Essay 2

A research project report

Topic: **Can we make asteroid mining an investable project for institutions?**

Candidate number: 15064716

Abstract

Assessing investability of asteroid mining requires a model for price-quantity dynamics for the mined commodity. I do this by estimating a simple SEM. The first question I answer is whether it'd be profitable to mine platinum with a technology described in a Caltech paper. Then I move on to analyze the estimates, along with using the model to construct a family of functions describing combinations of mining capacity requirements and riskiness of the project which are investable. I conclude the work by analyzing the methodology I used and offering possible improvements and extensions that would lead to a fuller set of insights.

1. Introduction

Since the first essay, I began the work on the second one by looking into ways of modelling the effect of a supply change. Then before anything else, I implemented the model I chose (python code and .csv files with data are linked at the end of the paper in section 4), which led me to refocus the project slightly. I still explore the investability of an asteroid mining project that would bring a near-earth satellite into orbit (Ross, 2001). It would then be mined for platinum (and I assume throughout the paper for simplicity it will only be used to mine platinum). After the estimation, it became clear that the model of my choice isn't usable for the situation I wanted to analyze, and the entire project would end up in a loss. Rather than then analyzing investability of a clearly loss-making project; I took a different approach and looked at asteroid mining startups like Planetary Resources, aiming to develop mining technology at fraction of the cost and already identifying commercially attractive asteroids (Lewicky, 2013). This is clearly not without risk, so I pick a few combinations of default rates and platinum volumes mined. I then calculate how much funding a startup can plausibly ask for at these combinations, making the final output a kind of guideline for the mix of technology development riskiness and mining capabilities that would be investable.

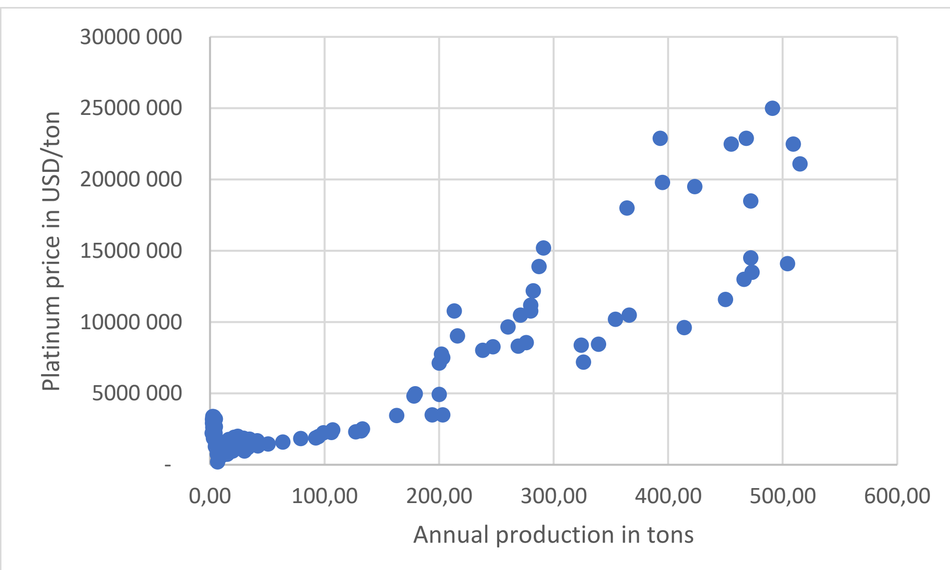
In part 2.1, I explain how I structure and estimate the model, along with answering the first (formerly set) question about whether the 2.6 bln. mission would be profitable for mining platinum. I take the slightly refocused path in part 2.2 and look at the combinations of mining capabilities and the amount of funding a startup could receive, for different default risks.

I end the essay with discussing where I see possible improvements in modelling and the analysis as such (section 3).

