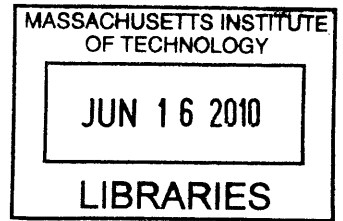# Material Scarcity from the Perspective of Manufacturing Firms: Case Studies of Platinum and Cobalt

by

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B.Eng. Metallurgical Engineering, McGill University, 2001

SUBMITTED TO THE DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
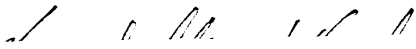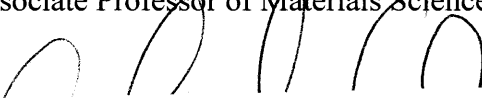
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Material Scarcity from the Perspective of Manufacturing Firms: Case Studies of Platinum and Cobalt

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ABSTRACT

Many agree that materials availability, especially non-renewable materials, is an issue of global concern. However, the implications and strategy options for manufacturing firms are not obvious. Manufacturers select materials and make decisions by selecting materials with the best set of properties and price that can be used in products to satisfy customers, who mostly do not base their purchases on materials used. There may be additional motivations and directions for action for manufacturers if scarcity is examined from their perspective.

A historical case study of the 1970's cobalt crisis was performed. The effects of cobalt scarcity and the responses taken by supply-chain firms downstream to primary producers were examined. In addition, a system dynamics simulation model of the platinum material system was built using historical data specific to the platinum market. The effects of platinum scarcity and the impact of pursuing recycling on manufacturer concerns were examined.

It was shown that scarcity affected manufacturers through process disruptions and unexpected increases in expenditures. Recycling, substitution and dematerialization were actions taken or encouraged by firms in the manufacturing industry that reduced the impact of scarcity. These responses take time to implement, are not available to all and lead to permanent market changes. It was recommended that they be considered early and incorporated as strategies for firms facing increased scarcity.

Multiple recycling scenarios were simulated. Recycling is a tactic already encouraged by manufacturers because it costs less than primary processing. The analyses, which specifically incorporate ore depletion and other materials availability constraints,

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demonstrate two added benefits to recycling. Recycling reduces future primary production costs in markets with inelastic demand and low discovery rates. Also, recycling is more responsive to price than primary production and stabilizes price in a market with rapidly-growing demand and long delays for primary production expansion.

In conclusion, manufacturing firms may not be adequately appreciating the benefits of recycling, dematerialization and materials substitution if they do not consider the effects of increasing scarcity. Moreover, because markets respond slowly to changes, manufacturers who can respond rapidly to increasing scarcity because they have a strategy in place can gain a competitive advantage.

Thesis Supervisor: Randolph E. Kirchain
Title: Associate Professor of Materials Science and Engineering

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I dedicate this work to my whole family, especially my mom, my dad, Ah-yi, Elena and Tim.

1 Introduction

Resource scarcity is a topic that has challenged scientists, engineers and economists over the past 200 years. Interest in this topic stems in large part from the dependence of economies on the finite amount of natural resources on Earth to produce consumer goods. In 1995, the USGS estimated that total resource consumption in the United States topped ten metric tons per person per year (Matos and Wagner 1998). Furthermore, although the level of global consumption was nearly eight times smaller, that level was growing two times faster. While these estimates are fraught with uncertainty, they point to one of the significant challenges that confronts engineers and scientists of the 21st century: how to deal with the unprecedented rate of material resource consumption.

The answer to this question is complex: resource consumption or use occurs in a complex and dynamic system in which the actions of governments, firms and consumers, as well as the geological endowment of the resources play a role. One particular category of resources, mineral resources[1], is of particular interest for this work in that these resources are *"non-renewable, non-perishable and non-consumable."*

What this means is that (1) these resources are finite, (2) left unexploited, the resources do not degrade over time and can be extracted today or in the future, and (3) through proper management, the resources can be recovered and recycled over and over again.

The finite nature of resource endowment is determined by geological processes. The decisions over extraction (when and where), use and end-of-life management are determined by political and economic factors. For example, for a given mineral deposit located within a set of political borders, the rights to extract the minerals may be distributed politically (ex: government-owned company or government-favored company) or economically (ex: sale of mining rights).

Mineral resources exist in varying degrees of quality, and therefore are not all equally easy to extract: certain resources will be located deeper in Earth's crust, at lower grades, in more remote locations (ex. Arctic) or in more thermodynamically stable minerals (U.S. Bureau of Mines 1980). Extraction of these different qualities of resources will come at varying costs. Knowledge of the

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[1] Mineral commodities refer to resources produced through geological events spanning time scales that are orders of magnitude greater than the time scales typically considered of relevance to the human race, millions of years vs. thousands of years (Tilton, J. and R. Gordon (2008). "Mineral economics: Overview of a discipline." Resources Policy.) They include metals, non-metals and energy minerals such as lead, gypsum and natural gas.

quality and location of these resources also comes at a cost that varies depending in part on factors such as remoteness of the location of the resource and the technological challenges to identify the resource.

When there are agents who desire the resources and are willing to cover the costs of discovery and extraction the incentives to mine and extract resources are created. Markets serve as a framework to set the conditions for an exchange of resources and currency between agents who own the resources and agents wishing to purchase resources. In a competitive market, each agent acts for its own best interest and price is set by the market. In such a market, prices will be an appropriate guide for users of these resources.

Since a resource exists at varying levels of quality and therefore costs of extraction, price will determine which resources can be profitably extracted at any given period of time. Some resources will require prohibitively high prices before costs of extraction can be covered. Advances in technology for discovery, mining and extraction help lower those costs and increase the amount of resources that can be profitably extracted[2].

On the use side, firms' profit motive will lead them to find ways to use expensive materials sparingly, to recycle materials cost-effectively and to substitute towards lower priced materials (Gordon 1987). In other words, the profits accrued by the firms that develop and exploit new technology serve as an incentive for technology advances: reducing costs through improved efficiencies, introducing new products to capture new markets, improving product characteristics to increase market share, etc.

As a result of these complexities, it is very difficult (if not impossible) to correctly predict future resource availability through examination of past trends. Still, many attempts have been made, mostly with the goal and perspective of understanding availability's effects on global social welfare.

From the perspective of global social welfare, a number of observations have been made about finite resource use. There are those who have noted that growing consumption of a finite resource could potentially mean hitting against a limit which could negatively impact economic growth. Early assessments of the consequences of reliance upon finite resources (Malthus 1798; Jevons

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[2] One way to observe this trend is to compare the present and historical size of reserves, the fraction of known resources that geologists estimate can be extracted profitably at current prices. For example, copper reserves over the past 30 years have increased despite continuous extraction (Ayres, R. U., L. Ayres, et al. (2003). The life cycle of copper, its co-products and byproducts. Dordrecht ; Boston, Kluwer Academic.)

