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Risk Assessment Of Space Mining Ventures Using Decision Modeling And Monte Carlo Simulation

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RISK ASSESSMENT OF SPACE MINING VENTURES USING DECISION MODELING AND MONTE CARLO SIMULATION

by

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Michael R. Jude
April 20, 2018

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I wish to express my sincere appreciation to the members of my advisory Committee for their guidance and support during my time in the master's program at the University of North Dakota.

To my wife, Barbara

Whose unfailing support gets me through all these crazy projects.

ABSTRACT

Private space exploration is beginning to receive a lot of attention, primarily driven by commercial efforts to mine asteroids. Such endeavors ultimately will require substantial amounts of investment. Yet, potential investors have no way of gauging the risk associated with space mining. The problem statement that drives this study is relatively simple: current estimates of space mining viability do not adequately factor risk into their analysis. Rather than attempting to build a business case for space mining, this research adopts a well-documented business plan and then attempts to assess the risk implicit in that plan. This research is not concerned so much with the rigor of the business case, though, as it is with proposing a way to assess risk within such a plan. Consequently, a space mining business case, developed at the University of Washington, is utilized to construct a Delphi survey of subject matter experts to gauge the reasonableness of the estimates used in the plan. Once ranges for the important variables are ascertained, a decision model is constructed and a Monte Carlo simulation is run to predict a range of reasonable outcomes. This approach, combining decision modeling with Monte Carlo simulation, indicates that the business case is very risky and depends on the cost to deliver various spacecraft technology, the volume of platinum group metals returned to Earth, and price of those platinum group metals. Rather than a net present value of more than $14 billion over

twenty years, as estimated by the University of Washington study, this analysis indicates a loss of nearly $2 billion over the same period.

CHAPTER 1: INTRODUCTION TO THE STUDY

Introduction

In November, 2010, Planetary Resources was formally organized as a space mining venture. Founded by Peter Diamondis, with such notable personalities on its board as James Cameron, David Vaskevitch and David Hill, its stated purpose is to mine asteroids. In 2013, Deep Space Industries was also incorporated to pursue asteroid mining. Additionally, other companies have at least indicated an interest in space mining: the UK's Asteroid Mining Corporation claims to be developing enabling technology to facilitate such mining activities. These companies assert that they will ultimately make significant amounts of money through space mining, but none, so far, have even been able to send spacecraft to an asteroid, let alone mine one. Yet, these company's public statements have been positive, and while each is a private company, depending on venture and crowd sourced funding, each asserts that it will ultimately be very profitable. The question is how reliable are their business plans? How can an investor ultimately assess whether their pronouncements are reasonable?

Assurances of space mining profitability are not new. In 1996, John S. Lewis, at the time a Professor of Planetary Sciences at the University of Arizona-Tucson, wrote a book on the exploitation of space resources (*Mining the Sky*, 1996). In it, he pointed out that, while natural resources were limited on Earth, they were virtually unlimited in space.

His book achieved a fair amount of popular acclaim, yet his work was not the first to point out the virtues of space resources. In fact, as early as 1977, Gaffey and McCord had published a paper about space mining.

Both the Lewis and Gaffey and McCord works justified space mining ventures as much on the economics of doing so as on the assumption that Earth resources would become increasingly difficult and ecologically destructive to obtain. Although economics was an important consideration, they all agreed, the need to save Earth from the predations of resource extraction and the resulting pollution loomed large for them as well. In fact, they all led with the assertion that Earth-based resource extraction could not continue to be viable in the long term.

Since these earlier works, the idea of space mining has gone through many iterations, with more recent works by Elvis (2012), Feinman (2014) and Andrews, et al. (2015) Each of these papers emphasize the riches to be had from space mining and each make some attempt to quantify the financials that might govern such undertakings. Yet, in most cases, the financial analysis is somewhat superficial. Gaffey and McCord (1977) as well as Andrews, et al. (2015) do go into some depth of analysis and even note the uncertainty associated with their figures, but the sort of financial analysis that is required needs to explicitly focus on the uncertainties associated with space mining. Such uncertainties can mean the difference between profitability and failure when marginal business undertakings are assessed.

It is precisely the notion of uncertainty in space mining that this study is intended to address. While earlier analysis was willing to err on the side of optimism, based on the need to save the planet, business ventures are not able to do so. Businesses must satisfy several constituents; not the least of which are investors and shareholders. These individuals expect a fair return on their investment, in a reasonable amount of time.

Defining risk is especially important now that several major business undertakings have been launched to exploit asteroid resources. In particular, Deep Space Industries (Deep Space Industries, 2013) and Planetary Resources (Morgan, 2012) are committed to mining asteroids to extract minerals that are in short supply on Earth, as well as delivering reaction mass to deep space probes and future human space settlements. (Morgan, 2012)

Yet, assessing risk is problematic when the nature of the business is speculative. Space mining has never been done and so depends on development of new technologies and new business processes. It is highly dependent on variables such as market valuations of mined resources, availability of investment capital and regulatory decisions. (Johannsen et al., 2015). Where financial analysis is done, it is often just in terms of direct costs and potential revenues. Obviously being conservative on the former and optimistic on the latter can lead to wildly optimistic assessments of success.

This study, then, seeks to determine the real risk associated with space mining. It does so by examining the various mission profiles associated with such ventures, examines the potential markets for space resources, examines the economics of space mining ventures, looks at the potential for investments in such undertakings, and factors in such considerations as regulatory and public policy impacts on space-oriented businesses. In each case, rather than try to pin down exact values, this study undertakes to define a range of probable values; ranging from highly pessimistic to highly optimistic. Once complete, a numerical analysis using Monte Carlo analysis is run to assess the likely outcomes and to define the variables that have the most impact on such outcomes. In this way, real risk can be determined.

Problem Statement

One of the more comprehensive analyses of a space mining venture has been done by Andrews, et al. (2015). In this study, the authors utilize a very structured approach to defining the costs and potential revenues associated with space mining. They depend on commercialization cost estimation when assessing the development and implementation costs of the necessary technology, which the authors note is usually only 30% to 40% of NASA guidelines. Additionally, the authors use basic market projections for demand of platinum group metals when estimating potential revenues arising from space mining efforts.

An issue with Andrews, et al. (2015) is that their cost estimation is optimistic, and their revenue projection is simplistic. While their conclusions may be completely reasonable, i.e., that space mining can be a profitable venture with an acceptable rate of return, the variability that exists in their assumptions could easily produce a significantly different outcome; one which yields a marginal business at best.

In addition to the authors noted above, writers such as Lewis (1996), Durda (2015), and Salter (2014) have chosen to focus on the revenue side of the financial equation. Even here, though, such exposition tends to focus on the potential revenues associated with such ventures rather than the difficulties or expense of generating them. As an analogy: small gold mining ventures rarely turn a profit after the costs of production are considered.

The problem statement that drives this study is relatively simple: current estimates of space mining viability do not adequately factor risk into their analysis. By doing an assessment of the variables that impact the financial analysis of space mining ventures, this study seeks to determine the impact of risk to arrive at a more realistic assessment of space mining viability.

Background

Space mining has received much attention in the popular press, for example, Young (2013), Earth Island Journal (2011), and Harris (2013). These articles are optimistic and generally give the impression that not only is space mining probable, but also substantial benefits will accrue to society once it happens. Possibly the most thorough analysis of such efforts, once again aimed at the popular press, is the work of Lewis in his 1996 book, *Mining the Sky*. Yet, even Lewis is superficial when it comes to quantifying the difficulties that would arise conducting space mining. Although acknowledging the need for new technology and space mining processes, his assumption is that these difficulties will be overcome because they must be.

However, as noted above, there is a significant amount of peer-reviewed work that also addresses the feasibility of space mining. The work by Gaffey and McCord (1977) seeks to lay out a plausible mission that would return the asteroid resources known at the time (primarily iron and nickel). Interestingly, their work also explores in some depth, the market dynamics of such mining and points out the chilling effect that dumping large amounts of asteroid-derived metals would have on terrestrial markets.

As noted above, one of the more comprehensive analyses of space mining was that done by Senior Space Design Class at the University of Washington in 2013. This work, outlined by Andrew, et al. (2015) is notable because it attempts to frame space mining ventures in terms of the infrastructure that would be required to conduct them. Consequently, the paper not only outlines the direct costs of such an undertaking, but also devotes a considerable amount of effort to the actual designs of the various spacecraft, space tugs, processing facilities and so forth. Unfortunately, while this paper is very comprehensive on the cost side of space mining, it is very light on the revenue side of the analysis. It appears to accept current metal demand processes as its baseline and assumes that by using loans from a hypothetical World Development Council, it would not be necessary to show an actual return on investment for nearly 20 years.

Additional work, examined in later chapters, by Elvis (2012), Gertsch (1992) and Duarte, et al. (1991) also examine space mining to varying degrees of comprehensiveness. However, each focuses on specific aspects of such ventures without bringing such analysis together into a cohesive financial analysis. This lack of financial rigor places such ventures, still, in the realm of speculation. Nevertheless, several companies have recently been formed to conduct asteroid mining operations. As noted previously, three of the more widely known companies are: Deep Space Industries, Planetary Resources and Asteroid Mining Corporation.

None of these companies have been forthcoming with their financial analysis, being private enterprises, but each has been assertive in its contention that space mining will be profitable. Planetary Resources has based its assertions on mining and returning to Earth, platinum group metals (Morgan, 2012). These metals, generally more valuable than gold, have wide applications in industry as well as being valuable intrinsically. If the value of the metals is high enough and the volume returned to Earth large enough, these companies feel it will be economic to mine them in space. Nevertheless, without a detailed financial analysis, these companies present great uncertainties to prospective investors.

Significance

As discussed above, much of the analysis of space mining has depended to some extent on the argument that it is increasingly difficult to obtain raw materials on Earth; and to the degree that new sources of minerals are found, they require increasingly ecologically destructive forms of extraction. As Macwhorter (2016) notes, Earth is increasingly subject to constraints on its ability to supply various elements necessary for continued global economic growth. At the very least, extracting the amount of materials needed from terrestrial sources will do irreparable harm to the ecosphere. As he observes, the obvious solution is to obtain such resources from space.

Gaffey and McCord (1977) preface their paper with largely the same argument as does Lewis (1996). In each case, the importance of space mining activities is first and foremost an environmental one. Ultimately, each tends to treat the financial dynamics of space mining as a secondary consideration. Yet, for political as well as fiscal reasons, private enterprise has been more willing than government to marshal the necessary capital to effectively mine asteroids or the other planetary objects. Thus, making an effective financial case for space mining and understanding the contributing variables is essential to attracting private capital to space mining ventures.

However, financial analysis, especially that which depends on predicting the cost to develop new, untried technology, is not an exercise in certainty. Many variables are necessarily uncertain or only certain within a given range of values. Consequently, financial projections for space mining ventures that assert a given outcome are untrustworthy to those who would invest the necessary billions of dollars to enable space mining.

What is required is a financial analysis for space mining which does two things. First, it must show potential returns for such a venture in terms of the significant variables involved; and second, it must provide a means for assessing the risk associated with achieving those returns. Doing so will provide an objective basis for investors to engage with space mining ventures.

Nature of Study

This study seeks to not only determine the viability of space mining in financial terms, but also set out a process for assessing future approaches as well. To that end, primary and secondary data sources are utilized to determine the controlling variables that might influence the financial outcome of a space mining venture. These variables are then utilized to build a numerical model of the space mining venture.

Since the exact approach to mining asteroids cannot be known with certainty making the value of each model variable equally uncertain, each is defined within a range of reasonable values, along some rational probability curve. That is, the curve of potential values will be weighted in favor of the most likely values.

Once the decision model is completed, a Monte Carlo analysis is performed that allows the variables to vary between their minimum and maximum limits along their probability curve. The output of the model is a curve of potential values and the probability of each. Additionally, by performing a sensitivity analysis, where each variable can vary while all other variables are held fixed, the most important variables are identified. This provides guidance to investors on how to assess the assertions of any space venture. If the success of the space venture is too heavily dependent on optimistic values for the controlling variables, then the venture can be said to be optimistic and high risk.

Finally, the resulting model is offered as a template for future analysis. As technology changes and as the assumptions that are utilized to build the model are either supported or disproved, the model can be refined to provide a tool for both space ventures as well as investors with which to assess the viability and risk of space mining ventures that have not yet been conceived.

It bears noting that this paper does not attempt to define the ideal business model for space mining operations. As the literature review makes clear, there are many mission profiles that could be used and it is not the intent or within the scope of this paper to determine which one will yield a positive business outcome. Instead, the approach here is to adopt a profile that is reasonably well documented in the literature and then apply a decision model analysis to that profile. The focus of this work is not the business approach, but the approach to business analysis.

Research Questions

The essential research question that this study seeks to answer is whether space mining ventures can be financially viable: that is, can they cover costs and return a profit substantial enough and quickly enough to satisfy potential investors? Subsidiary questions are:

1. What is a reasonable payback period and return in investment? While earlier work assumes that investors will be satisfied with long term returns—Andrews, et al. (2015) assumes that a hypothetical world bank would be satisfied with a 20 year pay back, as an example—privately funded business operations typically demand a more aggressive payback period.
2. Which variables are most important to financial viability? Certainly, costs and revenues are important, but typically costs are complex, involving many subsidiary costs or cost driving variables. For example, there are transportation costs, operational costs, taxes, labor-associated costs, etc. Likewise, revenue is not usually a simple variable. Potential revenues are influenced by what the market will yield for a given mineral resource, which in turn, is often driven by demand associated with the application of the resource.
3. How important are terrestrial production dynamics to the viability of a space mining enterprise? Hubbert cycles predict that any natural resource is going to follow a bell-shaped curve, where production increases, then peaks, before decreasing (Hubbert, 1962). How will Earth-based production influence the demand for space-derived minerals?

4. Can current technology support a business model that would deliver financial viability? As the US Apollo program proved, given enough resources and money, any space objective is possible. However, mining asteroids would be resource constrained. Is the technology necessary to mine an asteroid within the means of a private company?
5. What externalities are important to the financial model? Businesses do not operate in a vacuum. As noted above, taxation could be important, but also regulation and developments in parallel industries that might depress the demand for minerals that could be returned from an asteroid. For example, platinum is currently used in catalytic converters. Yet, if there is a shift in demand for gas powered vehicles to electric vehicles, catalytic converters would no longer be required to the extent they are now; thereby reducing demand for platinum.

These are important questions and are critical to space mining ventures seeking capital to begin operations. However, as important, if not more so, is whether the basic premise that space mining can be sufficiently lucrative that private enterprise will be incentivized to conduct it. Although several businesses, referenced previously, are currently engaged in space mining planning, none of them has currently done any mining. Before such firms trade publicly, it is essential to understand whether they have a chance at success.

Assumptions and Limitations

Although every effort is made to identify the various costs and benefits associated with space mining, the author is not prescient, nor are the individuals surveyed for this study. It is entirely possible that an important variable that might loom large in determining financial viability has been overlooked. As an extreme example, if a major war occurs during the time line of the space mining venture, it is highly probable that the finances would be directly impacted, possibly in a positive way. However, such an event cannot be included in this analysis, or if so, is simply assumed to be non-controlling. Likewise, there are undoubtedly variables that, at this point are unknown, but which may become known only as space mining is conducted. To the extent that the process for building this study's model is documented here, the researcher assumes that future work in this area will include the influence of additional important variables.

More important to this study, though is the basic assumption that a space venture can be numerically modeled with any certainty. Although not as complex as some modeling exercises, nevertheless, the number of variables and the range of values for each produces a significantly complex model; one which takes personal computer runs on the order of days to complete. The result is that, to obtain reasonably timely outputs, the resolution of the model is necessarily limited. The modeling software used can allow variables to vary in predefined increments: the finer the increment, the higher the resolution of the output.

In the case of this analysis, the increments are chosen with an eye toward maximizing resolution while minimizing the computer run time.

Finally, as will be seen in the literature review, there are many mission profiles that have been proposed to mine asteroids. In some cases, these mission profiles return very different cost structures. At this point, it is impossible to know which will be the one that ultimately proves most desirable and consequently a profile is chosen that is reasonably well documented. While this approach is not likely to provide absolute certainty on the financial viability of asteroid mining, it does illustrate an approach to analysis that can be applied to any reasonably well defined asteroid mining business case.

As noted in this chapter, the purpose of this study is to assess the viability of space mining ventures in such a way that risk can be identified and quantified utilizing numerical modeling. However, to build the model, it is first necessary to understand the primary variables likely to influence a financial outcome. This is accomplished through a review of the literature, to which this study now turns.

CHAPTER 2: LITERATURE REVIEW

Introduction

Space mining is currently a theoretical undertaking. Except for several grams of material returned by the Hyabusa mission, there has been no successful exploitation of asteroidal material mined on an asteroid (Elvis, 2012). Consequently, most controlling parameters associated with defining a successful space mining venture remain largely unknown or only loosely defined.

Business planning, though, depends on certainty. To provide an incentive for investors to provide the necessary capital to support a business, detailed financial plans are prepared. Before a company ever publicly offers stock, as an example, regulatory bodies insist that a full disclosure of the financial structure of the company be prepared and made available to potential investors. The more uncertainty in a business plan, the riskier it is said to be.

Yet risk is only loosely defined in the literature. As Ross, Westerfield and Jaffe (2013) note, there is no single definition for risk. Henderson and Hooper (2006) note that risk is the potential for something bad to happen. In the case of any space venture, the potential for a bad outcome can be very large. How does one include such considerations when assessing a space mining venture? One way is to use statistical modeling (Breyfogle

1999). However, such modeling depends on understanding the factors that contribute to the risk equation.

This literature review explores the concept of business risk as applied to space mining. Beginning with a review of literature associated with risk analysis in the context of high technology endeavors, the review then explores the various factors that likely contribute to risk, in a space mining context, with a special focus on those areas that can generate the most risk in the context of a space mining venture. The intent is not to perform an exhaustive assessment of such factors, but to provide a framework for further research.

Risk in the Context of Space Mining

Any assessment of the risk associated with space mining must begin with risk assessments by those who have conducted space operations. According to NASA (2011), risk is:

> "[T]he potential for performance shortfalls which may be realized in the future, with respect to achieving explicitly established and stated performance requirements. The performance shortfalls may be related to institutional support for mission execution or related to any one or more of the following mission execution domains: Safety, Technical, Cost, Schedule"

While this definition does not define risk explicitly, the use of the term *potential* suggests a numerical or probabilistic assessment of risk. This suggestion is confirmed later in the same source where risk factors are discussed in terms of the probability of failure occurrence in the context of various space mission elements.

Yet NASA's approach to risk can be seen to be very engineering oriented: that is, it seeks to define risk simply as an aspect of building a space vehicle and having it perform to specification. While this is undoubtedly of interest to a potential investor in space mining, it is only part of the equation. Investors seek a return above and beyond simply executing a mission without technical error.