2.1 Project execution and raw results

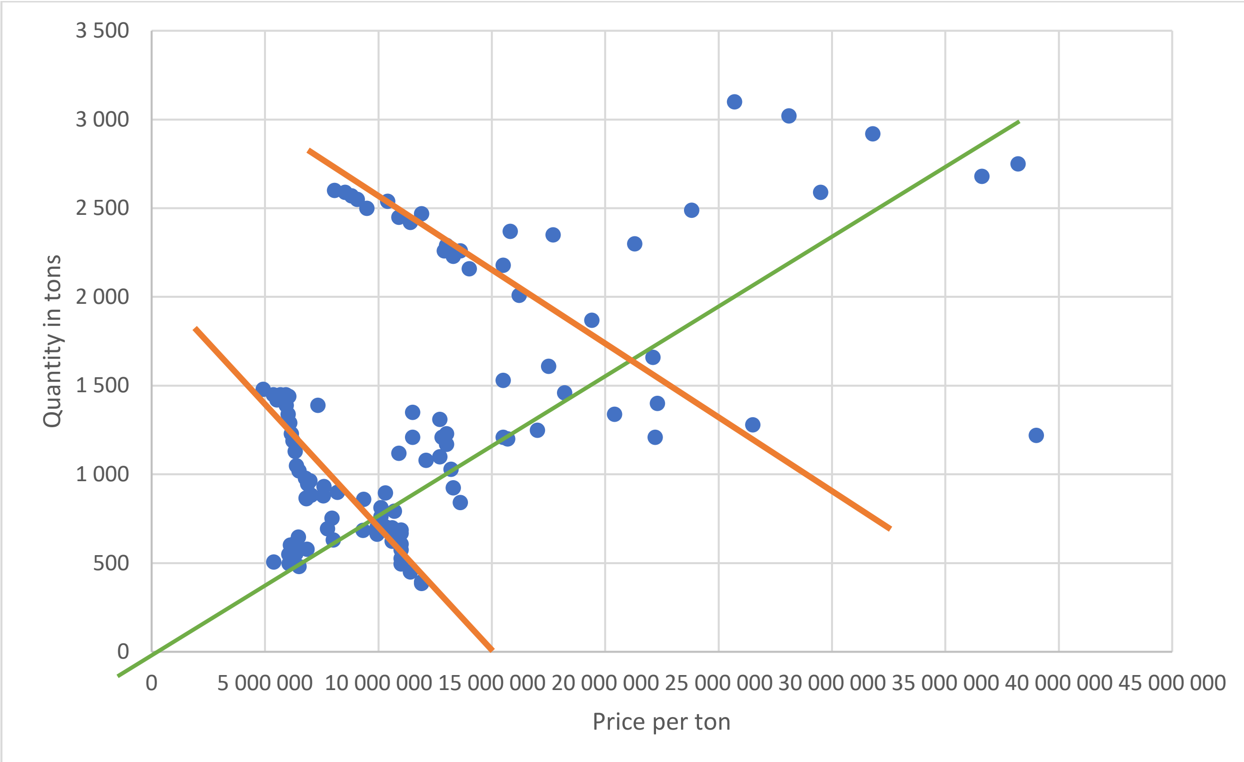
In order to find out how much profit can be made from the above mentioned asteroid mining mission, I started to explore the methods available already for demand (and supply) curve estimation. The problem with simply using a regression model on our dataset becomes obvious right when we look at the data, OLS will estimate something that looks like a supply curve:

Figure 1.1 : Platinum quantity vs price



In fact, the estimate we can imagine OLS will provide here is something between supply and demand curves. In principle, it may be possible to try 'untangle' the two curves manually, if the dataset allows. Such a solution may be possible for, say gold:

Figure 1.2 Supply and demand curve 'guesses' for gold



There, we can guess pretty easily what appears to be a single supply curve and multiple demand curves, caused by some shift in demand. So if we believe our ability to recognize them, we can simply run OLS on the relevant parts of the dataset and obtain supply and demand curves that way. In addition to this being unsystematic; it can't be used in every case. An example of that is our platinum price dataset – for reasons I'll explain later; it very much looks like only the supply curve can be obtained. That wouldn't be very helpful – having it as an only indication of the Pt price and quantity would not tell us anything. This is because quantity supplied and quantity demanded are equal at equilibrium, so (if we want to assume we're roughly at an equilibrium) the dataset shows us 'paths' traced out by equilibria rather than individual supply or demand curves.

I haven't been able to find a large number of resources covering the problem, every paper I've read seems to treat this problem a bit differently. The one by Baker (Baker, 1998) sets out the problem in an environment with differentiated products and estimates a firm-specific demand curve. Rasmunsen (Rasmunsen, 2007) used a slightly modified softmax (multinomial logit) to take care of interaction between demands for individual products, along with different product and customer characteristics. This also allowed for capturing the 'shifts' in demand curves. Other reading I've done seems to have been inspired by Rasmunsen, in that it follows the layout of the problem there by taking individual product and consumer characteristics to generate the 'shifts'. One example would be a relatively recent one by Bajari (Bajari, 2005).