1866) predicted the exhaustion of some key resources, accompanied by some form of negative impact on a global scale. Another dismal hypothesis was proposed by Ricardo in the early 1800's: the cost of resource extraction would increase as lower quality ores were depleted and that these increasing costs would have an increasing burden on the economy (Ricardo 1821, first published 1817). These high extraction costs could limit mineral resource use before exhaustion is reached (Ricardo 1821, first published 1817; Barnett and Morse 1963). Such dismal assessments have been reiterated more recently and given more attention during the period surrounding the 1970's oil shock (Meadows, Meadows et al. 1972).

A less dismal observation has also been made: although resources are finite, technological advances spurred by economic incentives have both increased the supply of resources and reduced dependence upon scarce resources (Barnett and Morse 1963; Chapman and Roberts 1983; Gordon 1987). Resource exhaustion has yet to halt global economic growth, despite the large population growth and exponential growth in the overall rate of consumption of natural resources. There has never been a case of global exhaustion of any mineral resource, including not only resources that are conventionally characterized as *"non-renewable, non-consumable and non-perishable,"* such as metals, but also resources that are *"non-renewable and consumable,"* such as oil. Moreover, resource prices have not shown long term upward trends from depletion of higher quality ores (Slade 1982; Krautkraemer 1998; Adelman, Watkins et al. 2003).

While historical economical measures indicate that the economy has not been harmed by its reliance on finite resources, environmental measures indicate that the environment has suffered from the deleterious effects of materials consumption that include all forms of releases to air, water, and land and resulted in the loss of biodiversity, and the destruction of forests, wetlands and other natural ecosystems.

Some argue that social welfare can be maintained by appropriately pricing externalities. In the end, these all of these arguments suggest that firms should not treat their use of non-renewable, non-consumable, non-perishable resources differently than their other business decisions. Those that recognize that economic mechanisms alone are insufficient to address the damages to environmental externalities do not look to firms to self address these issues. Instead other forms of societal intervention are advocated. In the end, there is little call in the literature for firms to take special action with regard to non-renewable, non-consumable, non-perishable resource use.

This absence of a call to action emerges in part because from the theoretical perspective of the economist, inhomogeneities in the behavior of the actors in the economy, including the failure of

some firms, does not impede the successful operation of the market. Observations made about global social welfare may be useful to policy-makers, but they may not be directly applicable to setting the strategies of individual firms. Even if intervention into markets for increasingly scarce raw materials is not warranted from a societal perspective, key firm level questions remain. These are: 1) Are there financial advantages for pursuing strategies that moderate increasing scarcity beyond what conventional price signals would dictate? And 2) If such advantages exist, what strategies provide the most value for a given materials-market context?

These questions are particularly interesting from the perspective of downstream firms, who may view themselves as distanced from the risks[3] of materials availability. Would action benefit those firms?

Increased scarcity could affect manufacturers in ways that matter: not just through increased costs of materials, but also potential disruptions of supply leading to an inability to meet customer demands, and variable costs leading to unexpected changes in expenditures and potential cash-on-hand limitations. The material systems on which manufacturers depend may have risks of increased scarcity as a result of physical constraints and institutional inefficiency in the upstream supply chain. Quantifying or even just understanding those risks requires extensive knowledge of a complex set of actors and their interactions and behavior dynamics. The actions manufacturers themselves take can further increase or decrease the risks of increased scarcity. In fact, responses to increased prices may even be limited for certain manufacturers based on delays to implement new processes, technological ability and costs.

The approach taken here will be to expand on the resource scarcity field in a number of ways. First, this research will focus on the perspective of private firms whose success depends on its ability to operate under changing economic conditions. For these firms, survival depends on becoming and remaining profitable and this includes the effective use of material resources that are finite. As will be presented later in Section 2, much of the previous work in this field has examined the impact of resource consumption on the economy, on future generations, on developing nations or on the environment. The observations made when the perspective taken is that of global social welfare are useful to policy-makers, but do not inform firms that depend on finite mineral resources on how to deal with the unprecedented rate of material consumption.

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[3] Risk is not explicitly explored in this work. A more complete description of risk is in the Appendix.

Second, the focus here will be on comparing technological tools that can be used in the future by manufacturing firms. Recycling, dematerialization and material substitution are examples of technological tools that have been discussed in literature as tools to increase material availability (Gordon 1987). Financial tools whose main purpose is to help firms deal with uncertainty in commodity markets will not be examined in detail (Gibson-Jarvie 1976; Christian 2006). This research will examine the effectiveness of recycling for dealing with material scarcity as well as examine how it can constitute a strategy for manufacturers to deal with uncertainty. Its role in reducing firms' dependence on materials will be examined for manufacturers in specific case study of platinum-using industries. Such technological strategies can also be applied by manufacturers interested in using mineral resources other than platinum.

Thirdly, this research examines the implications of using price as a signal of scarcity when delays are involved in implementing technological responses to unexpected market changes. Manufacturers require significant periods of time to implement changes that would allow them to change their material use patterns. This means that taking the economic view that material price is a key signal for agents active in markets may be detrimental to firms that only respond post-facto to price changes[4]. While it has been seen that expensive materials will be used more sparingly than inexpensive ones, historical experience has shown that this trend occurs as a result of many decisions with longer term implications for firms. Signals of scarcity are examined to understand the concerns for different material systems.

In addition to expanding on the literature, this work involved building and developing new modeling frameworks for modeling supply for a non-renewable material system. The unique model was built using the system dynamics simulation method that allowed the incorporation of the concepts of inefficiencies, delays and differences between decision-makers.

1.1 Scope: Materials and Manufacturers

Materials are any solid-state substance at any stage of processing that is used to make a final sellable product. This broad definition includes raw materials such as wood, concrete and metals, semi-finished products such as sheet, wire and tube metal alloys, and even specialized materials such as semi-conductors for electronics and nano-powders for cosmetics. For this work, the focus

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[4] This is not the first examination of price as an insufficient signal for decision-makers. The use of price to inform markets has been questioned by environmentalists who are concerned that market imperfections mean that price does not properly account for external costs such as costs to human health.

will be on non-renewable, non-consumable, non-perishable and non-fungible commodities. Most metals and some minerals fall into this category.

Non-renewable resources are those that exist in Earth's crust as a product of geological processes that occurred over thousands of years. *Non-consumable and non-perishable* resources have a constant total stock over time. These materials will retain their general properties, should experience minimal dissipation and can be collected at the end of product life for recycling despite being transformed during the production process. *Non-fungible* materials each have unique sets of properties such that they can only be substituted by other materials if tradeoffs are made. Use and processing of any given material requires a specific set of processing techniques and technical experience. *Commodities* are products that are sold in a competitive market where the price is known to all who desire to purchase it.