If then, as the literature suggests, risk is the probability of a bad outcome, it is rational to ask what might cause a bad outcome in space mining. If, as Sonter (1996) notes, space mining depends on such variables as the orbital dynamics of an asteroid, its material content, the cost of extraction and the value of any mined material, this begins to define the probability space for assessing risk. However, Sonter (1996) does not examine any of these factors in depth, relying instead on macro analysis to suggest a formula for determining where a positive financial outcome is possible. Andrews, et al. (2015) examine the prospect of space mining in a great deal more detail and develop a cost structure for space mining that includes such things as the cost to develop mining technology and space vehicles as well as operational costs associated with ground operations. They also include an analysis of the ability of a market to absorb space materials and the likely price such materials will fetch.

Many of the possible sources of risk are defined in terms of the mission profile selected and the mission profile depends heavily on where viable asteroidal material is located. While there are many asteroids within the solar system, generally these occupy the main asteroid belt and would pose significant hurdles, especially in terms of the required change in velocity (delta V), for any mission to exploit their resources. Sanders, et al. (2014) agree and further point out that relatively near asteroids, in terms of the energy budget to reach them, are of necessity the best targets for exploitation.

Granvik, et al. (2012) take a slightly different point of view with respect to potential asteroid targets. They postulate that the Earth is surrounded by many small asteroids, whose orbital dynamics make visits possible with a minimal delta V. If true, they later point out that low thrust missions could be used to reach and eventually exploit such asteroids. The disadvantage, as they point out, is that previously undetected asteroids often occur unpredictably. They propose holding spacecraft in Earth orbit such that the spacecraft can be diverted to such asteroids as they are detected. This adds to the complexity and cost of a space mining mission.

Near Earth objects (NEOs), the various sources seem to agree, pose the best opportunity for resource extraction; that is, they represent the least amount of risk associated with locating a viable target asteroid. Such objects demand the lowest transit times to reach which places extraction operations close enough to Earth that manned engagement seems reasonable. Such NEOs lend themselves to a variety of approaches with respect to mission profiles that could potentially be applied to mining operations. These generally reduce to two broad categories of mission approaches: in-situ mining, i.e., mining the asteroid in its orbital location; and local mining operations through retrieval of the asteroid to Earth or Moon orbit (Duarte et al., 1991). There are many examples of each in the literature. As an example, Badescu and Ebrary (2013) focus their analysis on in-situ mining, i.e., traveling to an asteroid and conducting mining operations there. Gaffey and McCord (1977), on the other hand, focus more on retrieving asteroids to extract valuable ores closer to the Earth. Both approaches have their advantages and disadvantages. Cenzon and Dragos (2013) point out that either mission is reasonable, depending on the economics, but do caution that moving asteroids to Earth orbit might carry an unacceptable potential for impacting the Earth with asteroidal material at orbital speeds. Interestingly, though, they also point out that having smaller asteroids impact the Earth might be the easiest way to mine asteroid resources, but once again, caution about the potential for causing damage on the ground.

Retrieving asteroids for local, Earth or Moon orbit, exploitation tend to reduce the cost of transportation and enable manned supervision, either directly or tele-operationally (Eldred and Roberts, 1992). Brophy, et al. (2012) also note that retrieving an asteroid, because it would involve moving large asteroid masses closer to the Earth, presents opportunities for international space exploration cooperation, as well as for developing technologies that would be beneficial to longer term space operations. Nevertheless, Brophy, et al. (2012) do acknowledge the safety concerns that exist with asteroid retrieval. These could be considerable, depending on the size of the asteroid, its rate of closure and the reliability of the technology used to move it. As they note:

> "The first question that must be answered in the consideration of feasibility is, 'could the mission be conducted safely?' In fact, moving a non-hazardous asteroid toward the Earth must not just be safe, but it must be completely perceived as safe to an interested, and likely concerned, public. Safety would have to be guaranteed by the mission design."

Brophy, et al. (2012) constrain the safety concerns by proposing the recovery of a carbonaceous asteroid of limited mass. If something were to go wrong, it would be no more dangerous than a larger meteoroid, many of which burn up in Earth's atmosphere each year. Due the limited nature of their proposed mission, a rather modest spacecraft is required to both rendezvous with and retrieve an asteroid: solar electric Hall-effect thrusters are the propulsion means selected. Sanchez and McInnis (2011), on the other hand, note that, given enough time, it is possible to move even large asteroids using available, or currently experimental, but reasonable, propulsion techniques. Massonnet, and Meyssignac (2006) also agree that moving larger asteroids is not only possible, but also could potentially be done by placing a mass driver on the surface of the asteroid and throwing off asteroidal mass with a sufficient delta V to provide a small, but constant push.

As noted above, however, there is an alternative approach to asteroid mining which does not require moving the asteroid into Earth proximity in the first place. That is in-situ mining, but it requires moving mining and processing technology to the asteroid (Benaroya, 2013). This approach has the advantage of avoiding the cost and risks associated with moving asteroids and consequently, is safer from the stand point of potential earth impacts.

Although in-situ mining is likely to be safer, at least from an Earth-impact perspective, it suffers from the need to manage mining operations at significant distances from the Earth and this makes direct human engagement unlikely (Andrews, et al., 2015). Consequently, such operations increase the cost of developing mining technology and increase the costs associated with transportation of mining equipment to the asteroid and recovery of valuable materials from the asteroid.

Both retrieval and in-situ approaches require the development of specialized mining and processing equipment. As Zacney, et al., (1996) note, technologies associated with micro-gravity extraction and processing will need to be developed, as will reliable transportation technologies. The cost to do so could potentially be considerable. Asterank estimates a cost of many billions of dollars to extract the valuable materials of one average-sized asteroid. Andrews, et al. (2015) agree and express such outlays in the range of tens of billions of dollars a year for twenty years.

It is important to note that both Planetary Resources and Deep Space Industries have intimated that they will utilize an in-situ approach to asteroid mining. UK's Asteroid Mining Company (Asteroid Mining Company, 2016), on the other hand, has not specified the approach it will use: concentrating instead on technology development that could apply to both approaches equally.

Both approaches, in-situ and local mining, require the development of several major pieces of infrastructure. As Zacney, et al. (2013) note, a mission to mine asteroids requires the development of a heavy launch vehicle that will be sufficient to loft significant payloads into orbit. Additionally, as noted by Andrews et al. (2015), a reusable transfer vehicle that can be used to transport mining equipment to and raw materials from an asteroid is required.

As Benaroya (2013) notes, mining spacecraft will also be required and could be challenging to develop. While Andrews, et al. (2015) go into some depth discussing the development of such spacecraft, they tend to minimize some of the difficulties, notably the impact of microgravity and low structural consistency of potential NEOs. In contrast Grandl and Bazso (2013) assume that a target asteroid will be characterized by low gravity and loose material and then develop a rather complete architecture for conducting mining operations. Unlike Andrews, et al. (2015), however, they do not attempt to develop a cost model for the technology.

Additionally, any mission profile cannot be accomplished without the dedicated support of humans, either in a ground support role or in space. Local processing is likely to be more conducive to direct human involvement so the costs to support such operations would be higher (Grandl and Bazos, 2013). However, both approaches require mission control personnel and the facilities to house them. It bears noting that the literature provides more substantial support for in-situ mining than for moving asteroids into Earth orbit and the existing private concerns are all adopting this approach.

As will be noted in the following discussion, risk factors that apply to space mining tend to focus on the indeterminacy of developing the necessary technology. Yet space businesses are subject to many of the same risk factors that apply to any business. Ross, Westerfield and Jafee (2013) suggest that most sources of risk can be tied to a standard balance sheet view of corporate finance. That is, each entry in the company's income statement and balance sheet has associated uncertainties; each of which generates some risk. As an example, they note that revenues are in some sense predictable, but often are influenced by conditions that are not under corporate control.

Financial analysis is essential to the development of a viable business model: to attract capital, investors must be assured of a reasonable return (Westow and Brigham, 1968). Although there are those that doubt that space mining will ever be financially viable on a stand-alone basis (Gardner, 2011), there are companies that are betting that such a financial justification can be made for asteroid mining. However, financial analysis depends on an understanding of both the cost and income sides of a balance sheet (Brealey and Myers, 1984). Rather than simply asserting that there is a great deal of money to be made in space mining, as Lewis does (1996), one must understand the cost to achieve such returns.

As Ross, Westerfield and Jafee (2013) note, corporate financial statements are typically characterized by an income statement and balance sheet. Included in the income statement are such things as: total operating revenue; cost of goods sold; research and development expenses; selling, general and administrative expenses; depreciation; operating income; other income; earnings before interest and taxes; interest expense; pre-tax income; taxes; net income and dividends. The balance sheet includes such entries as: current assets, which include cash and equivalents, accounts receivable, inventory; fixed assets, which includes property, plant and equipment, accumulated depreciation, and intangible assets; current liabilities, which include accounts payable, notes payable, accrued expenses; long term liabilities, which include deferred taxes, long term debt; and stockholders; equity, which includes the value of preferred stock, common stock, capital surplus, and accumulated retained earnings. Each of these line items applies to any company and especially to publicly traded companies and each can be a source of uncertainty, and therefor risk, when predicting the viability of a space mining business. A few of these items are explored in the following.

Risk and Revenue

The literature is rife with analysis of the cost side of the financial equation, at least insofar as identifying the major sources of technology development expenses (Wertz and Puschell, 2011). Revenue becomes somewhat more problematic where predicting the market for asteroidal material depends on understanding the dynamics of the commodity markets. Gaffey and McCord (1977) considered mining missions in detail and based their analysis on the proposition that M-class asteroids could be economically mined for iron. Their analysis looked at the economics of asteroid-derived material versus Earth-mined material, and showed that, given a market sufficiently robust to absorb new sources of supply, mining iron could be economically viable. Both Andrews, et al. (2015) and Sonter

(1992) calculate potential revenues by taking the market price of materials such as platinum group metals (PGMs) and multiplying that by an assumed production level. In the case of volatiles, whose use would remain in space, an assumed cost to transport similar material from Earth is used as a proxy value.

In fact, as Valentine (2002) points out, a discussion of the value of asteroidal material is highly dependent on context. If there is a long term and expanding human presence in space, it would be rational to assume that there would be a continuing demand for material to support such an occupation. In that case, the value of asteroidal material would be set by an in-situ market rather than a terrestrial one. Currently though, the value of asteroidal material is necessarily set by the demand for it on Earth. The value of material is based not only on its unit value—that is, the price it would demand in an open market—but also the amount of material that is delivered. The total revenue would be the unit value times the total number of units and the unit value is dependent on what the market will bear. As Gaffey and McCord (1977) note, this can depend on the total global demand for the material in question. A glut on the market of any material tends to drive the price that it will command down. Any risk analysis, then, needs to consider this relationship between demand and revenue.

Risk and Initial Capitalization

One topic that gets short shrift in the space mining literature is the difficulty or ease in obtaining initial capital. As noted previously, Andrews, et al. (2015) is one of the few evaluations that bothers to speculate on the source of space mining Investment. This analysis simply invents a new financial institution (a World Bank) that is willing to invest billions of dollars in a speculative venture and then accept a payback measured in decades.

In the absence of such an institution, though, a realistic assessment of space mining needs to adapt the realities of currently available investment resources: this means approaching lending or venture capital firms for funding.

Loans are generally granted based on the expectation of payback within a reasonable amount of time and with a reasonable return on investment (Brealey and Myers, 1984). Yet venture capital (VC) typically demands a quicker return on investment than banks do, and it also demands a higher rate of return (Bock, and Schmidt, 2015). Consequently, VC puts a higher premium on the potential of a company than it does on the results of a company. Nevertheless, as Zider (1998) notes, conventional constraints that would tend to deny either a loan or the interest of a VC firm can be largely overcome if a government is the primary investor. Governments can afford to accept long lead times to achieving payback or can waive payback completely.

Much has been said about the potential of space mining companies —that is, the value that might be returned. Many papers and texts explore the value of asteroidal resources from the perspective of composition. Sanchez and McInnis (2013), Blair (2003), and the previously noted Gaffey and McCord (1977) all establish a basis for believing that there is sufficient value in asteroidal material to warrant at least further exploration. Each of these sources predicate further exploitation on an assay of target asteroids. The notion being that only those asteroids that are proven to contain a viable amount of material will be mined. Yet, even to launch a prospector mission to assay an asteroid may require many millions of dollars; and this is even before any worthwhile material is returned to Earth. Focusing on valuation of resources is less compelling to VC investment than is the probability of payback (Zider, 1998). To this, VC fund managers often turn to an assessment of the management of the company as a surrogate for assessing the risk associated with the venture.

Barry and Mihov (2015) note that venture capital usually demands more certainty in the performance of a company that is seeking capital than do lending institutions. However, a venture capital firm will often finance a company with a higher risk profile and a need for more upfront investment. The implication is that a space mining venture, with a very high-risk profile and the need for a large initial investment, will need to approach venture capital sources to obtain seed funding. However, the company must demonstrate a well-structured operation to convince the investors that it has a high probability of being successful. Management activities must support the notion that the company is well run and will accomplish its business plan.

Brocken (2015) agrees with Barry and Mihov (2015) but feels that successful VC engagements also depend on the willingness of the VC firm to take an active hand in management. As Brocken notes:

> "Key success factors include business model innovation, collaborations and a strong business case, whereas failure factors include a lack of suitable investors, a strong incumbent industry and a short-term investor mind-set. Sustainable start-ups should focus on triple bottom line business model innovation, find opportunity in new technology and funding platforms and develop multiple business cases to create success beyond the 'green customer base'. Sustainable venture capitalists can help prove the success of sustainable business formats, mitigate financial risk through co-investments and exercise patience by balancing financial with social and environmental returns."

Brocken believes that VC managers have the responsibility to evaluate a prospective investment not only on the probability of a high return, but also on the ultimate impact on society of the undertaking. Zider (2015), although not disagreeing with this notion, emphasizes that VC will tend towards higher return opportunities, delivered on a shorter timeline. Consequently, societal impact, aside from environmental considerations, is not often factored into investment decisions.

Nevertheless, VC funding can be obtained if the payback is reasonably short term and reasonably high. Peters (2009) notes that a VC fund typically demands anywhere from ten to thirty times return on investment over a period of ten years. In other words, the VC fund expects to double its money every two years to consider the investment a successful one. While the actual performance of any VC fund is usually much less than this, the rapid doubling and relatively short time frame tends to define VC expectations. While Puri and Zarutskie (2012) are not as specific as Peters (2009) on return and payback, they do note that VC funded enterprises are held to higher financial performance standards and often fail when they do not meet those standards. Venture capital, then, expects high returns over short time frames. Thus, space mining ventures that depend on private funding must be prepared to execute relatively quickly on their business plans. This makes initial funding a significant source of uncertainty and therefore risk.

Risk and the Uncertainty of Project Externalities

Project externalities—factors outside the direct control of the project—to any decision are very hard to predict. Such factors, which may be addressable through the intervention of society, are not usually controllable in the context of project oversight, nor are they predictable. For example, agri-business depends on favorable weather, but when that does not materialize, product targets are virtually impossible to meet. Most contracts contain *force majeure* clauses that cover non-performance due to unforeseen circumstances.

In the case of space business, the potential number of unforeseen difficulties is rather high. In most circumstances, these unforeseen difficulties are expressed as uncertainties in the outcome (Clemen, 1996). However, there are classes of externalities for which one cannot assign a probability with any certainty. One that has a significant bearing on space mining is the impact of public policy rules and regulations which could significantly impact the profitability of space operations.

Especially in the case of the exploitation of space resources, there are international agreements which would seem to limit the ability of a company to profitably mine asteroids, e.g., The Outer Space Treaty of 1966 which prohibited national appropriation or claim by use or any other means any celestial body, but which granted freedom of exploration of such bodies. (Lee, 2012). Strict adherence to this treaty would seem to restrict a mining company from laying claim to any resources it might find and would effectively restrict its ability to profit from such ventures.

In 2015, largely to clarify the responsibilities and to encourage commercial space activities, the US Congress passed the Space Resources and Utilization Act of 2015, which makes clear that, while a company cannot claim an asteroid, it can, nevertheless, stake a claim to the resources it contains. (United States, 2015). While this would tend to resolve any conflict between sovereignty and commercialization, as Lee (2012) points out, there are still ambiguities associated with the ability of a company to profit from its claim. These issues must still be resolved, and although it is assumed by the companies involved that they will be solved in a way that will be advantageous to space mining, it is by no means certain that this will be the case. Nevertheless, as Shaw (2013) has pointed out, there is a rather large body of mining law that could presumably be adapted to ensure both universal access to mining rights, while ensuring that commercial efforts can profit. Shaw (2015) proposes adapting the US General Mining Law of 1872 for such ventures. This would provide a framework for recognizing claims among other considerations. Harn (2015) suggests that existing treaties ought to be adjusted to reflect the necessities of space commercialization and feels that current treaties either are, or could, stunt such commercialization in the future. To the extent that a well-articulated and unambiguous set of rules does not currently exist, the potential for international law to change during any space mining venture remains very uncertain. Risk, as a result, is high.

Finally, there is always a possibility of a "Black Swan" event that might turn a profitable business plan into an unprofitable one. Black swans, according to Taleb (2010), have three characteristics: (1) they are unlikely, (2) they have a major impact and (3) they spawn a great deal of post-occurrence analysis. Given the nature of space mining, the probability of a Black Swan is unquantifiable, but potentially significant in its impact on the business case.

Assessing Risk Using Statistical Analysis

As noted previously, risk is only loosely defined in the literature. Ross, Westerfield and Jaffe (2013) suggest assessing financial risk, for established markets, in terms of the expected outcomes of the market. When evaluated over time, a market will provide some average return, but will vary from time-period to time-period within some range of values that can be assessed statistically. Ultimately Ross, Westerfield and Jaffe (2013) suggest that the best way to think of business risk is in the context of statistical uncertainty. If an outcome can be expressed as the interaction of multiple variables interacting in some probabilistic way, then one can compute the statistical likelihood that an event will occur.

They point out that a good surrogate for risk is the amount of variance as defined by the standard deviation of the outcomes. Henderson and Hooper (2006) tend to agree but point out that a good working definition is simply the chance of a bad outcome. Yet, as they note, it is important for any investor to understand the risk associated with any investment.

Others, though, have somewhat different views of business risk. Linstone (1999), for example, argues that risk can be quantified in terms of technical, organizational and personal objectives. Risk can be assessed from any of these objectives and can be quite different depending on the objective chosen. While a specific objective might be successfully met from a technical perspective, it might be a disaster from a personal perspective. As Linstone (1999) notes, antilock brakes might prevent accidents due to slippage, but might encourage poor driving. So, risk might be multivariate and, in some ways, subjective. Clemen (1996) tends to agree with this notion and points out that risk can be defined in many ways. However, he notes that risk can be assessed by comparing expected outcomes to desired outcomes. In this, he is advocating taking a structured approach to objective setting so that such comparisons can be made.

An interesting perspective on assessing risk in relation to expected investment returns comes from Brealy and Myers (1984) who note that for any investment there is a spread of potential outcomes. The spread determines the risk. In other words, the more uncertain a specific outcome, the riskier it is. This notion is very close to that of Deming's total quality management (TQM) (Deming, 1993, 2000). Deming treats risk as the probability that a process would be out of statistical control. The following figure illustrates the notion.