The dataset I found unfortunately wasn't rich (large enough, in number of dimensions) enough to use any of these techniques. Therefore, being aware of the simultaneity problem, I decided to use a simple simultaneous equation model (Hausman, 1983) to obtain supply and demand curves. We can then simulate a series of supply curve shifts to see how the market would react (hopefully with a lower price) to a large amount of platinum mined from an asteroid.

First, let's look at the supply and demand curves for platinum I'll be estimating:

$$Qs = B_0 + B_1 plat\_price + e_s$$

$$Qd = A_0 + A_1 plat\_price + A_2 gold\_price + e_d$$

So the Quantity demanded Qd is a function of platinum price **plat_price** and the price of gold **gold_price**, with **intercept** A_0. The supply curve is simply a fuction of **plat_price** and the **intercept** A_0.

Since Qs and Qd are determined together, I start with the equilibrium condition Qs = Qd, hence:

$$B_0 + B_1 plat\_price + e_s = A_0 + A_1 plat\_price + A_2 gold\_price + e_d$$

$$B_1 plat\_price - A_1 plat\_price = A_2 gold\_price + e_d - e_s$$

$$\mathbf{plat\_price = A_2/(B_1 - A_1)\, gold\_price + (e_d - e_s)/(B_1 - A_1)}$$

$$= c gold\_price + const$$

So I first estimate the **reduced form equation** by OLS (the numbers below are the corresponding p-values):

$$plat\_price_{est} = \underset{0.01}{0.3625} gold\_price + \underset{0.000}{7.919e06}$$

Then I run OLS again to estimate Qs and Qd, replacing plat_price with $plat\_price_{est}$:

$$Qd_{est} = \underset{0.185}{1.853911e\text{-}05} * plat\_price + \underset{0.659}{3.044595e\text{-}06} * gold\_price \underset{0.355}{-9.668241e\text{-}12}$$

$$Qs_{est} = 0.000024 * \underset{0.0}{plat\_price} + \underset{0.65}{8.792}$$

What can be noticed immediately is the coefficient on platinum price in the supply curve – it's positive. This may be surprising but still plausible, mainly due to the fact that most of the demand comes from autocatalysts and jewellery (PGM Market Report, 2018)

Figure 1.3: Platinum Supply and Demand breakdown

Platinum Supply and Demand '000 oz			
Supply	**2015**	**2016**	**2017**[9]
South Africa	4,572	4,392	4,364
Russia	670	703	650
Others	865	988	962
Total Supply	**6,107**	**6,083**	**5,976**
Gross Demand			
Autocatalyst	3,228	3,327	3,285
Jewellery	2,746	2,412	2,227
Industrial	1,753	1,855	1,978
Investment	451	620	356
Total Gross Demand	**8,178**	**8,214**	**7,846**
Recycling	-1,715	-1,929	-1,980

It's used in autocatalysts which serve to eliminate a large share of the environmentally harmful pollution an automobile generates. This component is critical and isn't easy to substitute away from. In case a manufacturer does substitutes away from it, it usually is to other Platinum-group metals, all of which are included in the dataset. With this being said, along with regulations in place that require autocatalysts, it's easy to intuitively see why demand curve for the Autocatalyst market is horizontal. The second largest demand component, jewelery, is easy to intuitively see as a giffen good; hence an upward sloping demand curve. From all this, I fundamentally don't see a reason why the overall demand curve can't be upward sloping.

Check : the equilibrium

At this intermediate stage of the analysis, we might want to stop and try see what equilibrium price would we obtain now, in order to see the extent to which these curves are realistic. Simply evaluating $Qs_{est} = Ed_{est}$ at the current price of gold and solving for platinum price yields 12.71 mil. USD per ton, while the last point in our dataset has the price at 13.5 mil. USD. Though not entirely precise, we seem to have obtained a reasonable estimate for the (2015) equilibrium.