The complexity involved when thinking about scarcity means that there are many models of scarcity. It is possible that this complexity has been the main reason resource scarcity has been discussed for more than 200 years and still remains somewhat impenetrable. This project will not be able to capture all of the issues, but represents a first step to using new modeling tools in providing novel insights about scarcity from a private firm perspective.

Part of the complexity of thinking about scarcity has to do with the dynamics of the stocks and flows of materials that are non-renewable, non-consumable, non-perishable and non-fungible commodities.

Figure 1 depicts the materials economy as a network of resource flows, driven by a consumption rate deriving from the demand for applications that use the resource, and moderated by the availability of substitutes, alternative technologies and recycling rates. Underlying much of this dynamic are market notions, not only in terms of the segregation between resource and reserves, but also in terms of the way in that resource prices will influence demand, substitution and recycling rates.

The figure highlights a number of factors that affect material flow. Figure 1 includes the following factors:

- discovery

- technological change leading to improved extraction efficiency

- material substitution

- recycling

- technological substitution

These factors, or material leverage points, can be characterized as mechanisms interacting in a complex way to affect material scarcity. The leverage points can also be viewed as tied to decision variables, whose values are determined by firms participating within a material system. For example, mining firms can decide to cut mining exploration funding and thus reduce discovery rates when they are confident in their ability to satisfy short-term demand.
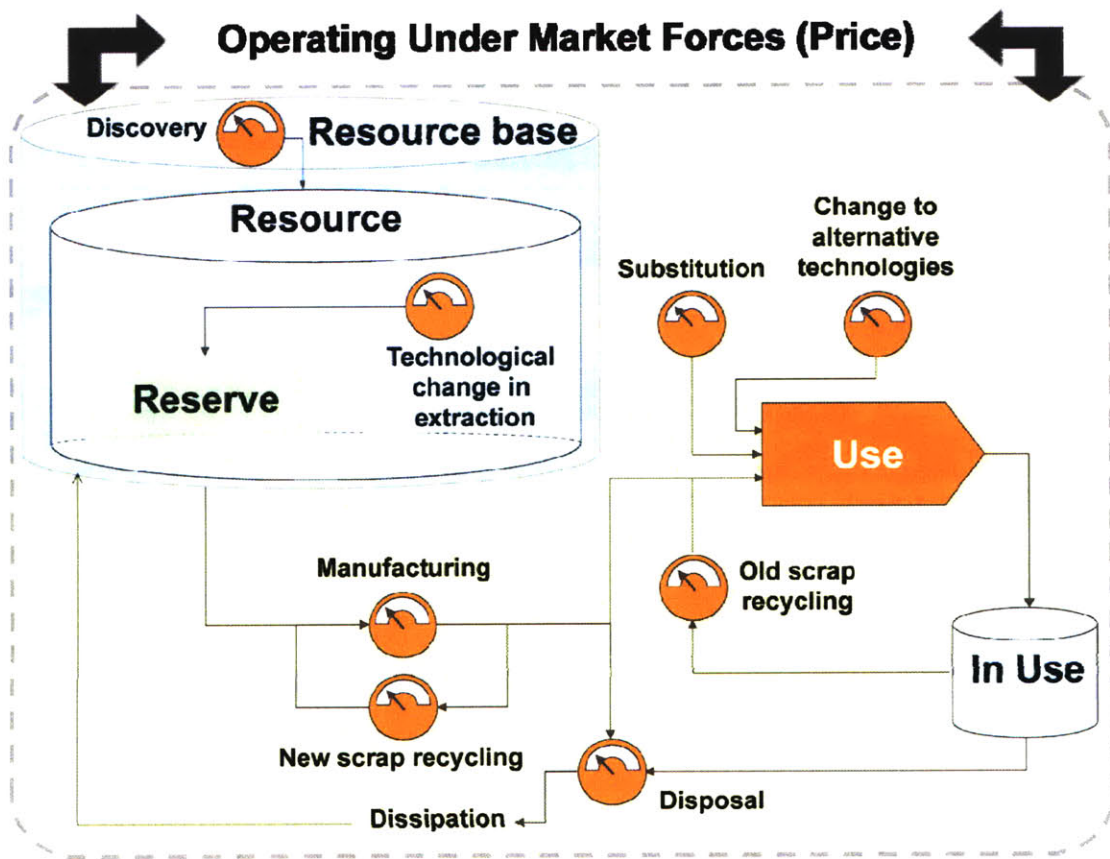
Figure 1: Material Flows and Leverage Points.

There are generally many firms that serve to distribute physical goods to the end consumer (Oxford University Press. 2006). These firms form a supply chain. The reverse supply is the distribution channel of a physical good to its point of origin or back to points within the supply chain for the purpose of proper disposal or recovery of value. The term supply-chain stakeholder refers to the

multiple firms within the supply chain and reverse supply chain (see Figure 2). Raw materials are extracted upstream and proceed down a supply chain towards final product manufacturing and sale to the consumer, with many distribution/delivery steps between each of the supply-chain stakeholders. Product manufacturers are industrial supply-chain stakeholders who buy materials and transform it to a product that can then be delivered and distributed downstream, ultimately to consumers. A material system refers to a system that includes all the stakeholders that participate in a material supply chain and market, including manufacturers.

For this work, the focus is on the manufacturer and therefore the term upstream firms will refer to those firms located upstream to manufacturers, especially primary producers. Downstream firms will refer to parts and product manufacturers who depend on a reliable supply of materials.
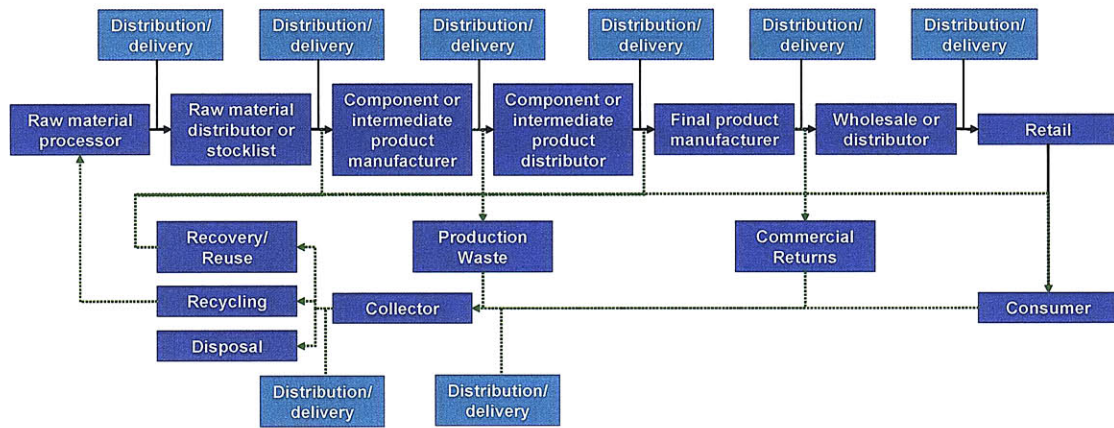
Figure 2: Diagram of the supply chain from upstream raw material manufacturer to downstream retail (lines in black) and reverse supply chain which includes disposal, recycling and recovery (lines in green).