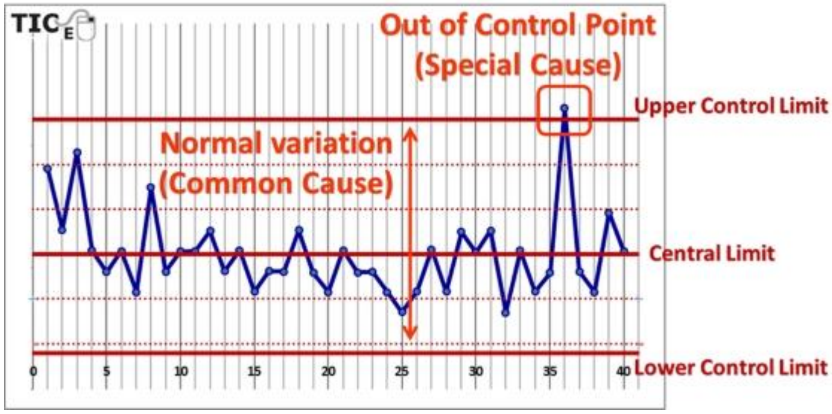

Figure 1. Control Chart (Microsoft Word Graphic)

As can be seen, if an outcome is within plus or minus three sigma (typically, three standard deviations) from the average, it can be said to be in control. If an outcome falls outside those limits then, the overall process is potentially out of control: the results are uncertain and therefore the process is risky. This approach is consistent with the approach used in Six Sigma. As Breyfogle (1999) notes, risk can be thought of as the probability that a result will be true. As he explains it, risk can be thought of as a test of a null hypothesis. To the extent that the null hypothesis is supported, the α Risk defines the probability that a false positive will be detected. Thus, risk could be assessed simply by measuring outcomes of a business process and then noting if they fall within the plus or minus three sigma control limits over time. This approach, while useful for a repeatable process, is less useful for a process that occurs infrequently; such as a space mining venture. Yet, the application of statistical methods is instructive.

One Six Sigma approach that is typically used to assess sources of error (e.g., risk) in a production process is the use of a fish bone, or Ishikawa, diagram (Sherkenbach, 1988).

As can be seen in the diagram, a poor outcome can occur due to many contributing factors. The total probability that a bad outcome will occur is the sum of all potential problems.

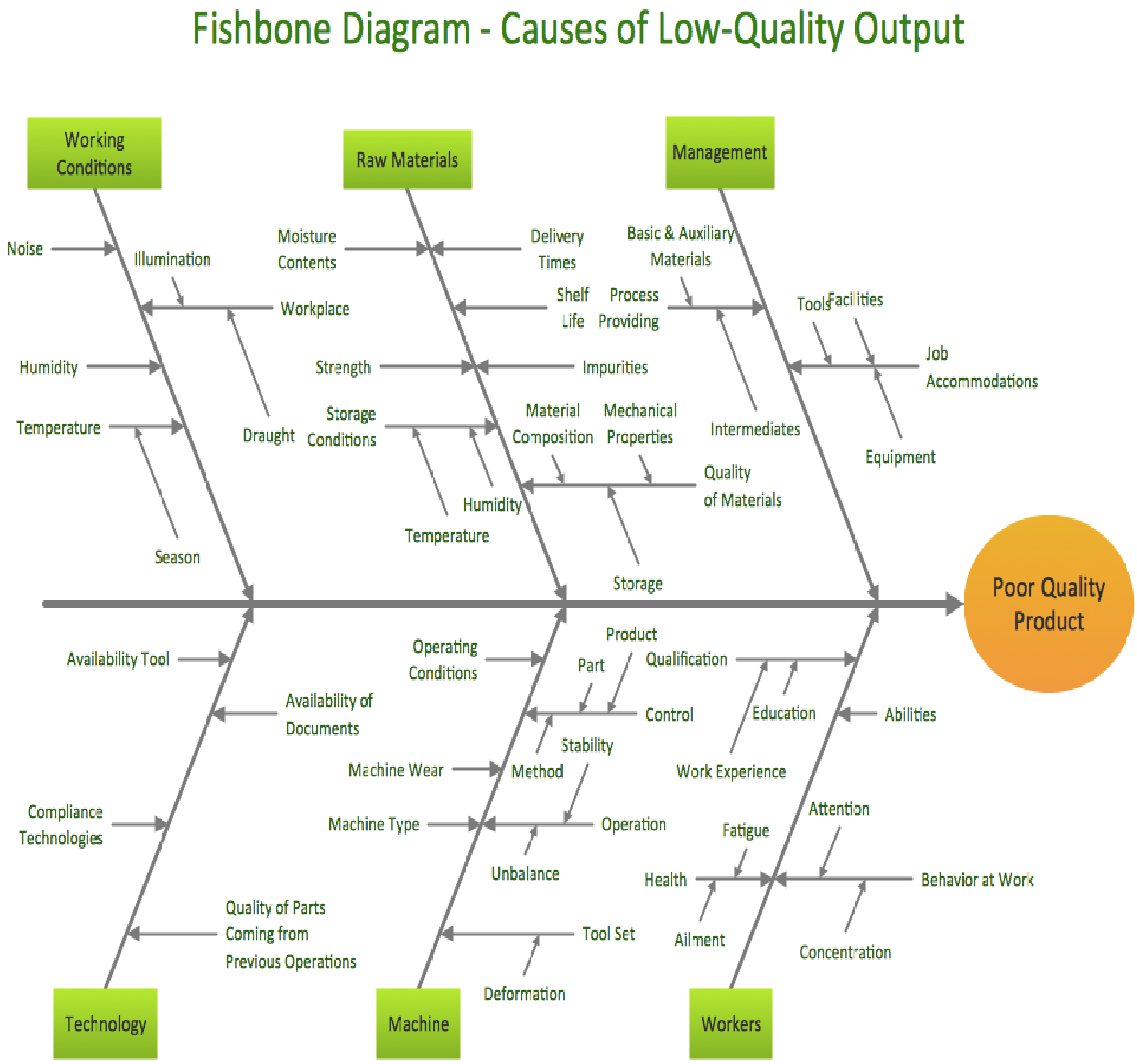

Figure 2. Fishbone Diagram (Microsoft Word Graphic)

This approach begins to suggest a practical approach to defining risk. If risk is the probability of a bad outcome, then identifying all the sources of a bad outcome allows one to develop a model for risk. This is, essentially, Clemen's (1996) approach. He combines the ideas of statistical analysis inherent in Six Sigma with the multi-variate approach of Linstone (1999) to develop decision models that can be used to map a business case into a probability space.

If risk is essentially a probabilistic function, as noted above, then it is reasonable to assume that a statistical approach to risk assessment would be an acceptable approach to assess risk. In fact, Wei et al. (2011) approach estimation in terrestrial mining ventures from this very perspective. They suggest an approach that utilizes Monte Carlo analysis to assess the overall risk associated with conventional mining venture, after identifying the salient variables that would apply to such a business. This approach treats the total probability of an outcome as the sum of all probabilities, as noted by Deming (1993). In fact, a Monte Carlo treats any problem as a set of variables that contribute to a desired outcome in known mathematical relationships and which can be simulated through a random sampling of input variable values (Kroese, et al., 2014).

Yet Monte Carlo simulations are primarily useful in the context of a set of variables whose likely ranges have been validated through the collection of primary data (Faulin, 2010). Although Wei and Jianglan (2011) have suggested a useful approach for mining, where the variables are generally known and whose parameters can be supported by years of mining experience, their approach begins to falter when applied to an environment, such as space mining, where the variables are only loosely understood and for which there is a dearth of historical data. Clemen (1996) notes that in such situations, it is necessary to treat the business as a decision model where, not only the impact of well understood variables can be included, but also variables for which background date is largely unknown.

An approach, then, that is supported by the literature is one where decision modeling combined with a Monte Carlo simulation could provide a reasonable approach to assessing the risk of a space mining venture. Such an approach yields a numerical model that can be used to ascertain the probability of a financial outcome. Although, as noted above, this is not the only way to assess risk, it still has the virtue of applying a structured approach to risk analysis that can be reproduced. It is also an approach that lends itself to risk assessment in the context of space mining.

Conclusions

The literature provides a framework for considering the development of a space mining risk analysis. It further provides some confidence that a viable mission profile can be developed to extract those materials and return them to Earth. It also provides some assurance that financial models can be developed which would support such undertakings.

The literature, though, provides no assurance that any of these things can be done in a time frame that would satisfy the most likely source of funding: venture capital. Additionally, the literature provides no assurance that space mining would ultimately be viable from a profit loss standpoint. In other words, the consensus seems to be: "we can do this, but we don't know if it will be a profitable thing to do." Though, the literature supports the assertion that space mining would have salutary Earth benefits in terms of reducing the impact of resource exploitation activities from a financial aspect, these must largely be ignored unless regulation or public policy provides some form of subsidy to encourage space mining. At this point that seems unlikely or at least unknowable.

Yet, armed with a structured approach to risk assessment, using a decision modeling approach with Monte Carlo simulation, the various variables that might impact the viability of space mining can be combined in a way that allows an objective assessment of the risk involved. This approach, while novel from the stand point of assessing space mining, nevertheless provides a way to objectively evaluate space mining business models and is the foundation on which the balance of this research rests.

CHAPTER 3: METHODOLOGY

Introduction

As noted in the previous chapter, this study is fundamentally a financial analysis. However, it is a financial analysis that also incorporates the concept of uncertainty. Although it is possible to know with some certainty many of the financial parameters associated with an enterprise, in an area where many new technologies have yet to be created, there can exist a high degree of uncertainty. In financial undertakings, uncertainty translates into risk.

Previous research has attempted to account for this uncertainty by adopting conservative estimates of the values of various variables associated with space mining (Sonter, 1992; Andrews, et al., 2015); impact of asteroid orbits, composition of asteroids, and such. These have almost always devolved into a discussion of technology and the costs to develop it. While useful, actual costs can be highly variable. Andrews, et al. (2015) simply note that they utilized an estimation process that assumes a higher technology production efficiency that that of NASA: they assume that technology can be developed at 30% of NASA's costs.

The methodology proposed here is different. It begins with a standard financial layout for a business case that has already been articulated (in this case Andrews et al., 2015). However, it assumes that the costs and revenues are uncertain and then attempts to bound the range of reasonable values using a combination of secondary and primary research. Once these variables have been identified and bounded—that is, when the maximum and minimum values have been identified— they are loaded in a decision modeling application and a Monte Carlo analysis is performed. The output of the Monte Carlo analysis is utilized to assess the conditions for a successful return on investment and to estimate the risk associated with the undertaking.

Qualitative Quasi-Deductive Research

A problem with space mining research is that it is either too focused on attempting to quantify costs (an objective undertaking) or it is too focused on benefits (often a very subjective point of view.) Thus, the conclusions are often tainted by either a too certain assertion of viability or an overly pessimistic pronouncement of potential. What is required is an approach that can accommodate both the qualitative assessments of experts as well as the researcher's opinion, while considering the quantitative data associated with such considerations as technology development. Qualitative Quasi-Deductive (QQD) research offers an approach that, while used primarily in sociological research, can provide insights in a wide variety of research fields.

QQD is a methodology utilized when the intent is to generalize to a hypothesis (Jude, 2000). It combines qualitative data, quantitative data, and researcher expertise to triangulate to conclusions which can serve to refute a hypothesis or support it.

Unlike pure qualitative research, where observation and subject interaction are the sole source of research data, QQD also utilizes numerical and statistical quantitative data to establish points of reference. Additionally, unlike many forms of research where there is a significant amount of effort devoted to excluding any potential researcher bias, in QQD the researcher's opinions and observations are given significant weight.

In the case of this research, the proposed working hypothesis is: "Space mining is economically viable." The null hypothesis is: "Space mining is not economically viable." If the hypothesis is supported—that is, if space mining is possibly of economic viability—then a secondary hypothesis can be tested: "Space mining is risky." Since assessing risk is likely to require both the collection of numerical, quantitative data as well as opinion, qualitative data, QQD is appropriate.

In practice, QQD requires research in the secondary sources to define a list of significant variables and their likely values. These values are then socialized with several subject matter experts to assess whether they consider the values reasonable or unreasonable and if so, are asked to provide what they would consider a reasonable value. However, in this case, a Delphi survey of subject matter that begins with the Andrews et al. (2015) business case is used to gauge subject matter expert agreement.

Once the variables have been validated and bounded, they are combined in a numerical decision model so that additional analysis can be performed. Finally, the researcher applies his knowledge and judgement to the modeling process to produce statistical outputs that can be used to assess the hypotheses.

Mission Profile

Even Monte Carlo simulations must begin with some certainty. The mission profile selected for analysis provides a base for analysis. As noted in the literature review, there are several mission profiles that could be adopted to mine asteroids. Including every one of them in a modeling exercise would generate a model that would not yield to analysis in any reasonable amount of time. Consequently, a mission profile is selected that represents an approach which has been adopted by Andrews, et al. (2015) as well as a current space mining company; Planetary Resources (Tullo, 2012). In this approach, Earth detection of likely asteroid targets is conducted prior to sending prospector spacecraft to assess the mineral content of potential targets. Once a target has been located, mining spacecraft are sent to extract the minerals, using some on-site processing. As additional asteroids are located, this process is repeated.

This profile, then, depends on developing ground infrastructure, heavy launch capabilities, transfer vehicles, space mining and processing technology and then effectively marketing any retrieved material. It also depends on obtaining financing at a reasonable rate and supporting an expanding work force with the normal compensation and benefits that would characterize any large company.

The purpose of this research is not to develop such a profile. The researcher does not have the expertise nor the time to propose a unique profile or to evaluate the technology required to carry it out. Instead, this paper takes a well-documented profile and then applies decision modeling techniques to it to assess the risk associated with the business case. As a result, this research begins with Andrews, et al. (2015), which lays out not only a mission profile, but then assesses the cost to develop the various technologies as well as the likely net present value (NPV) and return on investment (ROI) over a 20-year period. For simplicity, the Andrews et al. (2015) profile is hereafter referred to as the mission profile.

Building the Initial Financial Model

The starting point for the research is to build a basic financial model that is defined by the variables discovered in the research and defined by the selected mission profile. In the case of the mission profile, a basic income statement and balance sheet is provided. It provides a detailed list of cost and income sources, which are listed, with definitions, below.

Variable	Description
SSTO Development Cost	The single stage to orbit (SSTO) is a key piece of technology in the Andrews et al (2015) mining architecture. This variable represents the cost to develop such a launcher.
SSTO Development Duration	Technology frequently involves a development period. This variable represents the number of years that will be required to develop the SSTO.
SSTO Launch Cost	This variable represents the cost for a single SSTO launch.
SSTO Launch Rate	This variable represents the number of launch per year that can be expected for the SSTO fleet.
Prospector Development Cost	The Andrews et al. (2015) architecture depends on identifying target asteroids using prospector spacecraft. This variable represents to cost to develop such a spacecraft.
Prospector Development Duration	This carriable represents the length of ime in years required to develop a prospector spacecraft.
Prospector Launch Cost	This variable represents the cost to launch a prospector spacecraft.
Prospector Launch Rate	This variable represents the number of prospector spacecraft that can be launched per year.
Hawaii Launch Facility Development	The Andrews et al. (2015) business case depends on building a new launch facility in Hawaii. This variable represents the cost to develop such a facility.
Hawaii Launch Facility Development Duration	This variable represents the time frame required to build a Hawaii launch facility.
ReNet R&D Cost	Key to transporting mining equipment to asteroids and returned mined material is the reusable nuclear electric tug (ReNet). This variable represents the cost to design such a vehicle.
ReNet R&D Duration	This variable represents the time required to design a ReNet.
ReNet Development Cost	This variable represents the cost to develop and build a ReNet.
ReNet Development Duration	This variable represents the time required to develop and build a ReNet.

ReNet Cost per Unit	This variable represents the cost per new ReNet.
Space Manufacturing Facility Cost	The Andrews et al. (2015) architecture involves a space manufacturing capability. This variable represents the cost of a manufacturing facility.
Space Manufacturing Facility Duration	This variable represents the time required to build a space manufacturing facility.
Manufacturing Module Launch Costs	The manufacturing facility utilizes manufacturing modules that return processed material to the Earth. This represents the cost per module launch.
Manufacturing Module Launch Cadence	This variable represents the number of modules that can be launched per year.
Mining Equipment Development Cost	Andrews et al. (2015) proposes a mining spacecraft that will be able to extract water and PGMs from a target asteroid. This variable represents the cost to develop such a mining spacecraft.
Mining Equipment Development Duration	This variable represents the time required to develop the mining spacecraft.
Mining Spacecraft Cost per Unit	This variable represents the cost per mining spacecraft.
Personnel Requirement Initial	This variable represents the initial staffing for the space mining venture.
Personnel Cost Initial	This variable represents the initial cost of personnel.
Personnel Requirement Final	This variable represents the total staffing after 20 years.
Personnel Cost Final	This variable represents the final cost of personnel after 20 years.
Initial Number of Mines	This variable represents the first year of operation number of mines that can be supported after mines are established.
Final Number of Mines	This variable represents the total number of mines in operation after 20 years.
Initial Water Delivery	This variable represents the first year of operation amount of water that can be delivered to LEO.
Final Water Delivery	This variable represents the year 20 of operation amount of water that can be delivered to LEO.
Initial PGM Delivery	This variable represents the first year of operation amount of platinum group metals (PGM) that can be delivered to Earth.
Final PGM Delivery	This variable represents the year 20 of operation amount of PGMs that can be delivered to Earth.
Manufacturing Profits	This variable represents the revenue that can be expected from the space manufacturing facility.