Now we can use a series of supply curve shifts to see how the price would behave after we've transported a large amount of platinum back to earth and tried to sell it. Here, I just assume the market doesn't react to small changes in supply, so I calculate the overall effect by simulating a series of supply curve shifts, each happening due to an extra 1 ton of platinum obtained from an asteroid. The equation for price obtained from the equilibrium condition is the **reduced form** equation we've seen before:

$$\textbf{plat\_price} = A_2/(B_1 - A_1)\ \textbf{gold\_price} + (e_d - e_s)/(B_1 - A_1)$$

Thanks to running the 2SLS, we now have estimates for all the coefficient from structural equations (Qs_{est} and Qd_{est}). It's clear from this that an increase in supply decreases the price. Doing the above mentioned series of supply curve shifts shows us how exactly we'd decrease the Pt price by each mined ton:

Figure 2

Here we see the first flaw of the model – our project would lower the prices to zero at around 70 tons of platinum mined. I discuss this further in section 2.2. Though the results here are hopefully more precise than what many resources provide when simply not taking the effect of increased quantity on price. That would just multiply these 70 t with the latest (2015 in the dataset) price, which gives roughly 890 mil. USD. Integrating the above equation gives 448.05 mil. USD, which is dramatically lower.

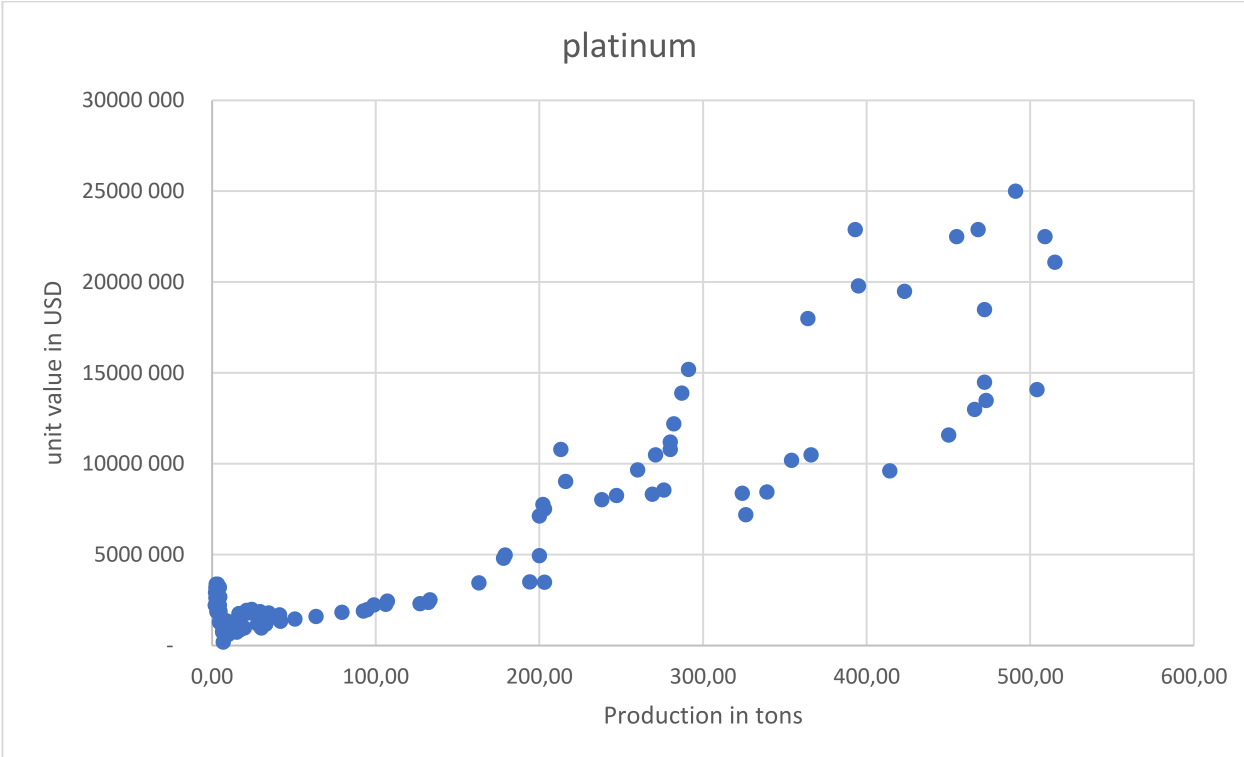
2.2 Analysis

As for limitations of the model, there's a number of ways to explain why the estimated price hits zero at 70 t mined.

Firstly, this represents a very large change in supply. The average annual growth of platinum supply for the last 20 years of the dataset was around 3%, so this big a shock is hard to model with this dataset.