The types of institutions that have been set up define the way that humans have elected to interact with material leverage points. Although past cost trends were overall decreasing, some individuals have suffered losses as a result of changing materials availability. These losses may be indicative of individual firms' inability to deal with the changing scarcity of materials. One possible reason is that the institutions that humans have set up do not always function in the same way as described by many of the theoretical frameworks (Hotelling 1931; Stiglitz 1974; Pindyck 1978; Dasgupta and Stiglitz 1981). This work will use a framework that considers inefficiencies in markets and how market actors behave.

1.2 Outline of Key Thesis Contributions

For this work, a historical case study and numerical simulation model were developed and used to examine material scarcity from the perspective of manufacturing firms. Additional motivation for manufacturer action in preventing increasing scarcity and direction for action that can be taken by manufacturers were proposed and explored.

This work begins by examining history to better understand some of the potential implications of materials availability. Historical experience indicates that there have been disruptions and panics in markets for these resources that have been blamed on the fact that they are finite. Such disruptions affect firms at all levels of a supply chain, including manufacturers. The best known example is probably the oil crisis in the 1970's, but such crises have also occurred in materials markets.

The 1978 cobalt crisis is an historic case of heightened material supply uncertainty: price increased 380% between 1977 and 1979. The specific conditions leading to this uncertainty were political unrest in a region that produced more than 40% of the world's primary cobalt, Zaire, a global economic upturn that led to increased demand for cobalt, changes in the US defense stockpile goals and speculation about the uncertainty.

The responses varied by industry. For example, while in some industries, recycling and material substitution rates increased over comparable pre-crisis rates, in other industries, where any response to price would require long delays due to technological limitations, there were minimal changes observed (Alonso, Gregory et al. 2007; Alonso, Field et al. 2008). Also, some responses, such as stockpiling, while quicker and technologically easier to implement, may have increased not just scarcity, but also the uncertainty in the cobalt market by increasing short-term demand.

The cobalt case study suggests that an effective long term strategy for efficient material use comprehends technological actions such as recycling and material substitution. These are actions that can be implemented by downstream supply chain firms, especially manufacturers. Moreover, the observations from the cobalt case suggest that there are important forms of information that firms that rely upon these finite resources should be using in addition to historical prices as a guide to action. Technological tools that firms have been motivated to use during periods of heightened supply uncertainty often require advance examination.

Further analysis of the implications of scarcity for manufacturers was done through simulation modeling. A modeling approach to examine materials-market context was developed. The model framework considers changing resource quality in supply and decision-making processes by

different actors in a material system. A system dynamics simulation model of the platinum market dynamics was built and used to examine effects of the risk of platinum scarcity on platinum-using industries. The model incorporated established system dynamic market model building blocks with unique structures, in particular, the supply structure. The developed supply structure simulated a supply curve that shifted as ore quality depleted, with depletion occurring as cumulative mining production increased. Insights on the effects of material scarcity on manufacturers who use non-renewable, non-perishable, non-consumable material commodities were gained from the analysis.

Two main issues were addressed in the analysis of the model. First the effect of scarcity on manufacturer concerns was established. Second, recycling was examined as a potential strategy, not just to decrease the present costs of materials, but also to reduce the future impact of increasing scarcity.

The model was used to examine hypothetical scenarios where platinum recycling is decreased from present recycling rates. For platinum, the recycled material is indistinguishable from primary material and can be used by manufacturers without any changes made to the process or product. In other words, for such systems, secondary material is a perfect substitute for primary material. This is not the case for many other systems, where recycled materials can be used but only up to a limited amount as recycled materials can introduce impurities to the process and/or change the properties of the final product. Recycling is often encouraged by firms as a cost-cutting tool because the cost of recycled materials is generally lower than the cost of primary materials. Using the model that focuses on the effect of scarcity, additional benefits to recycling were identified.

The net trend observed is that material prices increase. Price increases translate to higher material costs for manufacturers who use platinum. Another trend observed is that the variability of price over a future fifty-year period, as measured by the standard deviation of price, is also higher.

The mechanisms by which price and standard deviation of price increase as recycling is cut are found to originate from how recycling impacts a material system where scarcity is a factor. First, recycling substitutes for primary metal and reduces disposal rates: a decrease of recycling results in a higher primary extraction rate and increasing ore depletion over time unless discovery is able to increase sufficiently. With the model, higher costs of primary extraction are observed as lower quality ores are tapped due to the faster rate of primary extraction. Secondly, the incentives and delays of secondary producers are different than for primary producers: a system with lower recycling has less ability to respond to demand and has tighter supply. Tighter supply translates to

both higher prices and higher variability of price especially from small perturbations which are more likely to impact the system.

For a system where platinum recycling is increased from present recycling rates, there are limitations due to the high efficiency of the present platinum recycling system. In a number of industries, such as the glass industry where 98% of platinum used is recovered and recycled, there is very little room to improve on present practices and therefore the benefits are also limited. In fact, platinum secondary supply is estimated to be near maximum recycling efficiency at the present and therefore any attempt to further increase the recycling rate results in hitting the maximum rates. In hitting these maximum rates, the secondary supply system is shown to be less responsive to price increases and therefore less able to supplement primary platinum during periods of tight supply.

Higher prices and price standard deviation impact manufacturers who use platinum by increasing their unit material costs, increasing the uncertainty of their material costs and increasing their average unit expenditures over time. These three effects are suggested as motivation especially for firms whose demand for platinum account for a large fraction of total platinum supply, whose present recycling rates are low. Such firms, such as those in the automotive industry, are most likely to have a larger impact on the system as a whole.

Just as different industries have different recycling practices, with some being more efficient than others, an inspection of industry-by-industry performance at varying recycling rates shows that there are also differences in how material price motivates purchases. Industry-level differences are examined by comparing price elasticity and demand delay under varying demand and recycling scenarios. These differences are apparent when examining the average unit expenditures.

