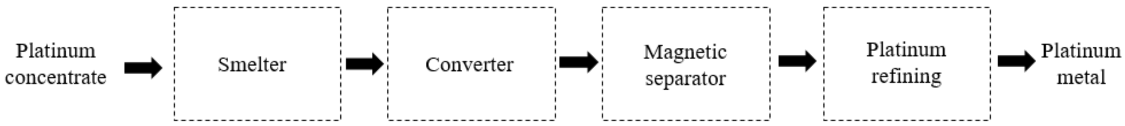



Fig.10 operational flow chart of a platinum mine in South Africa Source: Ranchod et al. (2015)

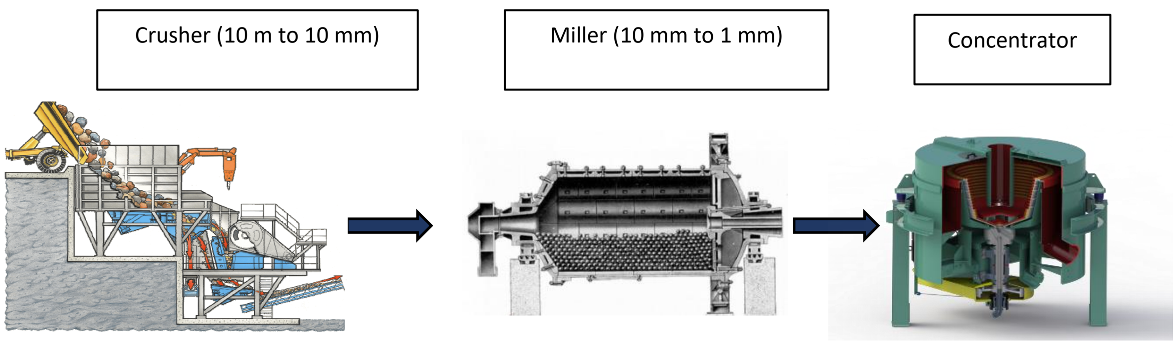
We see that a very complex process is needed in order to obtain pure platinum metal. But, for the sake of example, let's simplify the above schema to obtain just a platinum concentrate.




If we want to obtain platinum metal, further processing is needed:




As we are very far from all this processing, let's admit we reduce our project to platinum concentrate and not platinum metal (commodity). We will still need to add a crusher and a mill to our "processing equipment". These machines are not only big and heavy but also have low throughput rates. Ignoring size and weight, throughput rates for these machines are around f = 150 kg of Platinum per kg of Equipment per day (which is much lower than f = 400 kg/kg/day of our simple concentrator machine).



The end product of this process is not pure platinum but a "metal aggregate" with a higher concentration of platinum. We can estimate the platinum grade of this aggregate as 100 times the initial grade, this means a grade of 3500 ppm. For each kilo of this aggregate we can therefore obtain 3.5 grams of pure platinum. On top of that, additional processing losses must also be added and can be estimated at 20% of the final platinum metal quantity obtained. As a result, for each kilo of metal aggregate we can only get 2.8 grams of pure platinum.

Finally, this means that if we obtain a concentrate, selling prices should be 357 times higher than expected. The initial price of 71 372 € per kg rises to 25,490,000 € per kg. Such a price point makes obviously asteroid mining venture extremely unattractive for the foreseeable future.

To get to pure platinum in space, we would need to add a smelter. This is normally a huge facility and would have to be scaled down dramatically to fit into a rocket (see image below):

Unfortunately, adding a smelter would also reduce enormously the productivity of the processing chain, all the way down to f = 8 kg of Platinum per kg of Equipment per day, compromising also the attractivity of the project.

## 5. Conclusion

While it is true that the presence of high concentrations of PGM in asteroids can seem exciting and may offset the costs of going to space to retrieve them, a simplified model such as the one presented in this paper put in evidence the three main limitations:

-Grades in asteroids are higher than the richest mines in Earth. However, they are not rich enough to make them a very interesting target. To put it in context, there are some mines on Earth that exploit gold (which is trading at a similar price range), at higher concentrations (Fire Creek mine, United States)

-Rocket equation set strong limitations to the project, and at best, we can only diminish price to a 60% of the initial price.

-Last but not least, processing the raw material into pure platinum is extremely complex and, based on mining experience on Earth, they are very unlikely to fit into a one-ton equipment machine and even more problematic, provides sufficiently attractive throughput rates.

This brings up to the conclusion that despite potential higher-than-Earth concentrations of Platinum in some NEAs, these grades do not appear to be sufficient to make asteroid mining a viable option for the foreseeable future. Overall, those results suggest that asteroid mining will remain extremely speculative, even if we consider a time horizon of a 100 years from now and include in the model a drastic reduction in Earth-to-LEO transportation costs.

For further studies, it would be important to evaluate the potential of asteroid mining in three aspects:

a) Accessibility to NEA and ore
b) Degree of geology certitude of NEA grades
c) Feasibility of in-situ processing

Those three aspects can give us three basic indicators to estimate the risk and global feasibility for an asteroid mining project. Accessibility seems to be relatively well understood, but the last two remain highly speculative. New techno-economic analysis should fine-tune these keys elements to make asteroid mining analysis more robust.