Secondly, we could achieve a more theoretically correct model with platinum price being a nonlinear function of the quantity, one where we can make sure price is always nonnegative. This, however, seemed to me to be at the expense of the fit, which seems to be linear from data:

Figure 3, platinum production vs price per ton



Choosing the linear function provides a better approximation for effects of relatively small volumes of platinum imported.

Thirdly, as mentioned before already; the dataset aggregates all platinum-group metals, most importantly palladium and rhodium. Combining these is the most common way of substituting away from autocatalysts and having the data disaggregated would allow us to model this effect. There, the estimate for the demand equation has the potential to be much more precise, which the current p-value of 0.185 reflects

With the above in mind, it becomes clear that the maximum estimated mining gain from this single project of 448 mln. USD is far less than it's estimated 2.6 bln cost. Rather than taking the uninteresting path of calling this particular project infeasible, let's take another angle. Companies like Planetary Resources aim to develop mining technology for fraction of the cost of government institutions. Since their expected expenses can't be found anywhere (are probably kept secret), I thought it would be interesting to use the model we already have to look at some combinations of risk (default rate) and the mined amount to find out how large the project could be. That is, let's put ourselves in the position of a small asteroid mining startup such as Planetary resources and find out how much funding we'd get to develop our technology for a given default risk and the amount we'd target to mine.

This only extends the work done in section 2.1 for a given mined amount m, I'd just integrate the function in figure 2 from 0 to m. Now all that's left to do is describe how we're going to compensate our investor. We can use the example of a bond here, where the bond holder either pays the interest in full or defaults, a payout structure similar to the one for this project. Return on a bond can be written as:

Return = rf+ inf + dr

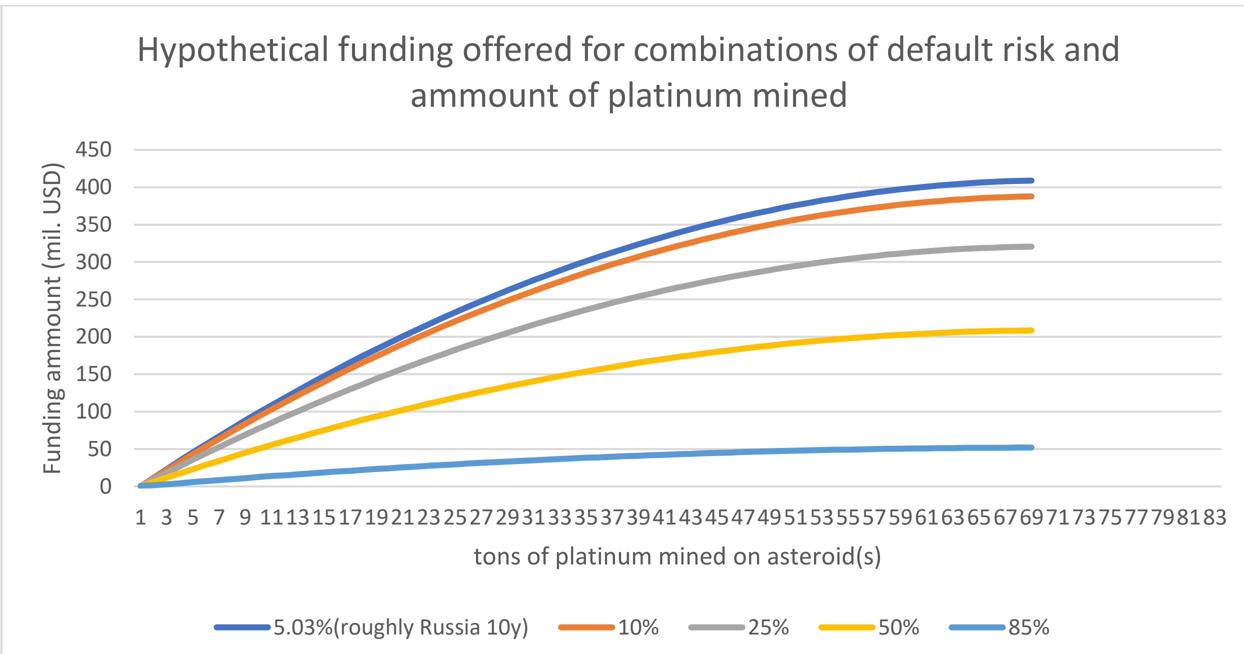
Where **rf** is the risk-free rate of return and **inf** is the annual rate of inflation, and **dr** is the default risk