Table 1: Andrews et al. (2015) Business Case Variables

Each of these variables influences the outcome of the resulting financial model; which is expressed as a net present value (NPV). It is possible to use these variables to build an influence model, as shown in the following figure. Please note that Appendix D shows the details of the model:

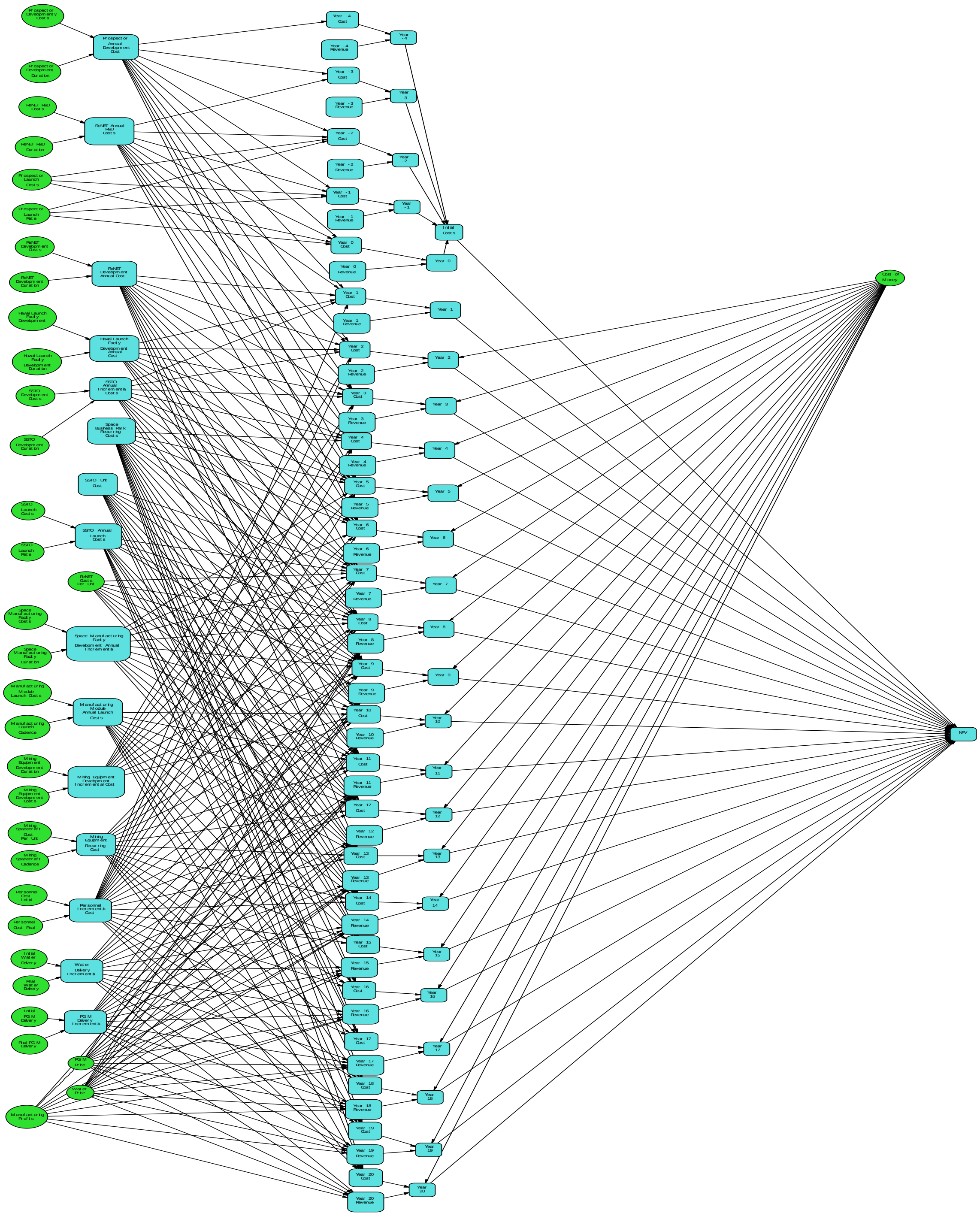

Figure 3. Decision Model

Each of the ovals in the diagram represent variables that can be changed; for example: the cost of money. The rectangles are computations. For example, each year is defined by revenues minus costs. Each is indexed by the cost of money as shown in the following formula:

$$NPV_{Year\ x} = (Year_X\ Revenue - Year_X\ Cost)/(1+Cost\ of\ Money)^{\wedge(X-1)}$$

Clearly each variable could simply be plugged into the influence diagram, or a spreadsheet. However, risk assessment requires that the certainty of each variable be assessed. What if the mission profile is wrong in its estimates? Conducting risk analysis requires that each variable be validated.

Validation of Variables

This study fundamentally depends on identifying and placing bounds on the variables associated with the asteroid mining business case. As noted above, the mission profile provides a list of variables that constitute an analysis of the overall business case. This provides a gross estimate of the viability of the endeavor. However, to assess risk it is critical to place bounds on those variables. For example, the mission profile identifies the development of a prospector-class spacecraft as a primary cost associated with mining asteroids and estimate the magnitude of that cost. Yet, it also indicates that it is estimating this cost based on NASA guidelines and then is assuming that private enterprise can produce such a spacecraft more efficiently than can government. Is this a reasonable assumption? Perhaps, but model building requires more certainty; or at least requires that the uncertainty be bounded.

The problem, then, is to determine not only whether the list of variables is accurate but identify the range of values each can have. There are two ways this can be done: interviewing subject matter experts whose experience qualifies them to estimate a variable range, using direct interaction to disclose their opinions. Or to develop a survey that polls a wide range of qualified respondents to first validate the variables and secondly to bound the variables statistically. The former involves qualitative data gathering and the latter involves quantitative data gathering. Yet without polling many experts, statistical certainty is virtually impossible to obtain. In an area so forward looking as space mining, the probability of finding a statistically reliable population to survey is unlikely.

For these reasons, the need for confidence in the variables involved as well as the need to map a range to a distribution, both qualitative and quantitative data sources are required. What is required is a survey that is more qualitative than quantitative. For this reason, a form of survey called a Delphi was employed (Brown, 1968).

In a Delphi, a list of questions is assembled that cover the area of interest. Then a selected panel of subject matter experts, who might be expected to know the subject area and who are also expected to have good judgement in the subject area, are asked to answer the questions and return their answers to the researcher. Once this is done, the researcher assembles and collates the responses and then returns the responses to the panel of experts. The experts are once again asked to evaluate their responses and are encouraged to change them if they wish. After the second pass, the results are assembled and are utilized for further research.

To conduct this research a panel of ten subject matter experts from academia and industry were contacted and asked to participate in a Delphi survey. Of the ten who agreed to participate, one recused himself based on an unfamiliarity with the subject material, three never responded after receiving the survey and six completed the survey process. Since the aim was not to achieve a statistical level of confidence, rather to bound the variables, the number of final respondents is not problematic. Appendix A provides the survey instrument used.

Some concern has been expressed during this research process that a Delphi, by providing each participant with not only the existing business case, but also the responses of the entire panel, might be biasing the outcome to conform the original business case. Bias, in a Delphi, is a distinct possibility and must be assumed. Yet, the point of a Delphi is to leverage the influence of a group to settle on a set of values. Since the panel participants are all anonymous, each is constrained to try to be as accurate as possible rather than be perceived by peers are being irrational in the context of the questions. Ultimately, peer pressure is utilized to try and constrain bias.

Protection of Human Subjects

All research involving human subjects is subject to institutional review to comply with U.S. federal regulations involving the use of human subjects. The University of North Dakota requires the submission of an Institutional Review Board (IRB) form and approval prior to conducting research with human subjects. The intent is to protect the confidentiality and to prevent harm to humans accessed during the research.

There are certain exempt classes of research that involve the collection and evaluation of human derived data: notably that information which has been compiled by government agencies and which is in the public domain. Although there is no intent to disclose the participants of this survey or use their responses in any way except to bound variables in a numerical model, IRB approval to conduct research was sought and received. In addition, an informed consent form was provided to each respondent to further ensure that the nature of and use of the research was well understood by the participants. This form is included as Appendix B.

Decision Modeling

Once the variables were validated and bounded, a decision modeling tool—in this case, Decision Programming Language (DPL)—was utilized to assess the business case. For each variable, a maximum and minimum value was extracted from the Delphi responses and a mean value was computed. Each variable, then, has a nominal value as well as a range of possible values. For example, the cost of developing a prospector spacecraft was specified as $150 million, as noted in Andrews, et al. (2015). However, this value is uncertain and is based upon an assumption that this spacecraft can be built more efficiently than can NASA. When posed to a Delphi panel, the estimates ranged between $150 million and $2 billion, with a mean value of $540 million. If each Delphi respondent is equally certain of his or her response, then the value placed in the model would be a smooth curve from $150 million to $2 billion, with a mean value of $540 million, as the following figure shows.

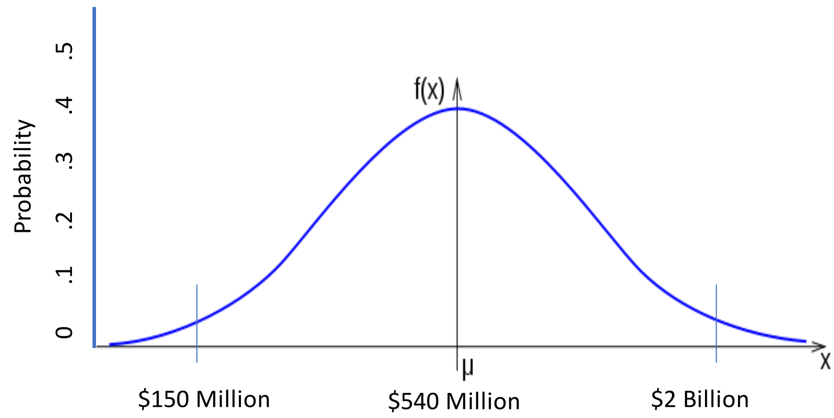

Figure 4: Variable Representation

As the reader will note, the example variable shown is represented by a Gaussian distribution centered on the proposed value, yet the range is not uniform—that is, the range is asymmetrical around the mean. This is due to the small sample size that a Delphi represents, nevertheless the nature of human responses still allows us to represent the distribution as a normal one. A normal, or Gaussian, distribution is appropriate with equally certain responses from a selected group of experts but may not be appropriate for uncertain responses or a range of responses that do not follow a smooth curve. Analysis of the Delphi results provides both the nominal value as well as the approximate distribution, however, as a default, a decision model can be loaded with the list of all responses, each of which have an equal probability of occurrence. In such a case, the variable would not be a smooth curve, it would be a table.

Clemen (1996) notes that the danger in such a modeling process is the temptation to include variables which ultimately prove to be irrelevant: a too extensive model generally makes numerical simulation problematic, as computational overhead drives the time required to run a simulation to unacceptable lengths. However, as the variables are assembled and bounded, it is often possible to ascertain those that are constant for all runs and then use assumptions to fix their value, rather than allowing them to vary.

In the case of this model, no tables were utilized, but for each variable a range was computed based, as noted above, on the average response as well as the minimum and maximum specified responses. When used with a standard gaussian distribution, the ranges can provide a good first estimate of influence. This is because, when the maximum and minimum values are not equidistant from the mean, they tend to distort the standard distribution in favor of the most influential metric: that is, the curve is pulled either towards the minimum or the maximum depending on the magnitude of the difference, as shown in the following figure. As noted above, this is a locational shift of values caused by a smaller than nominal survey size and is an artifact of a Delphi survey. In future representations of the distribution such shifts will be assumed in the results and the values represented accordingly.

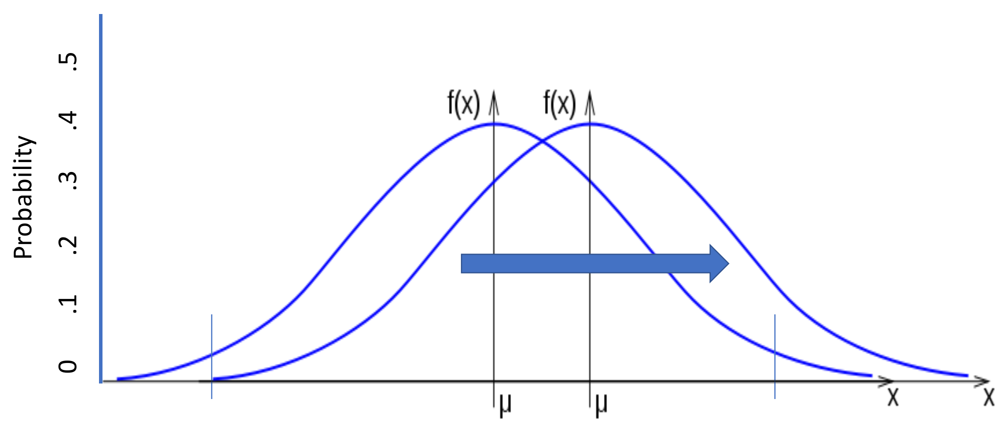

Figure 5: Gaussian Distribution Offset

As noted above, the Delphi was administered to the six subject matter experts and the responses were coded and tabulated. These values were loaded into the DPL model and sensitivity tests were then run, as discussed in the next section.

Monte Carlo Simulation

Monte Carlo analysis provides a novel way to assess the viability of and the implicit risk involved in a numerically represented model. As Clemen (1996) notes, Monte Carlo analysis involves representing each variable that impacts an outcome with a range of values and a probability curve that represents the distribution of those values. Once each variable is defined, a simulation is run where each variable can vary between its minimum and maximum limits along the probability curve: that is, each value of the variable is represented in the simulation in the same proportion as that of the distribution. For each combination of variable values, an output value is computed. Output values are collected, and a total output is generated.

The beauty of such an approach is that it provides insight into the relative impact of each variable; how much influence it has on the outcome. Additionally, it has the virtue of providing a likely range of outcomes that can be assessed in terms of the collective values that compose them. This allows for an assessment of the likelihood that such an outcome will take place by providing insights into the boundary conditions that would be necessary to achieve the outcome.

Monte Carlo analysis is not a panacea, however. If the range of a variable is unknown or poorly defined, the outcome of the model can become very uncertain (Kroese, et al., 2014). To tightly constrain the outcomes, certainty in the input variables is essential. However, since the purpose of utilizing a Monte Carlo for this exercise is precisely to illuminate the uncertainties associated with space mining, this possible deficiency is a virtue.

Monte Carlo analysis begins with the construction of a decision model, as noted above. Once the decision model has been input and debugged, the modeling tool is used to do two things. First a sensitivity analysis is run on the variables to determine which are the most influential to the outcome. As the following figure shows, this is in the form of a Tornado Diagram, where each variable can vary between its maximum and minimum values independently of the other variables. That is, each variable can vary between its maximum and minimum value following either a probability function or a table of values, while all other variables are held at their nominal value. This enables a determination of how much influence each variable has on the model's output. The variables are stack ranked in terms of their influence as shown in the following figure.

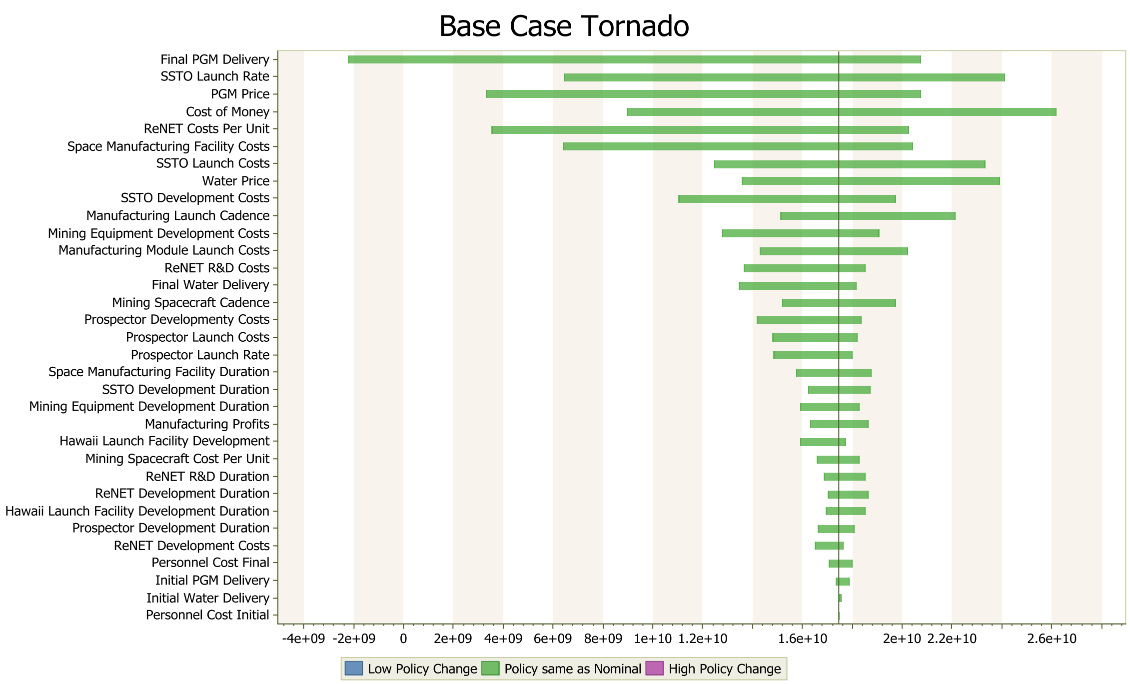

Figure 6: Tornado Diagram Example

The tornado diagram shown is set to the nominal value—the mean value for each variable—for each of the variables while specific variables can vary between their maximum and minimum in a linear fashion; that is, they are not biased by the gaussian distribution at this stage. As will be noted from the figure, there are variables whose influence is minimal, having no appreciable impact on the outcome.

Once these variables are locked on their nominal or average value, the tornado is run again to ensure that the outcomes are still consistent. This operation allows for refinement of the influence diagram to show only those variables that matter; that is, the variables that have maximum impact on model output. It also allows for the DPL simulation to ignore unproductive variables and relationships; significantly speeding up the simulation runs.

Finally, the Monte Carlo simulation was run, where all the variables could vary between their maximum and minimum, following the gaussian probability function. The output was then plotted for the model output, showing each value and its likelihood of appearing. The Monte Carlo analysis, then, tells one the probability of achieving a positive NPV, given the variables and it also identifies the variables that matter and the extent to which they matter. As an adjunct to the Monte Carlo run, it is possible to combine the Tornado with the Monte Carlo to generate a Tornado diagram that shows the relative impact of each variable in terms of the likely risk associated with each.

Combined with sensitivity analysis, which discloses how sensitive the decision model is to each of the variables, Monte Carlo analysis provides an overall picture of the likely outputs and their probability of occurring. An NPV that is only positive at a very high cumulative probability of outcomes, is very risky.

In the case of this model, once the variables had been input, several test-runs of the model were conducted to debug the code and to ensure that the model was performing appropriately. This was determined in two ways. First, Decision Programming Language application has an internal debugger that terminates a model run if a variable is mis-assigned or if a math error occurs—divide by zero, etc. Second, the selected mission profile had already computed a static NPV based on a spreadsheet representation of the business case. When the model was run, it returned a base case NPV—one using the specified or nominal values of the variables that was very close to the one that the mission profile business case computed. Since some iteration is conducted by the model in the base analysis, exact correspondence is not expected, but the difference was less than ten percent.

Once the model was debugged, a base case Tornado diagram was run and then a Monte Carlo was run to assess risk. In each case of the simulation runs, the model was set to the highest level of accuracy achievable with the computer system available. This limited the number of discrete data points per variable to 100 or less. In spite of this limitation, the runs still consumed days of simulation time. It should be noted that this is not necessarily a problem since, high levels of accuracy were not the objective, but a range of potential outputs were desired.

Conclusions

This methodology was designed to collect the primary variables likely to impact the financial model of a space mining venture. Utilizing a pre-defined space mining business case, a decision model was created that enabled the determination of variables that contribute to space mining success. Utilizing a Delphi survey, a panel of experts were polled to provide reasonable bounds to the variables in the model. Utilizing the Decision

Programming Language application, a Monte Carlo analysis was conducted to determine the risk associated with the modeled space mining business.

CHAPTER 4: ANALYSIS

The methodology specified in the previous chapter depends upon a process that begins with the construction of a business case. As noted, the selected mission profile has already done this, and a spreadsheet was duplicated for local analysis and is shown in Appendix C. The mission profile business case does a reasonable job laying out both their analysis as well as the timing associated with a space mining business. This business case forms the basis for the balance of this analysis.