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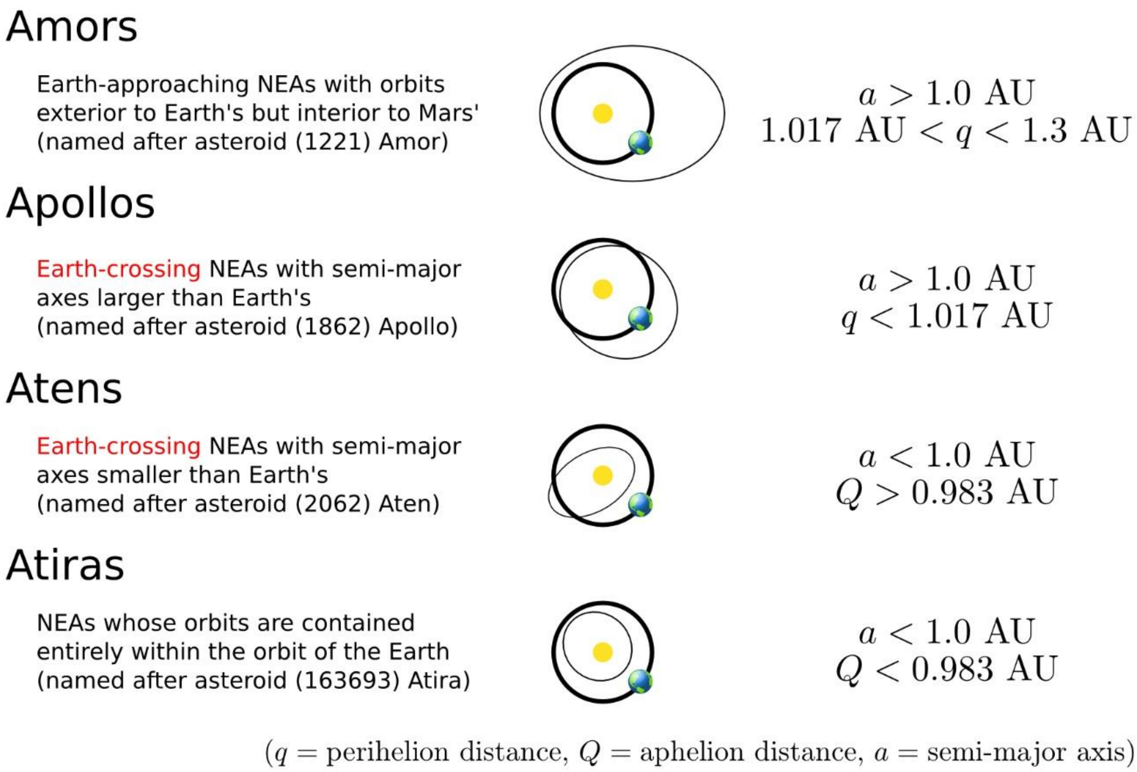
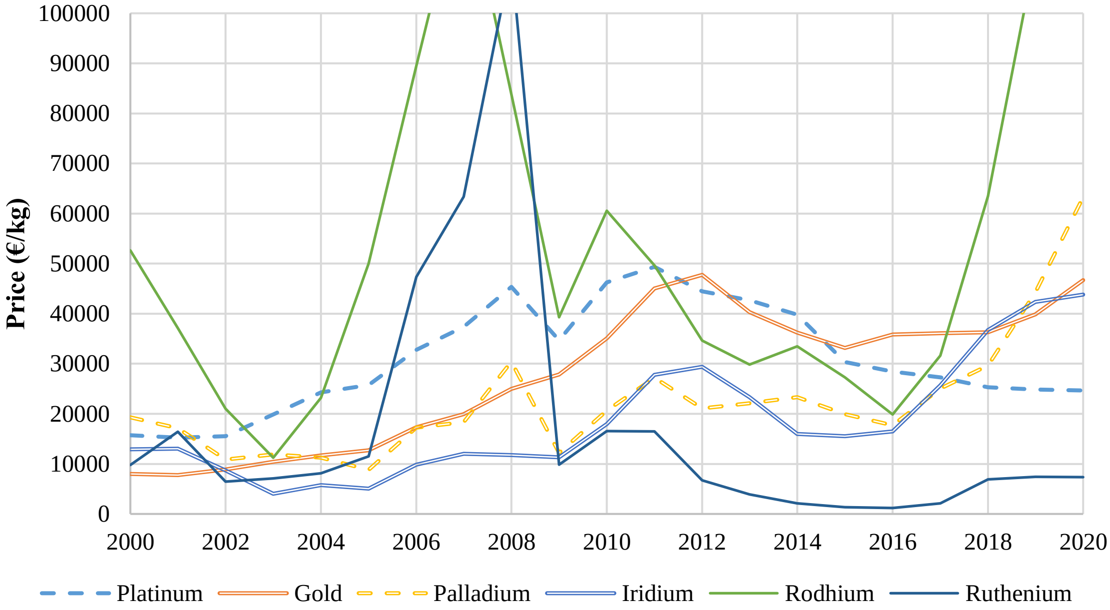
**Appendix A.**




Source : https://cneos.jpl.nasa.gov/about/neo_groups.html

**Appendix B.**




Source: Matthey.com