Then for every value of platinum mined m and dr :

$$\textbf{Funding}_{\mathbf{m,dr}} = \int_0^m plat\_price(m) * (\mathbf{1\text{-}rf\text{-}inf\text{-}dr})$$

I.e. we have to compensate the investor by offering a return slightly in excess of rf+inf+dr. I assume the inflation to be 2% which most of the central banks target, and approximate the fisk-free rate rf by the 5-year average annual return on US treasury TIPS notes – this works out to roughly 1.4%. The calculation is iterative but easy to do in an environment like python. The visualization can be seen below:

Figure 4: funding offered for combinations of default risk and ammount of platinum mined

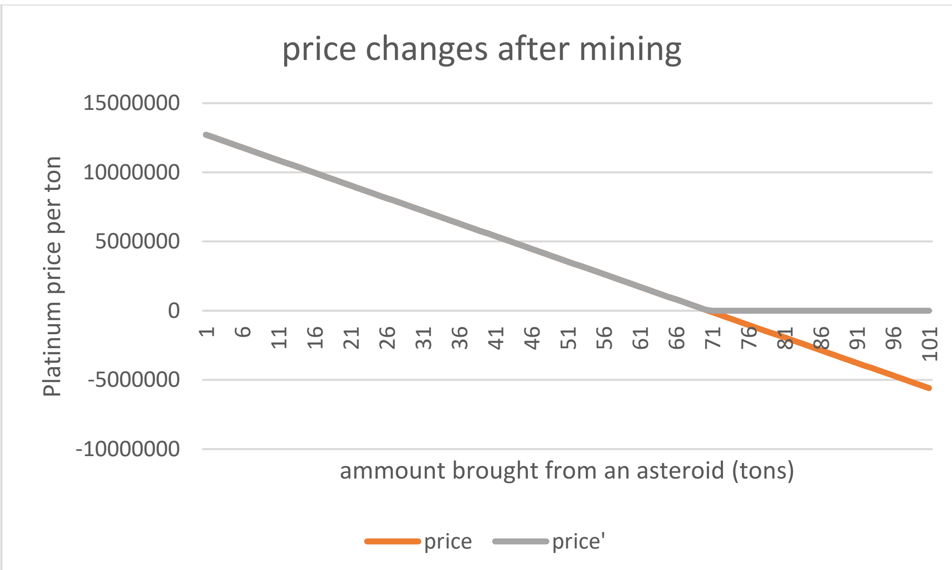


Note the concavity of the funding for every default rate caused by the diminishing marginal return to additional unit mined, consistent with the results of the model in section2.1. One interesting thing would be to note the fact that Planetary Resources received 50.3 mil. USD in funding already (Crunchbase). Given our many assumptions hold, we'd get the hint that the development of their asteroid mining technology isn't extraordinarily risky; at least from the graph above, where for the 85% default rate, we'd have to mine around 70 t of platinum.

2.3 Discussion

The demand and supply curves I made using a simultaneous equation model and estimated by a two-stage least-squares regression offers some insight into price-quantity dynamics. I consider a success that I've been able to do this with relatively plausible results; i.e. when estimating the current equilibrium; we obtain price platinum price close to the current one. This indicates that the model works relatively well for small price/quantity changes. What we've seen then is its inability to plausibly predict what happens after a very large supply shock, as the predicted price drops to zero at 70 tons of platinum mined from asteroid(s). Just to get rid of nonsensical predictions, we can in principle use a simple nonlinear transformation such as:

$$price' = \max(plat\_price_{est}; 0)$$



But that's about all it does - eliminates nonsensical output. The analysis was done in this spirit and due to lack of supply 'shocks' in the data, I imagine it very hard to model these large (>70 tons) changes in supply. What I can imagine doing if the scope of this project was larger is to obtain a richer dataset with larger dimensionality and try using some clustering algorithms to isolate palladium and rhodium; where we could then observe the likely substitution effects.