As noted in the previous chapter, each of the Andrews et al. (2015) variables had distributions in both value as well as timing. The following figure shows the resulting model that is defined by thirty-two variables mapped to the twenty-year time-period specified by the mission profile. Details of the model can be found in Appendix D.

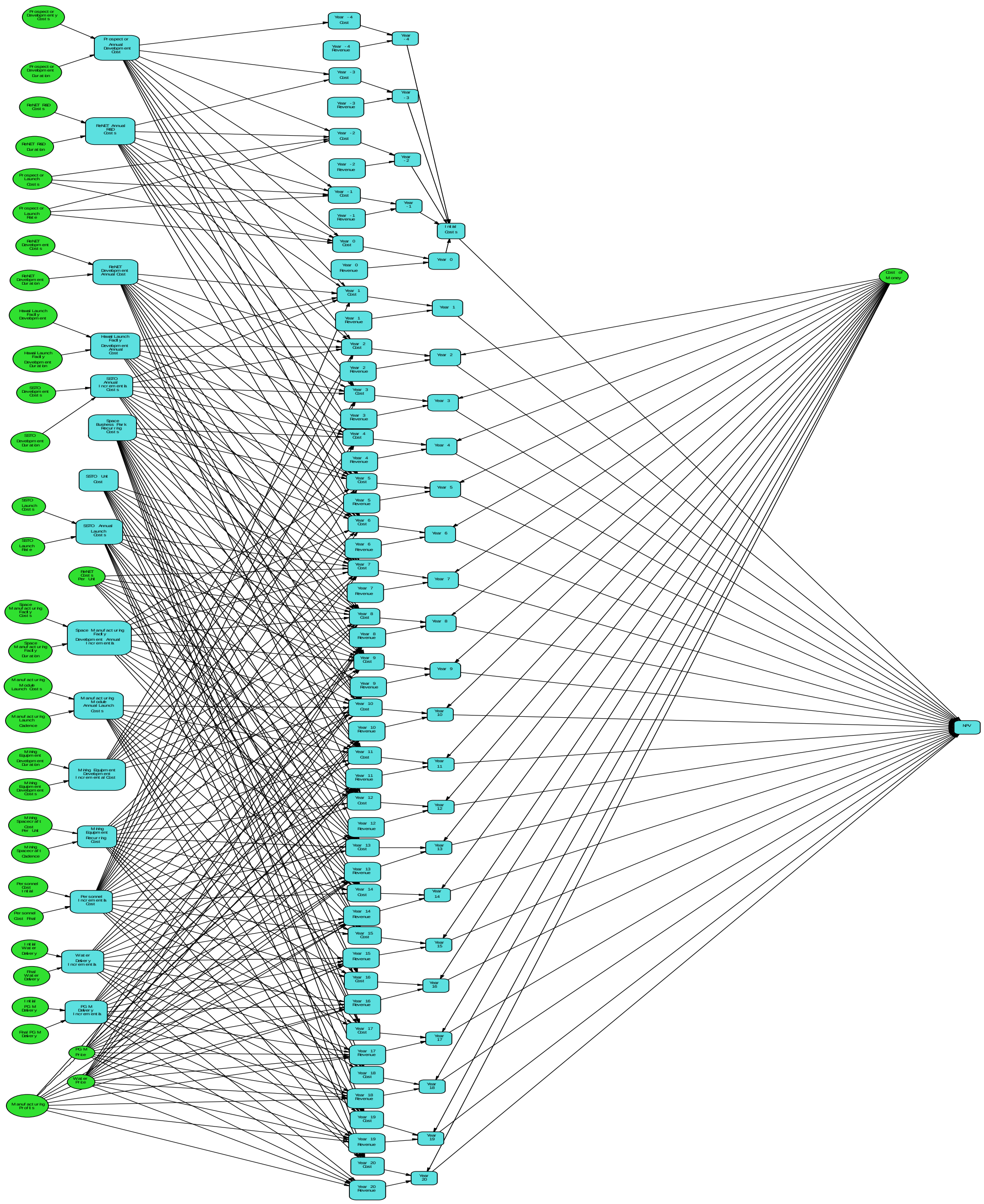

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Figure 7: DPL Model Example

This chart is unbiased, that is while it shows the variables in the business case and their relationship to the outcome, it lacks values that are verified by subject matter experts. The

Delphi survey provides these values and they are listed below, along with the ranges and mission profile estimates.

Variable		**Mission Profile Value**	**Delphi Variable Range Values**
	Min		$1,400,000,000
SSTO Development Cost	Nom	$1,800,000,000	$3,640,000,000
	Max		$10,000,000,000
	Min		6
SSTO Development Duration (years)	Nom	6	8
	Max		12
	Min		$9,500,000
SST0 Launch Cost	Nom	$9,500,000	$31,300,000
	Max		$50,000,000
	Min	26	12
SSTO Launch Rate (launches per year)	Nom		34
	Max	88	88
	Min		$150,000,000
Prospector Development Cost	Nom	$150,000,000	$540,000,000
	Max		$2,000,000,000
	Min		3
Prospector Development Duration (years)	Nom	3	5
	Max		10
	Min		$28,500,000
Prospector Launch Cost	Nom	$30,000,000	$44,000,000
	Max		$33,000,000
	Min		6
Prospector Launch Rate (launches per year)	Nom	6	8
	Max		18
	Min		$2,230,000,000

Hawaii Launch Facility Development	Nom	$2,230,000,000	$2,482,857,143
	Max		$4,000,000,000
	Min		5
Hawaii Launch Facility Development Duration (years)	Nom	5	6
	Max		10
	Min		$250,000,000
ReNET R&D Cost	Nom	$250,000,000	$625,000,000
	Max		$2,000,000,000
	Min		3
ReNET R&D Duration (years)	Nom	3	4
	Max		10
	Min		$2,900,000,000
ReNet Development Costs	Nom	$2,900,000,000	$3,057,142,857
	Max		$4,000,000,000
	Min		7
ReNet Development Duration (years)	Nom	7	8
	Max		13
	Min		$350,000,000
ReNet Cost per Unit	Nom	$350,000,000	$468,750,000
	Max		$1,000,000,000
	Min		$1,300,000,000
Space Manufacturing Facility Cost	Nom	$1,300,000,000	$4,187,500,000
	Max		$15,000,000,000
	Min		5
Space Manufacturing Facility Duration (years)	Nom	5	7
	Max		10
	Min	$125,000,000	$125,000,000

Manufacturing Module Launch Costs	Nom		$206,071,429
	Max	$285,000,000	$300,000,000
	Min	4	2
Manufacturing Module Launch Cadence (launches per year)	Nom		6
	Max	8	8
	Min		$1,500,000,000
Mining Equipment Development Cost	Nom	$2,530,000,000	$3,041,111,111
	Max		$7,590,000,000
	Min		4
Mining Equipment Development Duration (years)	Nom	6	6
	Max		8
	Min		$257,000,000
Mining Spacecraft Cost per Unit	Nom	$257,000,000	$292,000,000
	Max		$330,000,000
	Min		5
Personnel Requirement Initial (FTEs))	Nom	5	13
	Max		60
	Min		$1,500,000
Personnel Cost Initial	Nom	$1,500,000	$1,802,857
	Max		$3,600,000
	Min		100
Personnel Requirement Final (FTEs))	Nom	410	380
	Max		512
	Min		$30,000,000
Personnel Cost Final	Nom	$123,000,000	$118,571,429
	Max		$185,000,000
	Min		2
Initial Number of Mines (mines)	Nom	2	2

	Max		2
	Min		15
Final Number of Mines (mines)	Nom	37	34
	Max		37
	Min		56
Initial Water Delivery (metric tons per year)	Nom	75	72
	Max		75
	Min		549
Final Water Delivery (metric tons per year)	Nom	1463	1,332
	Max		1,463
	Min		15
Initial PGM Delivery (metric tons per year)	Nom	20	19
	Max		20
	Min		139
Final PGM Delivery (metric tons per year)	Nom	370	337
	Max		370
	Min		11
Max Delivery Ramp up	Nom	11	13
	Max		22
	Min		$500
PGM Price ($ per ounce)	Nom	$1,000	$906
	Max		$1,000
	Min		$186,2672,727
Manufacturing Profits	Nom		$2,069,636,364
	Max		$2,276,600,000

Table 2: Delphi Survey Values

As can be seen from the table, the variable values returned from the Delphi participants, in most cases, were substantially different from those specified by the mission profile. These values were loaded into the Decision Programming Language model and sensitivity tests were then run, as discussed in the next section.

Using the modeler, a base case Tornado diagram was generated, as shown in the following figure:

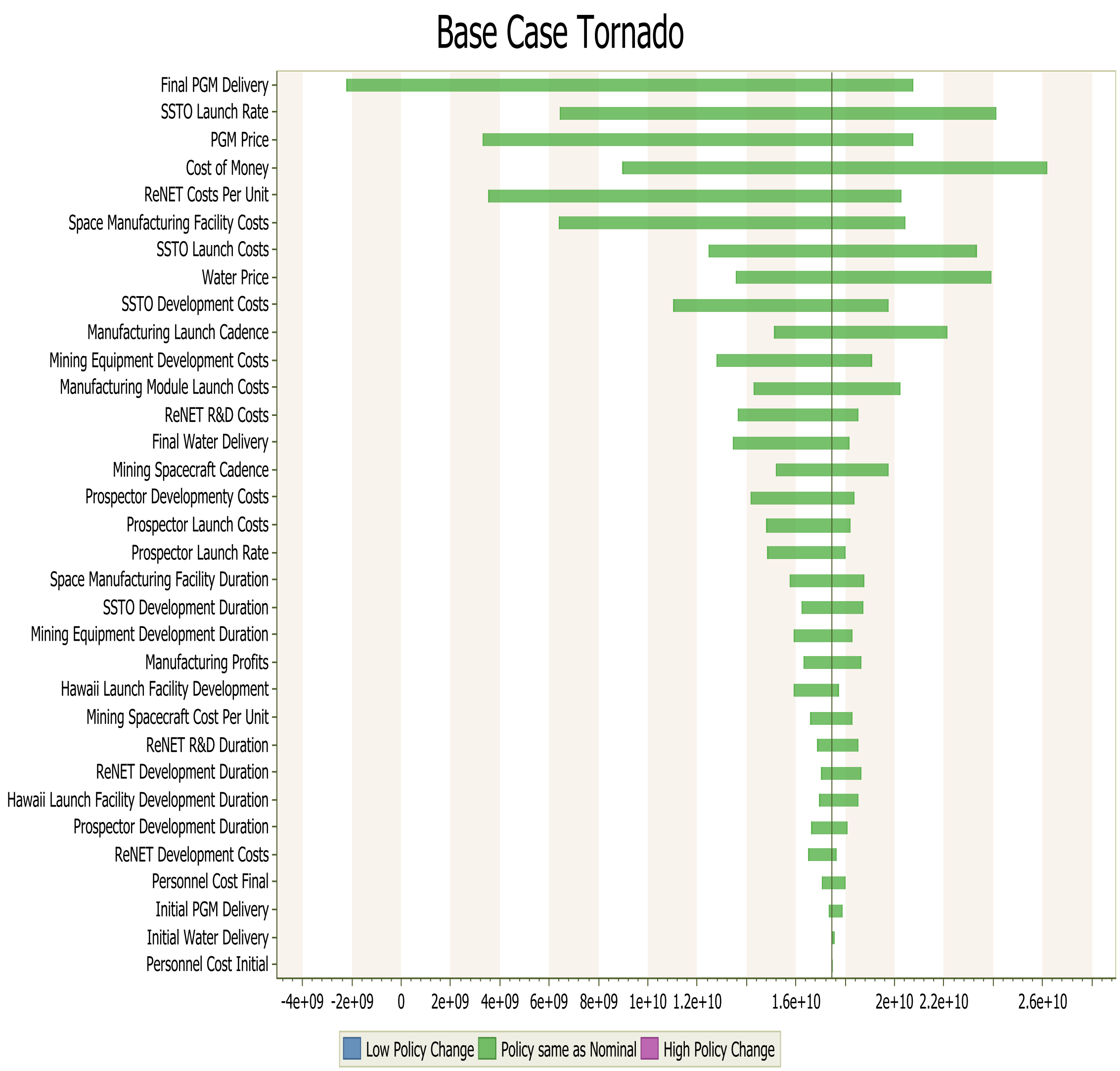

Figure 8: Base Case Tornado Diagram

As will be noted, the model indicates the most likely NPV value of the Tornado is approximately $17 billion. This compares favorably with the Andrews et al. (2015) of $14 billion over twenty years. However, this output does not consider the probability of an occurrence and simply weights all occurrences equally. When a weighted Tornado is run, that considers probability distributions of each variable, the run exceeds the capabilities of a desk top computer.

To reduce simulation times to a manageable level, the base Tornado is used to identify the variables with the minimum impact on the overall simulation. Each of these variables is then set to its nominal or mean value, as determine by the Delphi data, and the Tornado is run again to ascertain if it agrees with the base case. In the case of this model, the 14 lowest impact variables were set to their nominal value and the Tornado was rerun. Fourteen variables were selected because, at that point, the modeler was able to complete a run in a reasonable amount of time. The following Tornado is the result. As can be seen, the expected value is the same, but the variable list is greatly reduced. Although the expected value is the same, it is likely that the variability of the output has been impacted. Consequently, the outcome is slightly more uncertain that it would be including all the variables.

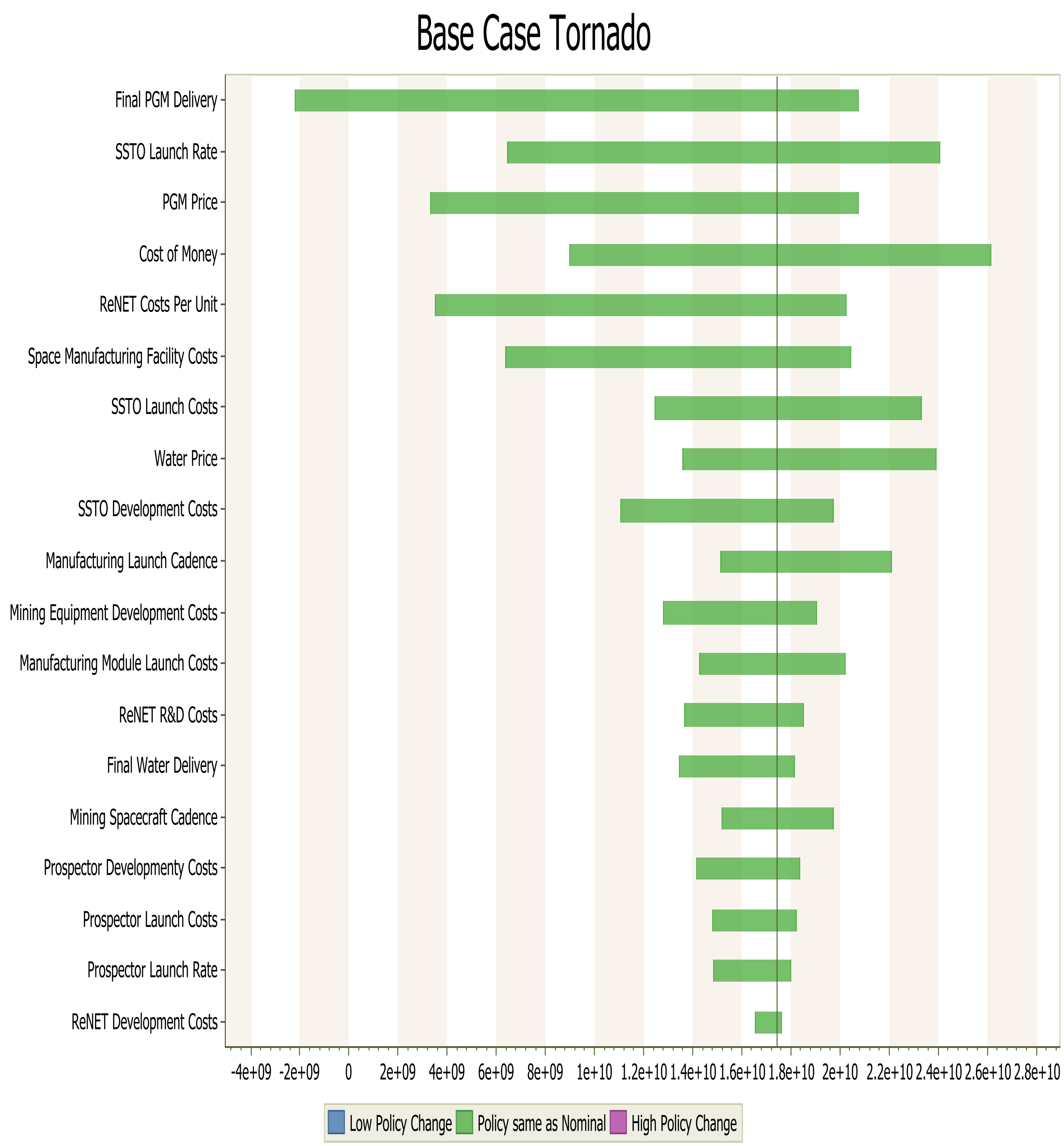

Figure 9: Reduced Variable Tornado Base Case

At this point, a Monte Carlo run is possible and was run. Even with a reduced variable set, the model required six days to run on a desk top computer. While a faster run is possible using a more powerful machine, this run was acceptable for the purposes of this analysis, since precision is not the objective; simply a demonstration of the utility of the technique. The following figure is the Monte Carlo output that resulted from the run.