Industries that account for a large fraction of primary platinum demand, expect rapid growth in demand for platinum in the future and have few alternatives to using platinum would benefit most from increasing the recycling rates overall, especially those for their products. An example would be the automotive industry, which presently accounts for about half of primary platinum use, will likely require more platinum as developing countries implement emission standards on their vehicles and has low price elasticity for platinum demand and long delay times to implementing new technologies.

As with recycling, the ability to respond to price is a factor that should be considered. Responsiveness of demand to price through purchasing decisions is a key factor in industry-level

differences in expenditures. Firms with the ability to not just respond, but respond quickly to price changes are more protected from changes in prices, especially upward spikes. Two technological tools that help firms in this regard are dematerialization and material substitution. These are not examined in detail but are proposed as tools for consideration in future work.

1.3 Document Roadmap

With this work, I hope to reach manufacturers concerned about better managing supply risk and motivate them to manage resource scarcity risk while suggesting tools to reduce that risk. In Section 2, a review of literature frames the discussion of resource scarcity. Resource scarcity is a field of study that extends back more than two centuries. Much of the focus of resource scarcity literature has been on global social welfare, especially economic, social and environmental concerns. As a result, manufacturing and business literature that have emphasized the importance of supply risk management were also reviewed for a perspective of manufacturer concerns.

Historical cases of material supply shortages are examined in order to fill the literature gap in the area of manufacturer-level concerns for resource scarcity. The results presented in this section show that firms, especially manufacturers, should be concerned for resource scarcity. The perspective of material scarcity as a concern for global social welfare does not sufficiently provide motivation and direction for action to manufacturers. The cobalt crisis is one of the two historical case studies presented in Section 3.

Firms have limited resources and need information to better address their concerns for resource scarcity. Not all materials have the same level of resource scarcity risk. In Section 4, metrics that compare different materials were presented in a framework that can help firms to think about the types of resource scarcity risks that they face.

The metrics are suggested as a useful screening tool. If used appropriately, they provide a snapshot of the relative risks of scarcity associated with using different materials and indicate the type of risks that are more likely, either physical constraint or institutional inefficiency. However, at times, different metrics for the same material provide different assessments of resource scarcity. Especially in these cases, firms may want to think of the dynamics of materials systems that may change the levels of risk in the future. It is particularly important for firms interested in using new materials (materials that they haven't used before) to consider material system dynamics, since their decision to use that new material may impose stresses on those systems. To examine the

dynamic behavior of material markets in the face of scarcity risks, a simulation technique was selected to expand the analysis. Sections 5 and 6 describe the method used and how it was applied.

The simulation model was built around the platinum material system and multiple scenarios were assessed. The analyses are presented in Sections 7. The last sections present recommendations for manufacturers and recommendations for future work. Finally, the appendices contain additional documentation for the model (Sections 10.2, 10.3, 10.4, 10.5 and 10.6) and a case study on the use of metrics (Section 10.1). A number of relevant definitions, such as reserve, resource, recycling rate and recovery rate, are also provided in the appendices (Section 10.7).

2 Resource Scarcity: a brief overview

The question of materials availability is an issue that has been addressed many times over the past 200 years by scientists, engineers and economists, and it is an issue with many layers of complexity. This section will not be an exhaustive review of this literature, but instead begins with an examination of the most basic notions of scarcity.

Concern about materials scarcity is about the fear that a material will run out if more is needed than is available. After all, the Earth is of a limited size and has limited resources, whereas human population is capable of continuously increasing and humans are capable of continuously consuming more. This viewpoint was expressed early on by Thomas Robert Malthus in the late 18th century (Malthus 1798) and this document will refer to the notion that scarcity is tied to material exhaustion as a Malthusian perspective of scarcity.

The exhaustion of a material or resource, leaving future generations with one less resource upon which to satisfy future needs, could have grave consequences. However, estimates of all the materials found in the Earth's crust indicate that the likelihood of running out of any of the common metals mined today is much smaller than the possibility of not being able to access and extract those metals for a reasonable cost. This may be expressed by noting that the size of the world's resource base for most materials is much larger than the size of the world's reserve. The resource base is an estimate of all the material in the Earth's crust including material that is still undiscovered and the reserve is an estimate of the material that is in discovered ore bodies and that is economically extractible. In this view, then, scarcity is not about exhaustion, but rather about the expense of extraction. This observation was first made by David Ricardo in the early 19th century (Ricardo 1821, first published 1817) and in this document, the notion that scarcity is tied to high extraction costs is referred to as a Ricardian concern.

Ricardo's analysis of cost is based on his observation that resources existed in different qualities and that those resources of highest quality, requiring least effort to access, were first consumed. The lower quality resources would require greater amounts of effort (energy, capital, labor,...) to extract.

This is just part of the material scarcity equation. An added layer of complexity in the concept of scarcity is that it embodies more than just the effort required to obtain a material. It is also a measure of the amount of effort those who use the material are able (willing) to spend to obtain the material. Thus, a notion of scarcity should embed a concept of market forces. For example, one

might say that a resource is scarce when the marginal cost of obtaining an additional unit of resource is greater than the market price for that resource.

The dynamics of materials markets can also be added to the model of scarcity. An example of market dynamics is the changing technologies that allow for reduction in extraction costs or the possibility of substitution that cap market value.

Moreover, our analysis of markets should incorporate the potential for market failure -- that the markets will not function efficiently or that other institutions, such as governments, may interfere with the assumptions that are required for efficiency, such as information, competition, etc. in the structure of the market. In an inefficient market, there may be actors who decide to sell below cost or to build stockpiles during periods of high prices. The dynamics of a material system may be affected by such cases of institutional inefficiencies.

It is worth noting that within the literature reviewed, most of the focus to date has been on scarcity from the perspective of the aggregate economy (Dasgupta and Heal 1974; Solow 1974; Stiglitz 1974; World Commission on Environment and Development. 1987; Cleveland and Ruth 1997; Simpson, Toman et al. 2005). This work will focus on firm-level motivations to act upon scarcity concerns and as such, will include a literature review on manufacturer concerns that may be relevant in the case of increasing scarcity.

2.1 Malthusian Perspective

The first approaches to the materials limitation issue were taken by economists in the 18th and 19th centuries. Among the most often cited is Thomas Robert Malthus, an economist who published an essay in 1798 looking into the effect the population boom would have on food supplies (Malthus 1798). Noting the rates at which population and food supplies were increasing, he predicted a future decrease in food per person because population was increasing faster than the food supply.