3 Discussion and Conclusions

What I don't do in section 2.2 is try to find preferences for risk-averse agents. I figured the visualization would be very confusing if I tried functions with different degrees of convexity (we already have different default rates); adding another dimension with multiple 'made up' preferrences. So about the only way to neatly extend this would be to do a research into risk preferrences of retail investors and try find (or estimate) some realistic function that would reflect them. Though this is nice to have, it's not really necessary, as it's not hard for me to imagine institutions investing in this being risk-neutral. Moreover, it's fitting that, as explained in the first essay, returns on this can be assumed to be uncorrelated with some market portfolio. This makes the kind of marketing for this investment opportunity easier – with every hedge fund manager looking for 'crisis-proof' investments, this may very well be one of them. Also mechanically; this would be reflected in steeper slopes of the curves in Figure 4; which happens because of a relatively lower risk premium thanks to returns being uncorrelated to the market portfolio.

Finally, with more time I'd probably repeat the analysis with mining for multiple resources. Platinum was chosen because of its high price, but other precious metals and gasses can be mined too. Mining multiple resources then makes for less of a supply shock and subsequent commodity price drops

I've only been able to answer my original question: **Can we make asteroid mining an investable project for institutions?** to an extent, the way I modeled the problem; along with concentrating on exclusively platinum mining led me to conclude the original mining expedition costing 2.6 bln. USD wouldn't be profitable, at least not initially. And the loss in excess of 2 bln. From the platinum mining project means it's necessary to reuse the technology greatly. Having to then move to smaller-scale projects that my model would let me to analyze, I found no example of a cost estimate for an expedition. This led me to refocus my work a bit, and concentrate on the price adjustment more that analyzing the project from the standpoint of an institutional investor as inspired by the Fangan paper in my first essay (Fangan, 2013). Rather than that, I put myself in the position where I raise money for a small space exploration startup, and use the model to see what funding I can get for various default rates and amounts of Platinum to mine. This can be used as a planner for the entire effort, not just the first expedition – if we're going to make multiple trips and reuse the technology, this can be taken into account relatively easily. If this, however, means the project will take many years to complete; it's relevant to discount for the time value of money as well, which I didn't include in my calculations. I'd expect taking some ideas from the Rasmunsen paper to improve the model also, mainly trying to model interaction between various precious metals through cross-price elasticities. Lastly, looking at spillover effects of asteroid mining, such as environmental benefits (Celik, 2016) can extend the economic analysis to the point where we can talk about increasing general welfare also.

Overall, I'm relatively happy with the project; though there's much to improve on the modelling side. I haven't been able to find any structured way for estimating the amount of funding for such projects for investors online, so there's hope that with some additional improvements outlined here and throughout this paper, this could serve as both a tool for startup founders in this space which hints how much funding they can ask for to finance their technology; as well as a rough check for venture capitalists about plausibility of claims about profitability of asteroid mining

4 References

[1] Baker, 1998: Estimating the residual demand curve facing a single firm

[2] Rasmunsen, 2007: The BLP Method of Demand Curve Estimation in Industrial Organization

[3] PGM Market Report, 2018, available at : http://www.platinum.matthey.com/documents/new-item/pgm%20market%20reports/pgm_market_report_february_2018.pdf

[4] Crunchbase: Planetary Resources overview, available at: https://www.crunchbase.com/organization/planetary-resources

[5] Essay 1: Accelerating progress in space travel: Can we make asteroid mining an investable project for institutions?

[6] Celik, 2016: ORBITAL ENVIRONMENT CONSIDERATIONS DURING THE CLOSE APPROACH PHASE OF MISSIONS TO SMALL BODIES

[7] Bajari, 2005: Demand Estimation with Heterogeneous Consumers and Unobserved Product Characteristics: A Hedonic Approach

[8] Ross, 2001: Near-Earth Asteroid Mining

[9] Lewicky, 2011: Planetary Resources—The Asteroid Mining Company

[10] Hausman, 1983: Chapter 7 Specification and estimation of simultaneous equation models

[11] Fangan, 2013: Can Financial Engineering Cure Cancer?

5 Data sources and model implementation/calculations

The dataset is obtained by combining gold and platinum data from US Geological Survey: https://minerals.usgs.gov/minerals/pubs/commodity/platinum/

Quantities are in gold and prices in USD per metric ton, unless otherwise stated. This is the reason for coefficients in the regressions being very small. Note I refer throughout the essay to Platinum for simplicity, but this includes all Platinum-Group metals.

My iPython notebook can be found at: https://github.com/mrminister/escosci

(this contains some spreadsheet calculations+ data vizualizations also)