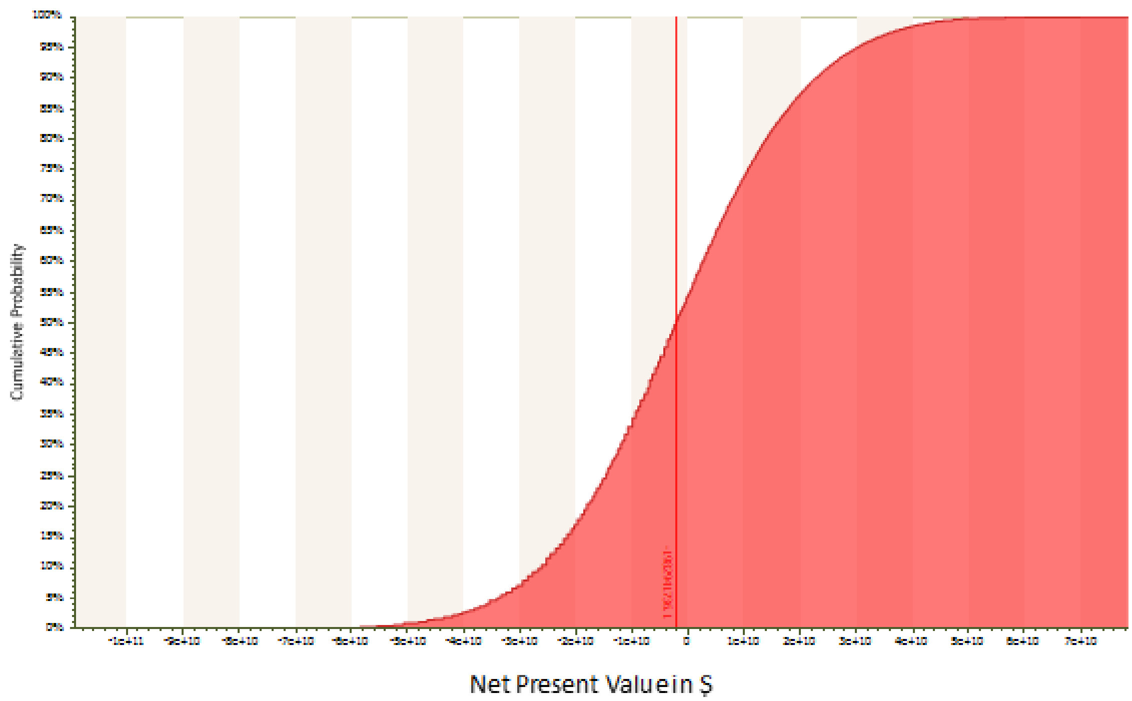

Figure 10: Monte Carlo Output

This chart is read as a cumulative probability. That is, a value is selected from along the X axis and the probability of achieving that value **or less** is read on the Y axis. This chart indicates that the most probable outcome at the 50% level is approximately negative $2 billion or less. In other words, when probability is considered, the twenty-year NPV for the Andrews, et al. (2015) mission profile is negative.

Although this cumulative probability chart is a useful way to imagine returns, another approach to displaying the outcome is to simply map the salient values to a Gaussian distribution. When that is done, the following chart is the result:

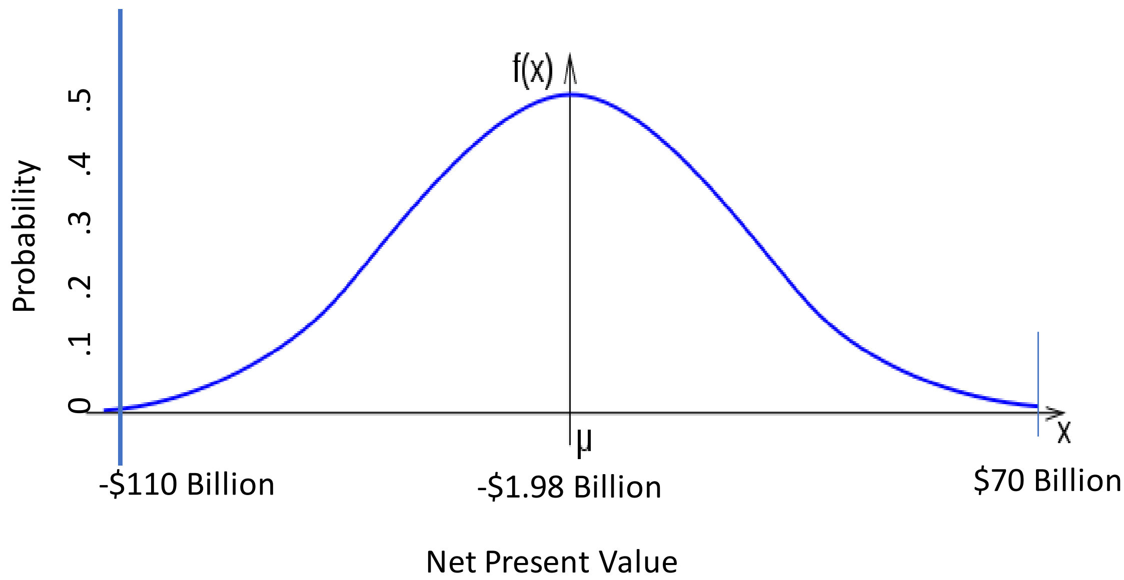

Figure 11: Monte Carlo as a Normal Distribution

Two things to note here are that the distribution is not really normal, it is weighted to the negative and second, the potential for very positive and very negative values only occurs at very unlikely levels of probability. As a result, when looking at the most probable range of values, as well be done below, the range will be less extreme. Yet, the mean value is negative, denoting the possibility of a risky venture.

A negative NPV on a Monte Carlo simulation does not necessarily mean that a positive NPV is not possible. Taking the Monte Carlo simulation and merging it with a Tornado run, gives us the following figure and shows the amount that each variable contributes to the Monte Carlo outcome within the plus or minus 3 sigma range. (This run took four days on a desk top computer.)

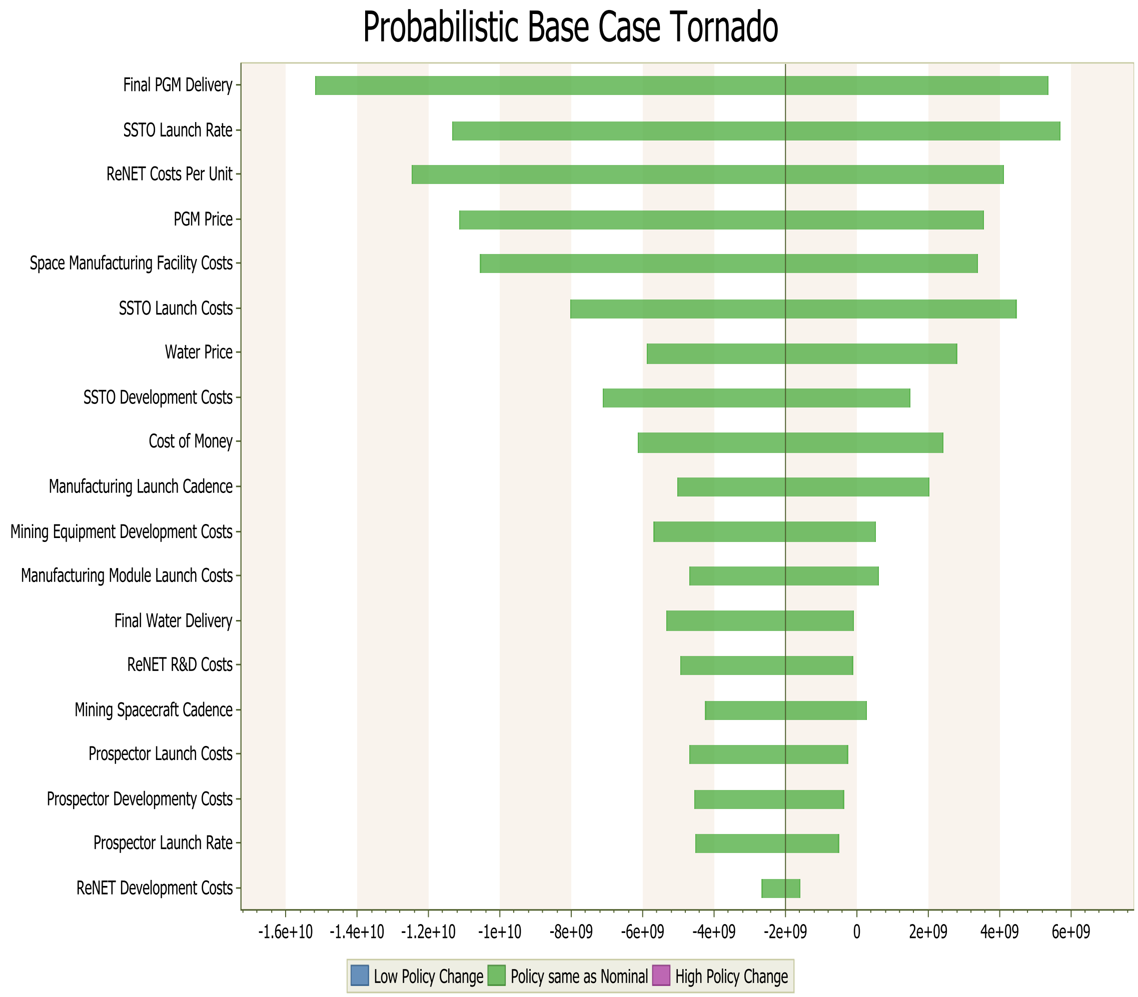

Figure 12: Probabilistic Base Case Tornado Diagram

As can be seen in this figure, the final PGM delivery has the most impact on the NPV, followed by SSTO launch rates, the unit cost for a ReNET, and PGM price. This means that if these variables can be held to values that are on the optimistic side of estimates, it is possible to achieve a positive twenty-year NPV. In other words, the following conditions would need to be met:

Variable	Andrews et al. (2015) Value	Model Optimistic Value
PGM Delivery Final	370 metric tons	370 metric tons
SSTO Launch Rate	88 per year	88 per year
Unit Cost for ReNET	$350 million	$350 million
PGM Price	$1000 an ounce	$1000 an ounce

Table 3: Required Variable Values for a Positive NPV

In each case, the value that the mission profile business case proposes is at the upper limit of the Monte Carlo analysis. In other words, if Andrews et al. (2015) miscalculated these variables, the NPV will go negative. It must be noted that while three of these variables are ostensibly under the control of the mining project, one is not. This is the price that PGMs can demand in the market, once delivered.

As noted in the literature review, this price is virtually impossible to predict; especially twenty years in the future. If the price of PGMs declines, especially in the presence of space derived material, then delivery rates would need to be increased or other costs reduced for the business case to remain viable. Since, in the case of delivery rates, the Delphi consensus is that the mission profile projected amount is optimistic, a reduction in PGM price could indicate a risk factor for which it is impossible to compensate.

Assessing the Hypotheses

As noted in the introduction, the purpose of this research was to test the following two hypotheses:

Hypothesis 1: Space mining is economically viable, and

Hypothesis 2: Space mining is risky.

In terms of Hypothesis 1, the Monte Carlo simulation shows that, at least for the business case proposed by the mission profile business case, it can be. Over a twenty-year time-period the model shows that NPVs can range from a minimum of negative $16 billion to a high of $6 billion. This is short of the $14 billion estimate that Andrews et al. (2015) anticipate, but it still includes NPVs that may seem acceptable to investors. So, since the null hypothesis is disproven and Hypothesis 1 is supported, it is appropriate to look at Hypothesis 2.

However, it is with Hypothesis 2 that a more precise answer to economic viability lays. As noted above, the most probable outcome is a negative NPV of $2 billion with the possible potentially ruinous value of negative $16 billion. The bottom line is that this venture would have to be considered very risky and, to show a positive return, several variables must conform to optimistic estimates.

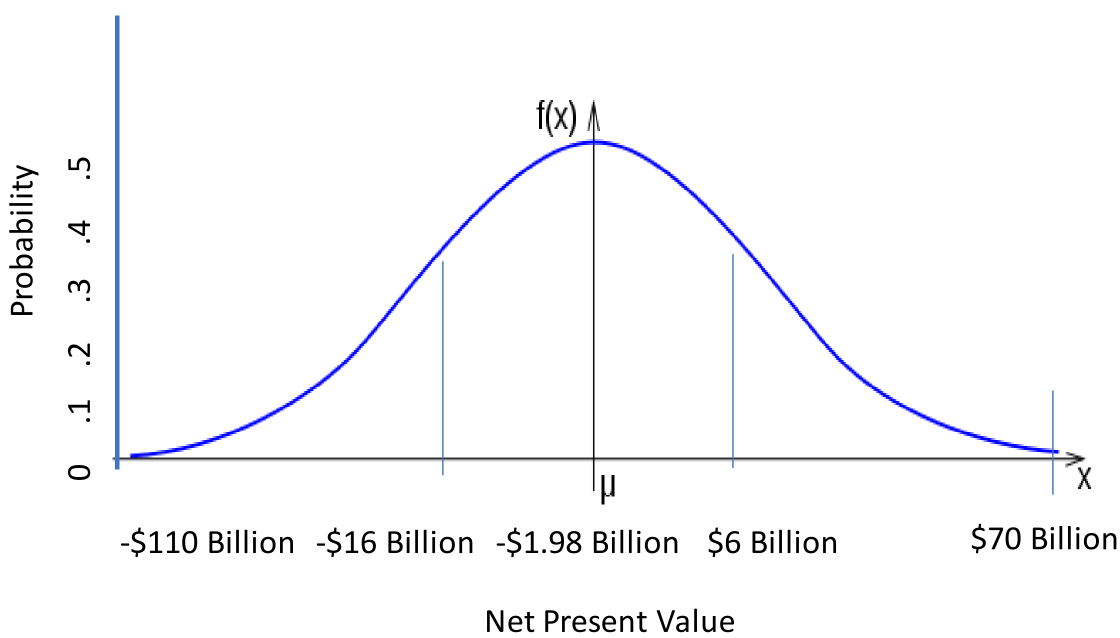

Figure 13: Distribution of Outcomes

In terms of assigning a risk factor to the space mining endeavor, it is possible to compare the expected outcomes from the Andrews et al. (2015) analysis to the expected outcomes from the Monte Carlo analysis. At a most probable level, the difference is between $6 billion and negative $16 billion. That is a delta of over $24 billion; or in other words, the magnitude of the range of potential outcomes is greater than the absolute value of $14 billion expected by the business case. Additionally, looking at the probability distribution in Figure 10, it is possible to say that the probability of an NPV less than 0 is 55%; consequently, a risky venture.

CHAPTER 5: CONCLUSIONS

This research set out to test the notion that decision modeling using a decision model with Monte Carlo simulations could be used to assess the risk involved in a space mining venture. Space mining, by its very nature, is uncertain: after all, no one has done space mining to date. Initial results indicate that such an approach can be useful in determining the risk involved in ventures for which there are no widely agreed upon solutions such as space mining.

Although this analysis ultimately concluded that the Andrews et al. (2015) approach is a risky proposition, it also identified the primary variables that drive such risk. The viability of the project depends on their mining venture’s ability to deliver the projected amounts of PGM material to Earth, as well as their ability to deliver new spacecraft technology for a reasonable price.

One factor for which the mining project has no direct control is the price for which PGM materials can be sold once delivered. As noted in the analysis, a dramatic decline in the price for PGMs could ultimately render any ameliorative actions on the part of the space mining venture moot. One could suppose a scenario, however, where the mining company was able to manipulate the price of PGM materials through selective withholding of those materials—as in the case of diamond mining, for example—however it is likely that a space mining venture would be sufficiently high profile that any success it had returning materials to the Earth would be well known and therefore would be factored into the market price. In any case, such a strategy would, of necessity, extend the timeline for the entire project and would delay any financial return; perhaps to an unacceptable duration.

One aspect of the Delphi that was not taken into consideration for the modeling exercise was the commentary that the Delphi respondents provided on such aspects of the business case as the ability to develop technology and the impact of regulatory constraints. One example is the dependence of the SSTO on an inflatable heat shield. One respondent noted that such technology might not be viable in such an application.

Another comment had to do with the design of the SSTO itself. The assumption in the Andrews et al. (2015) business case is that the liquid oxygen and liquid hydrogen tanks could share a common bulkhead. One respondent pointed out that this design would be very complex and subject to catastrophic failure since the two liquids are stored at a very different temperature, thus imposing a severe temperature differential across the bulkhead. It is by no means certain, the respondent pointed out, that material science could deliver such a bulkhead.

Additionally, most of the respondents expressed skepticism on the ability to build or orbit a ReNET spacecraft. Since the spacecraft design depends on a fission reactor, the likelihood of obtaining permission from the various regulatory authorities was doubted. Although there are different technologies that could be used in place of a reactor—solar electric, for example—currently this business case depends on the relatively high thrust that such a nuclear driven rocket could provide. Once again, this is a source of risk that the model did not factor, but which might render the entire enterprise questionable.

This exploration into assessing risk cannot be considered to be complete, but instead must be evaluated as pointing the way towards new approaches to assessing risk in space mining. Considerable work is required to make such an approach reliable enough to utilize in the business setting. However, to identify likely causes of risk, with the aim of mitigating them, this approach can provide a first pass for any company or its investors to evaluate its plans for mining space-derived material.

Finally, it bears noting that while this approach seeks to define risk as a probability of a desired outcome not happening, it says nothing about the subjective assessment of risk. What would be considered very risky to one person, may not be risky at all to another. It is true that, in space exploration generally, risk factors have been considered acceptable that would be considered completely unacceptable in other areas of endeavor: for example, while the space shuttle program had a relatively acceptable rate of failure, it still managed to have two significant failures that led to the loss of two crews. This level of failure in a commercial airline would effectively shut down civilian air travel. Just so in space mining. Although this analysis indicates a 55% chance of losing $2 billion or more over 20 years, it still indicates that rather substantial gains could be made if things turn out well. A person who is risk averse would focus on the loss side, while a risk tolerant person would focus on the optimistic side.

So, this analysis will not tell one that a space mining venture should not take place, merely that, if one chooses to pursue such a venture, that there is a possibility of substantial loss. The point is not to dissuade an investor; just to ensure that such an investor is well informed.

Recommendations for Further Research

As noted in the introduction to this paper, this exploration into risk and asteroid mining is, by its very nature, preliminary. Utilizing a previously developed business case contributes to uncertainty since the underlaying research and rationale for the various business case components is not available. Beginning from first principles would likely provide better insights into the true variability of each of the factors upon which the business case is founded.

Additionally, because this paper was a result of an academic investigation, rather than a true business analysis, limitations of time, budget and access to subject matter experts tend to limit the comprehensiveness of the analysis that could be conducted. The author suggests that a more extensive follow on study be conducted where, rather than depending on a small Delphi panel, variable definition and bounding be conducted using a conventional survey with a sample size that enables statistical certainty.

It also bears noting that this analysis is simply a snap shot in time. Space science is rapidly changing, and this approach only examines the viability of space mining using the data and technology currently available. It is entirely possible that this same analysis run in six months or a year might produce entirely different results. Although the model that this research utilized can certainly be updated periodically, a more rigorous approach that provides a way to modify the business case on a routing basis, which then automatically updates the risk analysis might be a more productive approach; especially for a business that is assessing the possibility of engaging in space mining. Such an approach, while useful, is well beyond the scope of this study, but might suggest a fruitful idea for future analysis.

While decision modeling and Monte Carlo analysis is one way to approach risk assessment, as the literature review notes, it is by no means the only way. A profitable approach to further research might involve utilizing several approaches to assessing risk and then comparing the results: in a sense using triangulation to approach a true risk assessment.

Finally, it bears noting that the author is quite supportive of asteroid mining and believes that such an endeavor is a worthwhile goal of space industry. The fact that this is a risky business should not be a surprise: after all, it has never been done. However, engaging in a business venture without a true appreciation of risk is not conducive to positive outcomes. Even very risky ventures find investors after all, but ventures run into problems when they over promise and under deliver: attracting early investors who may expect a substantial return in the short term, but who are ultimately disappointed when returns are less than they desired. Businesses that attract the wrong kinds of investors typically founder when expectations are abused. Better to have investors who are well informed and who have a good appreciation of the business' risk dynamics. Hopefully, this paper suggests a way that risk can be assessed and explained to potential investors in such a way that the business starts on a realistic footing that ultimately yields a successful outcome.