> "The power of population is so superior to the power of the earth to produce subsistence for man, that premature death must in some shape or other visit the human race. The vices of mankind are active and able ministers of depopulation. They are the precursors in the great army of destruction; and often finish the dreadful work themselves. But should they fail in this war of extermination, sickly seasons, epidemics, pestilence, and plague, advance in terrific array, and sweep off their thousands and tens of thousands. Should success be still incomplete, gigantic

inevitable famine stalks in the rear, and with one mighty blow levels the population with the food of the world." - (Malthus 1798)

Jevons raised a comparable concern for coal shortages in England in the 1800's with the following statement:

> "Coal in truth stands not beside but entirely above all other commodities. It is the material energy of the country—the universal aid—the factor in everything we do. With coal almost any feat is possible or easy; without it we are thrown back into the laborious poverty of early times.

> With such facts familiarly before us, it can be no matter of surprise that year by year we make larger draughts upon a material of such myriad qualities—of such miraculous powers. But it is at the same time impossible that men of foresight should not turn to compare with some anxiety the masses yearly drawn with the quantities known or supposed to lie within these islands." - (Jevons 1866)

Underlying Jevons' quote is a notion that scarcity results from exhaustion of limited resources. Both Malthus and Jevons predicted that it was just a matter of time before the growing consumption rates on an earth with limited resources would result in scarcity. In other words, their model of future consumption represented scarcity as a consequence of geophysical constraints on resource availability.

Global consumption rates over the past century have, in fact, been growing rapidly. For example, in the U.S., consumption of all materials has been increasing almost exponentially since 1900 (see Figure 3). With the economies of industrializing nations, in particular China and India, growing at a pace that outstrips the US, the global resource consumption has skyrocketed.
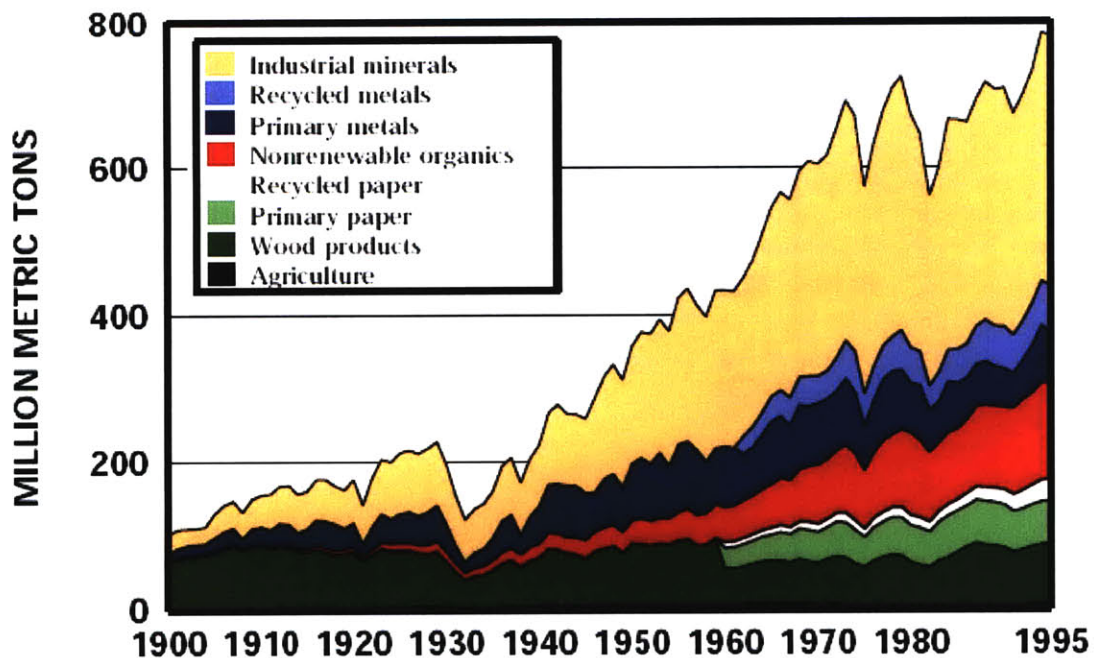
Figure 3: US raw material consumption (not including crushed stone and construction sand and gravel) 1900-1995. (Matos and Wagner 1998)

More recently, growing consumption rates have caused scientists to take a concerned tone (Matos and Wagner 1998; Lifset, Gordon et al. 2002; Graedel, Van Beers et al. 2004). With varying levels of sophistication, these studies of physical measures have compared the quantity of material that has been discovered and is being discovered with the consumption rate of that material. Extrapolative models are often used in these studies to predict future levels of extraction and consumption.

The concept of scarcity tied to exhaustion of resources has been explored most frequently by comparing the global reported reserves[5], (the amount of a mineral known to exist and estimated to be economically extractable) with the present rate of consumption. As can be seen in Figure 4 below, this type of analysis can be alarming as many metals have estimated depletion times falling within the next half century.

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[5] USGS gives definitions for the following geological terms: reserve, reserve base, resource, and resource base. Please see Additional Resources Section for definitions.
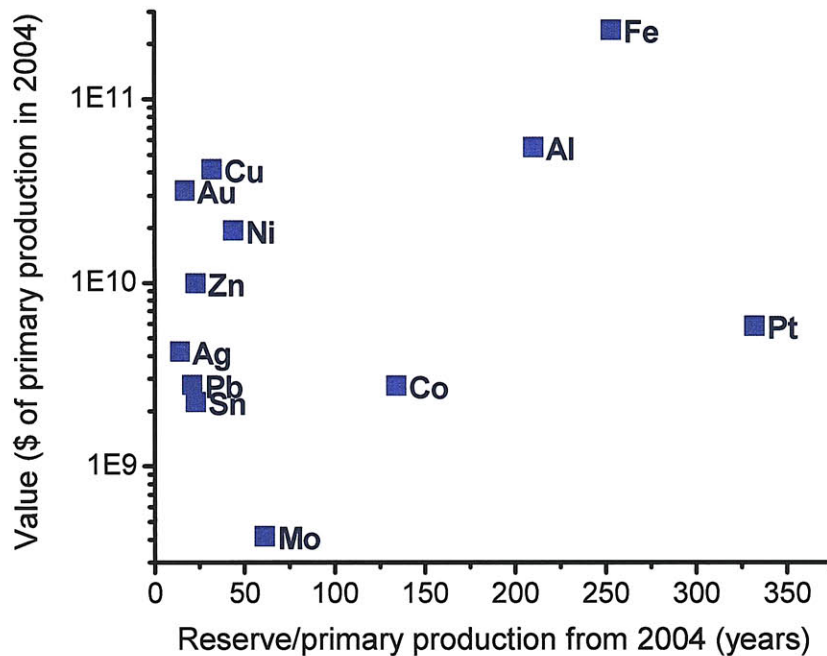
Figure 4: Estimation of time to depletion of reserves for metals of different value. This assumes that reserves and consumption remain constant in the future. Value is defined as primary production in 2004 times the average price in $US in 2004 for each metal. Reserve/primary production for 2004 is less than 50 for many of the metals with value greater than $1 billion US.