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APPENDIX A: SURVEY INSTRUMENT

Introduction: Asteroid mining has become a topic of interest in space sciences. Several companies have begun to develop the capability to detect, explore and mine asteroids to extract valuable minerals and other materials to enable both deep space exploration as well as provide new sources of raw materials to Earth-based markets. To date, financial models for space mining enterprises have been somewhat superficial and have not included any detailed risk assessment. This survey is part of an attempt to assess risk in the context of space mining.

Nature of Survey: This survey uses an approach called a Delphi, which has proven to be very accurate in a variety of fields. The approach is to poll a panel of subject matter experts on their opinions on a specific topic; in this case, asteroid mining. Responses are returned in writing and a summary of all the responses is prepared.

The summary, with personally identifying information removed, is provided to the panel and each respondent is asked to provide any modifications to the original response that, upon reflection and review of the other panel member's responses, seems warranted. When the final responses are returned, once again in writing, a final summary is prepared and returned to the panel for their use.

The results of this survey will be used to develop a general survey to assess costs and risks associated with asteroid mining ventures.

Timeframe: This research is being performed as part of a research project to support a Master's Thesis at the University of North Dakota. Therefore, it is constrained by the academic calendar and so timely responses are desired. Please plan to return your comments no later than two weeks after receipt of the survey. All comments will be edited for grammar and spelling prior to summarization and return, so there is no need to be careful about the construction; your opinion is what matters.

Privacy: All participants will remain anonymous to the other panel members. Review of first round responses is conducted to ensure that all points of view are considered by each participant, not to promote a debate.

Questions or Concerns: If any portion of the survey is unclear or there are questions as to intent, please contact the researcher by phone at 303 466 2377 or by email at: mjude@soropro.com. If your need is immediate, you can also contact the academic supervisor for this research, Dr. James Casler, 701-777-3462, casler@space.edu. Thank you for your participation.

Scenario: This survey depends on a model for asteroid mining developed by Andrews et al. (2015) (paper attached) as an exercise for a graduate level space science course. The basic mission profile calls for developing and launching prospector space craft to search for asteroids with a significant mass fraction of platinum group metals (PGM). Next a single stage to orbit (SSTO space craft will be developed to transport space craft components into low Earth Orbit; a nuclear-powered tug will be developed to transport mining equipment to the asteroid and processed material back from it; and a mining and processing spacecraft will be developed to mine material on the asteroid. Once everything is in place, PGMs will be delivered to Earth and volatiles like water will be delivered to low Earth orbit (LEO).

Survey process: In the following questions, each component is presented to the survey respondent and an assessment is asked for. In each case, the Andrews et al (2015) description is provided along with their estimate of total unit cost. For each example, please provide your estimate of the cost as a range of values (example: $5 million to $10 million) as well as some narrative on why you chose this value. In each case, please be as concise as possible and note that your responses will be shared with other respondents (although the sources of the responses will be kept confidential).

Space Mining Survey:

Question 1: Andrews et al. (2015) believes that to support building the necessary space based infrastructure a Single Stage to Orbit (SSTO) launch vehicle must be developed. This vehicle depends on a combination of proven technology (rocket engines) and advanced materials including a new inflatable heat shield. The Andrews et al. business case assumes that such a vehicle could be developed and tested for $1.8 billion in 2010 dollars over a period of six years. Please specify what you think the appropriate cost and development ranges are and why:

Answer:

Question 2: Andrews et al. (2015) estimates that the launch costs (operations and recurring costs) for this SSTO would be approximately $9.5 million at an initial launch cadence of 26 launches per year, topping out at 88 launches per year. Please specify what you think the appropriate cost and cadence ranges are and why:

Answer:

Question 3: Andrews et al. (2015) believes that the first step to mining asteroids is to develop prospector spacecraft capable of sampling NEO asteroids. They estimate that this development would take three years and $150 million. Please specify what you think the appropriate cost and development time ranges are and why:

Answer:

Question 4: Andrews et al. (2015) believe that prospector spacecraft can be launched for $30 million per launch using a conventional launch vehicle at an initial cadence of six per year. Please specify what you think a reasonable launch cost and cadence would be and why:

Answer:

Question 5: Andrews et al. (2015) believes that a new launch facility will be required in Hawaii and will be developed for $2.23 billion over a period of five years. Please specify what you think a reasonable cost and construction duration would be and why:

Answer:

Question 5: To transport mining equipment to an asteroid and return mined material from an asteroid, Andrews et al. (2015) proposes the development of a REusable Nuclear Electric Tug (ReNET). They estimate that research and development for such a vehicle could be completed in three years at a total cost of $250 million. Please specify what you believe would be a reasonable R&D value, R&D duration and why:

Answer:

Question 6: Andrews et al. (2015) estimates it would require seven years and a total cost of $2.9 billion to design, develop, test and build a ReNET. Please specify what you believe would be a reasonable cost to produce such a vehicle and your reasons why:

Answer:

Question 7: Andrews et al. (2015) believe that each ReNET could be built for $350 million. What do you believe a reasonable unit cost for such a vehicle and explain why:

Answer:

Question 8: Andrews et al. (2015) propose that a space manufacturing facility be developed and estimate such development would take five years and $1.3 billion. Please specify what you believe to be a reasonable cost to deploy such a facility and how long such a deployment would take:

Answer:

Question 9: Andrews et al. (2015) believe that such a space manufacturing facility could be supported with four processing module launches per year, increasing to eight launches at an initial cost of $125 million, topping out at $285 million. Please specify what you believe a reasonable launch cadence and launch costs to be and why:

Answer:

Question 10: Andrews et al. (2015) believe that asteroid mining equipment can be developed for $2.53 billion over a period of six years. Please specify what you would consider to be a reasonable cost to develop, test and build such equipment and how long such efforts would take:

Answer:

Question 11: Andrews et al. (2015) believe a mining spacecraft could be built for $257 million. What would you consider to be a reasonable cost to produce such a spacecraft and why:

Answer:

Question 12: Andrews et al. (2015) believe that initially operations could be supported by five people at a total cost of $1.5 million, ultimately growing to 410 people at a total cost of $123 million. What would you consider to be a reasonable number of people to support a space mining operation and why?

Answer:

Question 13: Andrews et al. (2015) believe that a mining operation that begins with two asteroid mines, growing to 37 could initially deliver 75 metric tons of water per year back to low Earth orbit, increasing to 1463 metric tons per year, after 11 years. What do you believe a reasonable amount of water would be, why?

Answer:

Question 14: Andrews et al. (2015) believe that a mining operation that begins with two asteroid mines, growing to 37 could initially deliver 20 metric tons of platinum group metals back to Earth, growing to 370 tons per year, after 11 years. What do you believe a reasonable amount of platinum would be, why?

Answer:

Question 15: Currently the world production of platinum is approximately 170 metric tons per year. The price per ounce is approximately $1000. Do you believe that this price will remain constant in the presence of space-derived platinum: remember that Andrews et al. (2015) estimate delivering 370 metric tons of platinum per year at full production? If not, what do you believe a reasonable price for platinum would be when space-derived platinum is delivered to the market? Why?

Answer:

APPENDIX B: INFORMED CONSENT FORM

UNIVERSITY OF NORTH DAKOTA

Institutional Review Board

Informed Consent Statement

Title of Project: **Risk Assessment of Space Mining Ventures using Monte Carlo Simulation**

Principal Investigator: *Mike Jude, 303-466 2377, mjude@soropro.com*

Co-Investigator(s):

Advisor: *Dr. James Casler, 701-777-3462, casler@space.edu*

Purpose of the Study:
The purpose of this research study is determine if a numerical decision model using Monte Carlo simulation techniques can be used to assess the risk inherent in a space mining venture.

Procedures to be followed:
You will be given a 15 question survey where you will be asked to express your opinion on the reasonableness of various cost components of a space mining proposal. For each you also be asked to state what you believe a reasonable range of cost values would be. Once you and each of the other respondents have provided answers, your responses will be summarized and edited for brevity and then you will be asked to look at all the summarized responses, after which you will then be given an opportunity to change your responses based on what other respondents have said.
Risks:
There are no risks in participating in this research beyond those experienced in everyday life.

Benefits:

- You will be helping to develop a new technique for assessing business risk, which you may be interested in applying to your business decisions in the future.
- You will receive a copy of the final report which you can use as you wish within your business or academic pursuits.

Duration:
The survey and follow on review should take no more than one hour total.

Statement of Confidentiality:

The survey does not ask for personal information and no personal information, aside from that necessary to contact you by email, will be maintained as part of the project documentation. All personally identifiable information will be removed from any responses you provide.

All survey responses that we receive will be treated confidentially and stored on a secure server. However, given that the surveys can be completed from any computer (e.g., personal, work, school), we are unable to guarantee the security of the computer on which you choose to enter your responses. As a participant in our study, we want you to be aware that certain "key logging" software programs exist that can be used to track or capture data that you enter and/or websites that you visit.

Right to Ask Questions:
The researcher conducting this study is Mike Jude. You may ask any questions you have now. If you later have questions, concerns, or complaints about the research please contact Mike Jude at 303 466 2377 or Dr. James Casler at 701-777-3462 during the day.

If you have questions regarding your rights as a research subject, you may contact The University of North Dakota Institutional Review Board at (701) 777-4279. You may also call this number with problems, complaints, or concerns about the research. Please call this number if you cannot reach research staff, or you wish to talk with someone who is an informed individual who is independent of the research team.

General information about being a research subject can be found on the Institutional Review Board website "Information for Research Participants" http://und.edu/research/resources/human-subjects/research-participants.cfm

Compensation:
You will not receive compensation for your participation. You will, however, receive a copy of the completed thesis.

Voluntary Participation:
You do not have to participate in this research. You can stop your participation at any time. You may refuse to participate or choose to discontinue participation at any time without losing any benefits to which you are otherwise entitled.

You do not have to answer any questions you do not want to answer.

You must be 18 years of age older to consent to participate in this research study.

Completion and return of the survey implies that you have read the information in this form and consent to participate in the research.

Please keep this form for your records or future reference.

APPENDIX C: ANDREWS ET AL. (2015) BUSINESS CASE

Years after go-ahead	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
NEO architecture/prospector DDT&E ($M)	40	80	30																						
Prospectors Launched			6	6	3																				
Prospector recurring cost ($M)			180	180	90																				
Space Business Park DDT&E ($M)						50	100	200	120	50															
Space Business Park recurring ($M)									20	60	100	100	80	60	60	40	40	40	40	40	40	40	40	40	40
SSTO DDT&E ($M) 5 of 15 amortized						120	300	500	500	300	100														
New Launch Base [Hawaii]						150	600	1000	400	80															
Number of SSTO launches												26	50	50	57	56	56	58	61	8	88	8	8	8	8
SSTOs delivered year												1	1	1	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0	0	0
SSTO recurring costs (ave rest for 15=$580.62 M)												574	574	574	144	144	144	144	144	144	144	144	0	0	0
SSTO launch costs ($M)												248	477	544	534.2	534.2	553.3	582	76.32	76.32	76.32	76.32	76.32	76.32	76.32
ReNET R&D Costs ($M)		50	120	120	30																				
ReNET DDT&E costs ($M)						50	300	700	1150	700	300	150													
ReNET delivered year												4	5	5	6	5	5	5	6	0	0	0	0	0	0
ReNET inventory on orbit												4	9	14	20	25	30	35	41	41	41	41	41	41	41
ReNET recurring costs ($M) (TFU=$350M)												1134	1253	1172	1332	1079	1044	1019	1194	0	0	0	0	0	0
Space manufacturing DDT&E ($M)										100	300	500	300	100											
Space manufacturing launches										0	0	0	0	0	4	6	6	8	8	8	8	8	8	8	8
Space manufacturing recurring costs ($M) (TFU=$125M)										0	0	0	0	0	125	293.6	273.4	342.7	328	317.1	308.4	301.1	295.2	290	285.4
SM modules on orbit															2	5	8	12	16	20	24	28	32	36	40
Manufacturing Profits ($M)															204	510	836	1224	1632	2040	2448	2856	3264	3672	4080
Mining equipment DDT&E ($M)							80	150	400	1100	600	200													
Mining equipment recurring costs ($M) (TFU=$257M)												462.6	956	880.8	835	803.2	778.6	758.8	742	0	0	0	0	0	0
Operation cost MY/yr						5	10	15	20	25	30	60	110	160	210	260	310	360	410	410	410	410	410	410	410
Operations cost ($M)						1.5	3	4.5	6	7.5	9	18	33	48	63	78	93	123	123	123	123	123	123	123	123
Mines delivered into operation												2	5	5	5	5	5	5	5						
Average working mines each year												2	7	12	17	22	27	32	37	37	37	37	37	37	37
Water back to LEO SOC (mT)														75	263	450	675		1050	1238	1463	1461	1463	1463	1463
PGM product back to Earth (mT/year)												0	0	20	70	120	170	220	270	320	370	370	370	370	370
Investment yearly totals, 2010 $M	40	130	260	300	120	251.5	783	1555	2196	2443	1659	3512	3798	3457	3328	3091	2906	2966	3153	700	691.3	684.2	534.6	529.3	524.7
Profits yearly, 2010$M						0	0	0	0	0	0	0	14	573	2154	3828	5971	7842	10212	12183	14176	14784	15392	15800	16208
Net Cash Flow, 2010$M						-251.5	-783	-1555	-2196	-2443	-1659	-3512	-3784	-2884	-1174	737	3065	4876	7059	11483	13484.7	14099.8	14857.4	15270.7	15683.3
Cumulative cash flow, 2010$M						-251.5	-1035	-2338	-3751	-4639	-4102	-5171	-7296	-6668	-4058	-437	3802	7940	11935	18541	24967	27583	28956	30127	30953
NPV ($M) 20 year NPV						$14,364																			
ROI						34.67%																			
Nondiscounted 20 year ROI						227%																			
Yearly mine PGM product (mT)			10																						
ReNET water return trip (mT)			150																						

APPENDIX D: DECISION MODEL DETAIL

The following diagrams show the variable level detail for the business case decision model. Although all the connection areas are not shown, the ranges for each are specified.