Unfortunately, reserves do not actually account for the amount of metal that can be found in the earth's crust. In other words, even if all the metal that is within the reserves today is consumed, there would not be physical exhaustion. The size of reserves is a decision variable. It can be viewed as an inventory for storage for mining firms, allowing them to buffer against changing metal demands. Reserve size depends on the price of the metal as well as the amount that mining and extraction companies choose to spend on exploration and extractive technology development. As an illustration of this point, the size of copper reserves over the past half century has at times increased despite growing consumption rates (see Figure 5). The global amount of metal in the earth's crust is actually much greater than the size of the reserves[6]. The global *resources* or *resource base* more accurately identify the total global supply, although much of the metal within it

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[6] Since the sizes of reserve can increase (with new discoveries, decreasing costs or increasing prices) and the consumption rate can decrease (with substitution and improved engineering efficiency), past scarcity predictions have not been very accurate. One example is that of mercury, which was highlighted by a study in 1972 for its eminent depletion Meadows, D. H., D. L. Meadows, et al. (1972). Limits to growth; a report for the Club of Rome's project on the predicament of mankind. New York, Universe Books.. Mercury was substituted for other materials during the end of the 20th century and has not yet been depleted, despite alarmist predictions.

are not presently "available" due to lack of exploration data and economic or technologically unfavorable conditions. However they can be made available through increases in price, new technologies and increased exploration.
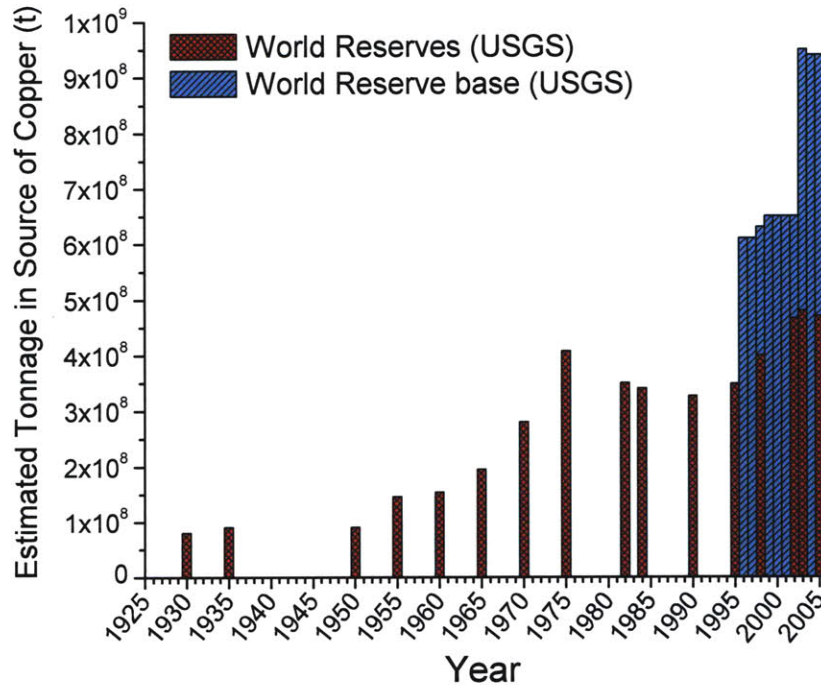
Figure 5: Historical estimates of copper reserve and reserve base (U.S. Geological Survey 1932-2006).

It has also been pointed out, in the context of a modeling study of global oil reserves, that the greatest concern for physical exhaustion is not so much that it could occur, as, that it could occur unexpectedly due to overestimation of recoverable resources (Sterman and Richardson 1985). The dashed lines in Figure 6 identify two possible pathways of estimates of ultimate recoverable resources. Sterman and Richardson noted that overestimation of resources could result in inefficient allocation of exploration effort, overvalued lease tracts and complacency in the development of substitutes & recycling infrastructure.

Ultimately, the greatest advantage of Malthusian perspective on scarcity, its simplicity, is also its greatest drawback. However, this is not to say that this concept cannot or should not be used in building an understanding of scarcity. Metrics comparing reserve or resource size with consumption rate and consumption growth are easily constructed because historical data is readily available for most materials. Malthusian scarcity can be used to build metrics as a first step in screening for potentially scarce materials (Alonso, Field et al. 2007).

ESTIMATES OF THE
ULTIMATE RECOVERABLE
RESOURCE

ULTIMATE
RECOVERABLE
RESOURCE

BARRELS

CUMULATIVE
PRODUCTION

1940

TIME
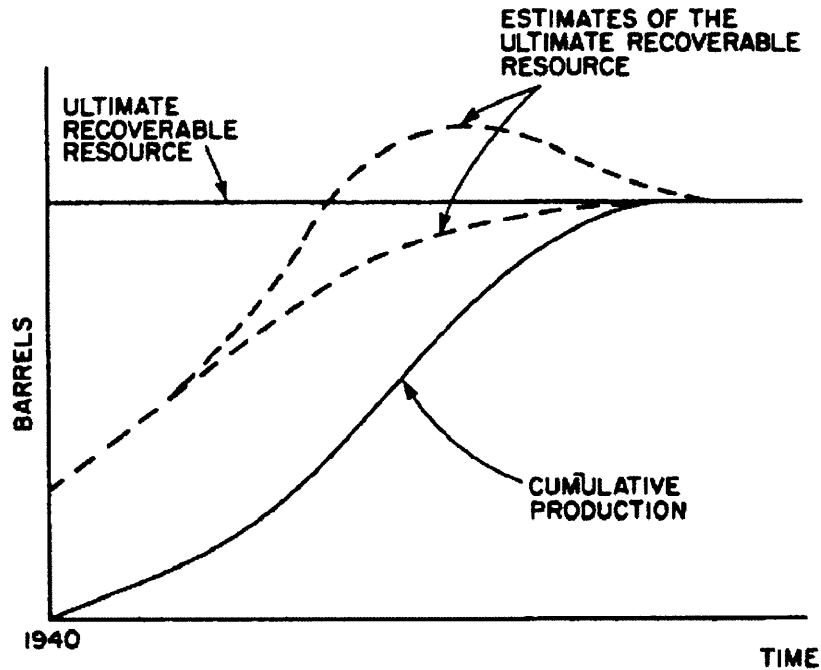
Figure 6: Possible paths of estimates of the world's ultimate recoverable resource. (Figure and caption taken from (Sterman and Richardson 1985)).