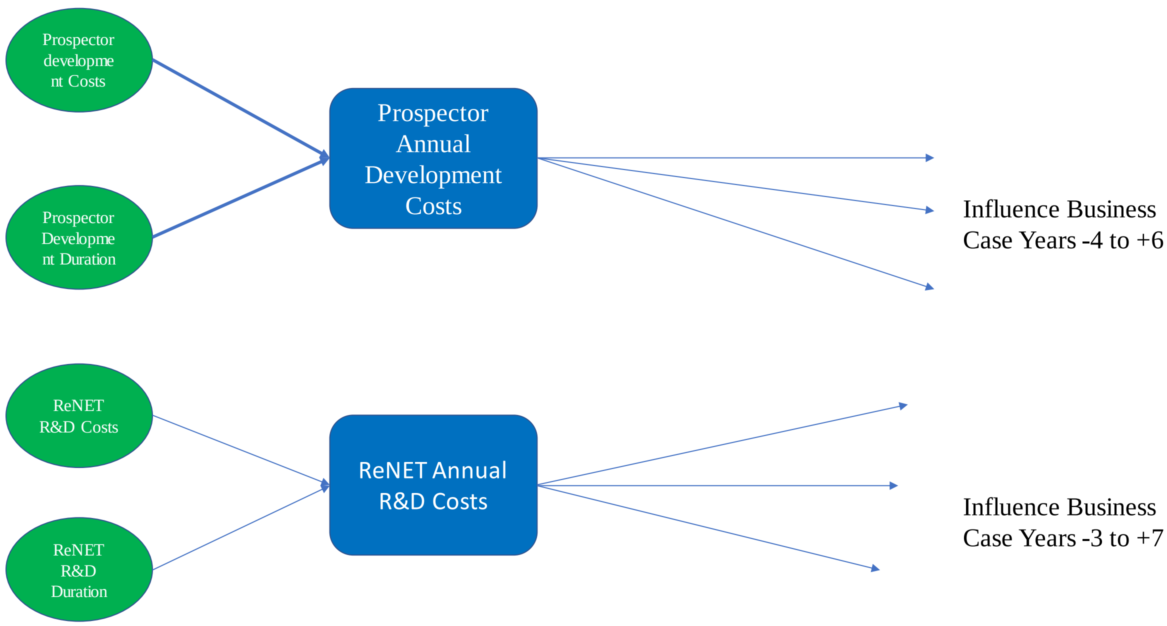

Figure 14 Decision Model Sub-section 1

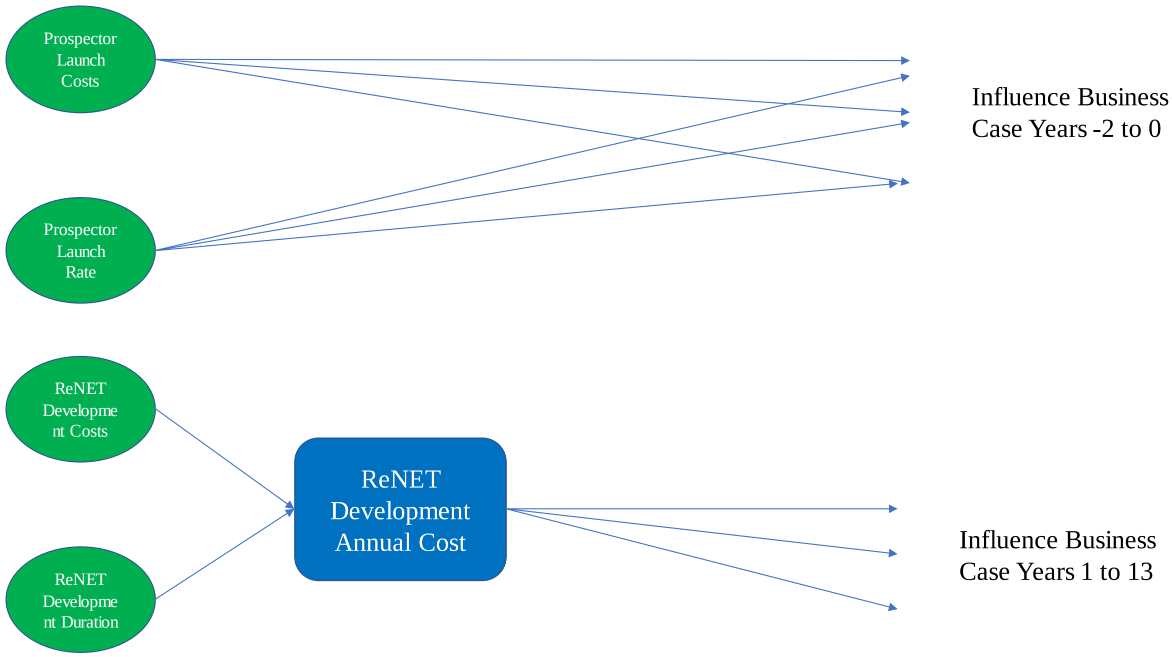

Figure 15 Decision Model Sub-section 2

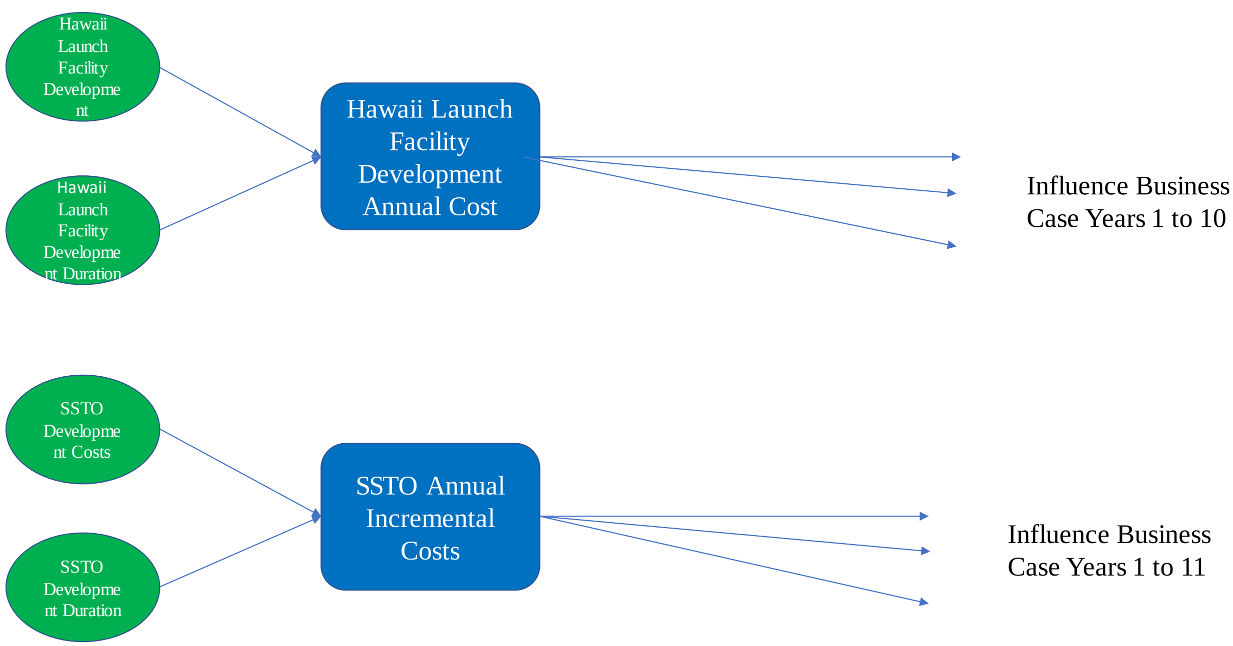

Figure 16 Decision Model Sub-section 3

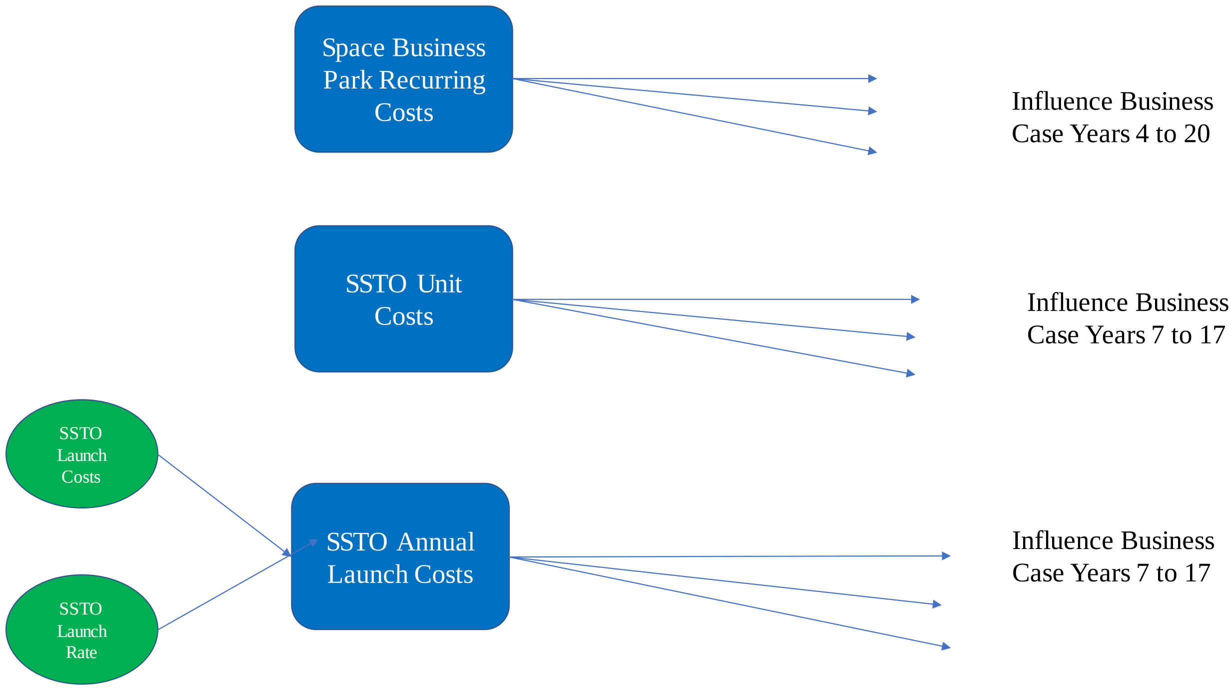

Figure 17 Decision Model Sub-section 4

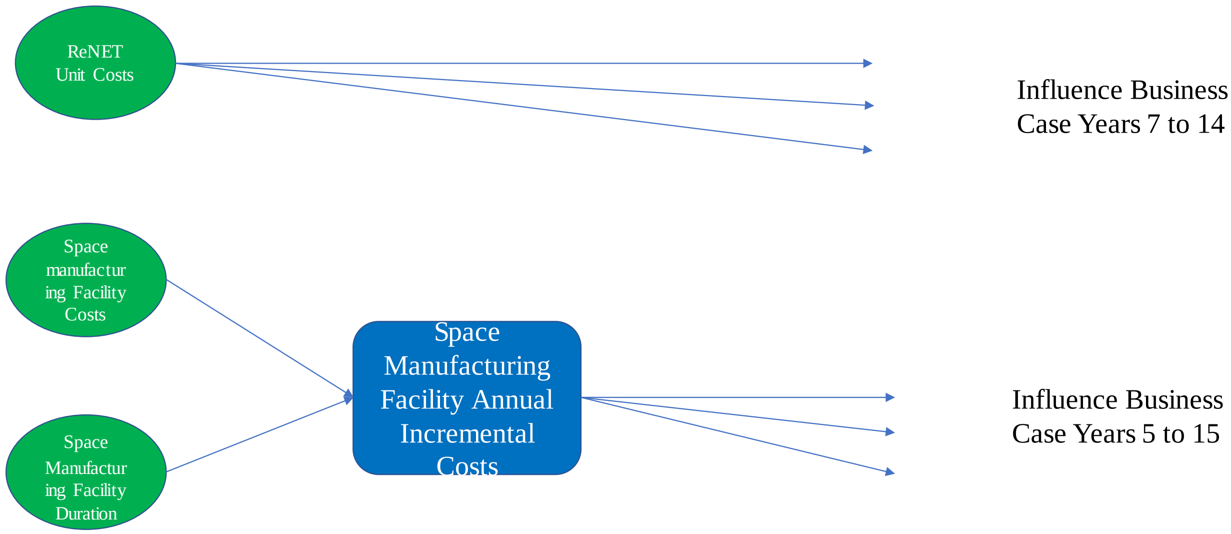

Figure 18 Decision Model Sub-section 5

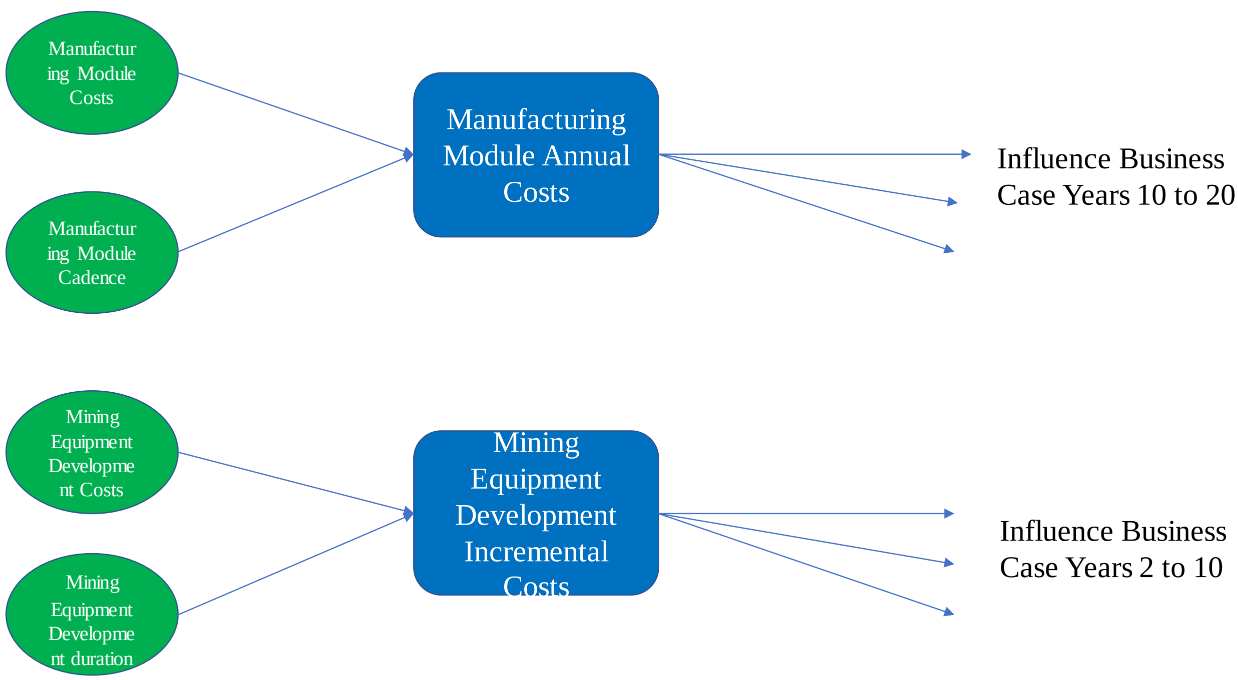

Figure 19 Decision Model Sub-section 6

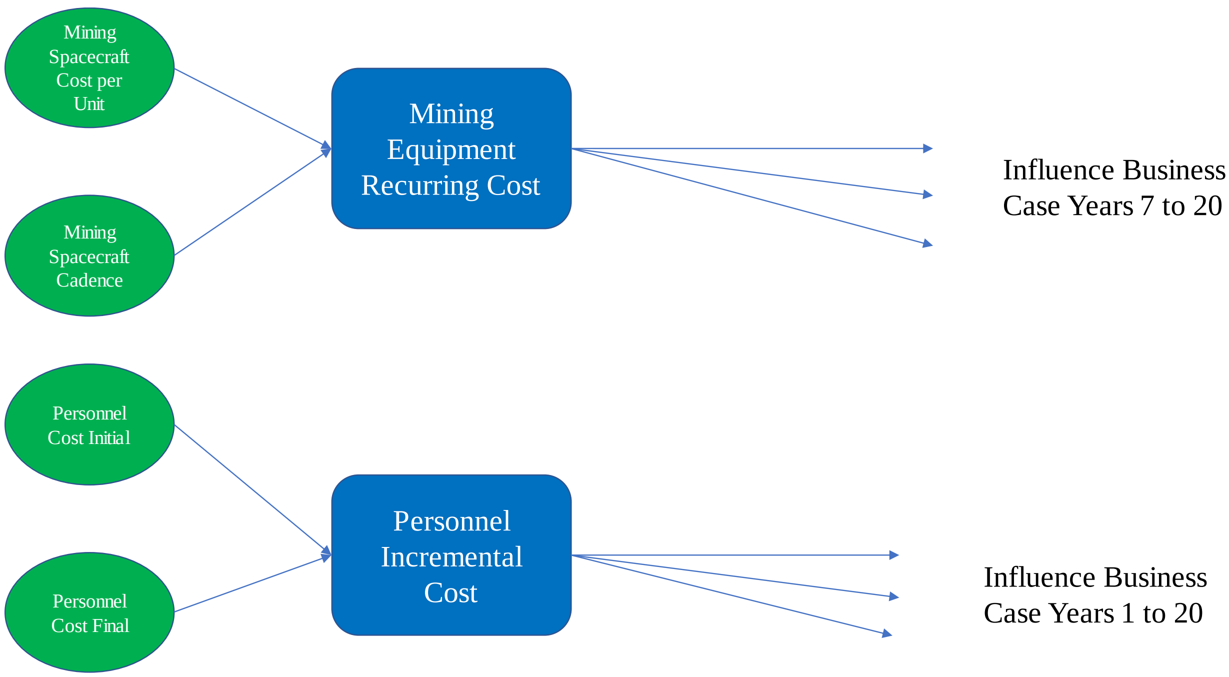

Figure 20 Decision Model Sub-section 7

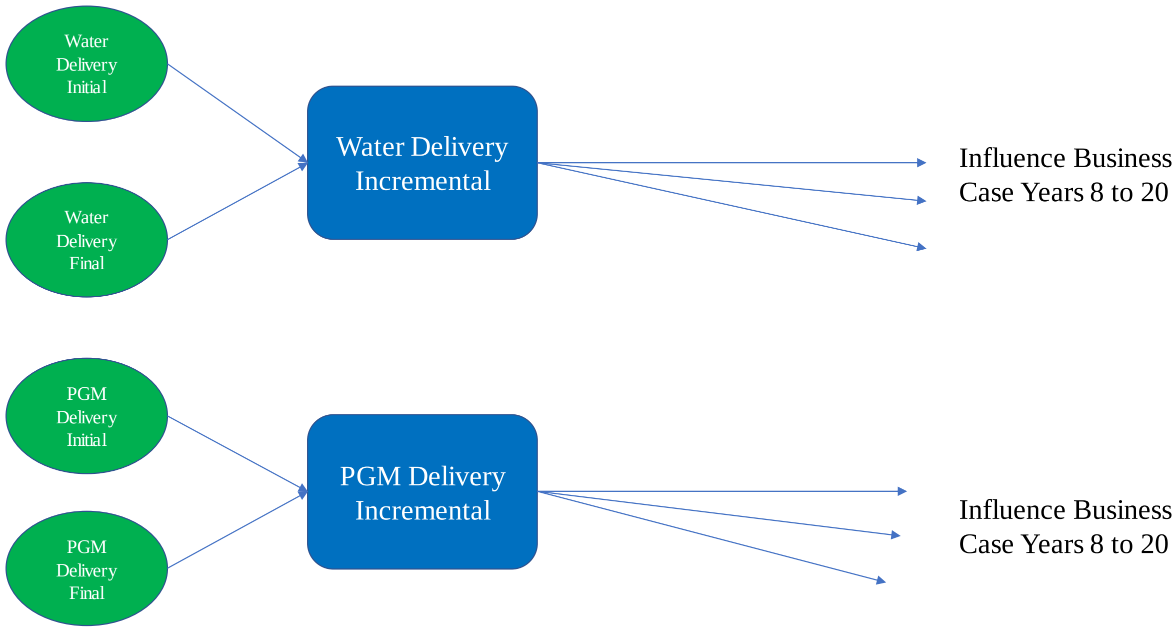

Figure 21 Decision Model Sub-section 8

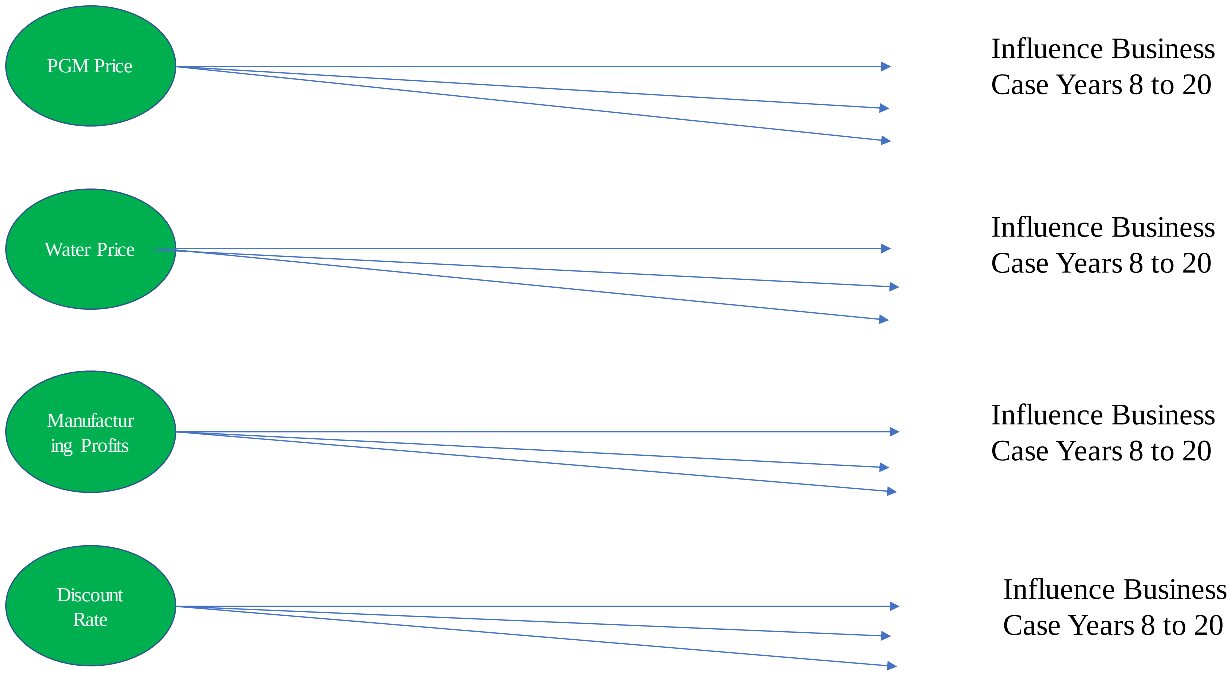

Figure 22 Decision Model Sub-section 9

GLOSSARY OF ACRONYMS

DPL: Decision Programming Language. An analytical application marketed by Syncopation Software. Useful for building decision models.

IRB: Institutional Review Board. The panel responsible for reviewing and authorizing research utilizing human subjects.

NPV: Net Present Value. The sum of all present values for a financial model conducted over several years. Utilizes the time value of money to discount future values.

PGM: Platinum Group Metals. Refers to the metals in the platinum group (or cluster) in the periodic table: ruthenium, rhodium, palladium, osmium, iridium, and platinum.

QQD: Qualitative Quasi-Deductive. A research methodology that blends qualitative and quantitative research.

ReNET: Reusable Nuclear Electric Tug. A spacecraft designed to transport mining equipment to an asteroid and mined material from an asteroid. Powered by a nuclear fission reactor.

SSTO: Single Stage to Orbit. A spacecraft that requires only one stage to achieve Earth orbit.