2.2 Ricardian Perspective

In the early 19th century, economist David Ricardo refined the notion of geophysical constraints, based on the observation that resources occur in different levels of quality. The quality of a mineral resource may be characterized as a combination of the ore body's proximity to centers of consumption and to the earth's surface, the concentration of metal in the ore body, the size of the ore body and the ease of separating the metal from its mineral form[7]. High quality ores are usually easier to discover and to extract and for reasons of efficiency are usually extracted before lower quality ores. Therefore, scarcity is not merely a consequence of resource exhaustion, but instead derives from the increasing difficulty and cost of accessing lower quality resources (Ricardo 1821, first published 1817). Over time, increasing inputs of labor, capital or improvements in technology would be required to extract each additional ton of resource. Scarcity would therefore arise from an increase in cost from a combination of geophysical and technological constraints resulting in a greater proportion of total labor and capital expenditures devoted to mineral extraction.

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[7] Given the same technology, the quality of an ore body will determine the cost required to extract a metal. For example, an ore body located near a center of consumption will require less transportation costs to bring it to the consumer. Also, an ore body located near the surface of the earth will require less digging time and energy costs.

The concept of cost being an indicator of scarcity was applied in various instances to non-renewable resources, particularly energy resources.

For example, the concept of scarcity arising from increasing costs was applied to the case of coal in England by Jevons who predicted increases in cost and inevitable negative economic effects:

> "In considering the geological aspects of the question, I endeavour to give some notion of the way in which an estimate of the existing coal is made, and of the degree of certainty attaching to it, deferring to the chapter upon Coal Mining the question of the depth to which we can follow seams of coal. It is shown that in all probability there is no precise physical limit of deep mining, but that the growing difficulties of management and extraction of coal in a very deep mine must greatly enhance its price. It is by this rise of price that gradual exhaustion will be manifested, and its deplorable effects occasioned." – (Jevons 1866)

Jevons was correct in predicting that the increasing cost of extracting coal would lead to the decline of British coal production even before all the coal had been mined. However, rather than suffering "deplorable effects" Britain simply increased imports of coal and later used alternative sources of energy such as oil, natural gas and nuclear energy.

A recent study of scarcity looked at the supply curve for oil in the US (Adelman, Watkins et al. 2003). Adelman and Watkins noted that the US supply curve for oil shifted leftward between 1973 and 1999 (decreasing production of oil at a given price), indicating increasing supply scarcity of US oil. However, this same trend was not observed for natural gas during the same period. Data on global reserve values for oil were also studied for the period between 1982 and 2002. The global data did not show increasing worldwide scarcity. Hence, it was concluded that the data did not support the hypothesis of increasing scarcity worldwide during the period examined, although increasing scarcity for oil produced in the U.S. was observed.

Although energy has been the focus of much of the research efforts in resource availability, other natural resources have also received attention. Barnett and Morse (1963) analyzed mineral resource trends for various cost-based metrics, including labor-capital costs, cost per unit of GNP and cost of extractive output. They observed that labor-capital costs and costs per unit of GNP had decreased over nearly a century of collected US data.

In the absence of observed price increases, these recent studies generally emphasize the market effects of price changes leading to changes in demand and substitution. Barnett and Morse's study concluded that, as long as the market is free and competitive, supply limitations to a given material

would not check human progress. Rather, supply limitations (decreased availability) will lead to price increases that will lead to pushes to search for new sources, increases in efficiency & recycling rates and the development of new technologies, with possible future substitution of more expensive materials for currently less expensive materials. Past concerns about scarcity (e.g. coal and mercury) support this view that market forces can take care of future problems in materials availability.

This conclusion unfortunately does not consider consequences at the firm level because the perspective of such studies was at the level of the aggregate economy. For example, in the case of coal, Britain's coal economy did essentially disappear (in this case, the upstream supply chain firms), as Jevons had predicted, even if the rest of Britain's economy barely suffered. The type of question in this case that indicates that there may be firm level motivations to act is: "What happened to those firms that depended on a steady production of British coal?"

2.3 Sustainability Concerns

Social and environmental costs of resource consumption, such as all forms of releases to air, water, and land from mining and extraction processes, have common property characteristics (Ayres and Kneese 1969). These external costs need to be identified and accounted for to ensure first that they are properly covered and paid for by those who generate these costs and second that resources are not overutilized because of underpricing. Identifying the external costs of natural resource extraction and consumption involves considerations for human health, biodiversity, poverty, global development, among many other issues (Simpson, Toman et al. 2005).

Much literature exists that tries to identify and quantify exogenous costs of resource production and consumption. Gordon et al. modeled copper use in developed nations and calculated the stock of copper in use per capita for the United States and a number of European countries. If the developing nations were to require a similar level of copper stock per capita to achieve a similar level of standard-of-living, then the estimated global copper resources would be insufficient to satisfy their needs (Gordon, Bertram et al. 2006). A report of the mining, minerals and sustainable development project identified corruption, human rights, mineral wealth distribution issues as well as pollution and inefficient extraction from artisanal mining as problems associated with natural resource extraction in many developing nations (MMSD 2002). At the product end-of-life, the costs of responsibly disposing of products are not always covered by those who dump the products and there is the concern that hazardous waste is being exported to developing nations (Basel Action Network 2006).

These and other externalities have indeed led to resource underpricing, although improvements in regulations and increased scrutiny of firms have led to more responsible environmental practices, better accounting of environmental externalities and some improvements in corporate social responsibility (Slade 1982; Gerard and Lave 2005; Paquette 2006; Secretariat of the Basel Convention 2006).

The literature addressing concerns for resource sustainability has in general been framed in terms of aggregate social welfare. In practice, many policies designed to move towards more sustainable resource use have been implemented in the form of international conventions, and national and local regulations since global concerns for scarcity do not necessarily translate to private actions. This research will frame sustainability concerns from the perspective of individual firms. Some of the questions that need to be answered are: Are there benefits that are not being considered that would further motivate firms to utilize materials in a different way? Moreover, are there benefits to considering risks of increased environmental regulations or public scrutiny for firms as scarcity increases?

2.4 Manufacturer Concerns

For this work, one of the goals is to frame the risk of scarcity for manufacturing firms in terms of manufacturer concerns. The ability for firms to procure the materials when they are needed at both the lowest price and a predictable price is very important for all types of manufacturers, not just those who use non-renewables. The importance of a reliable supply has become of particular interest for firms as they try to cut costs by cutting inventory and move towards just-in-time delivery in a global supply chain that recent events have shown to be vulnerable to disruptions such as 9/11 (Sheffi 2001; Lensing and Massachusetts Institute of Technology. Engineering Systems Division. 2003). A review of business literature examining supply chain management identified some of the risks facing firms. These risks could gravely impact profits.

- increased costs, including material costs

- inability to fill customer orders

- loss of customer satisfaction

- negative corporate image

- tight credit and liquidity -> tied to a firm's ability to raise cash and therefore tied to a firm's growth, market share and stock value

- unplanned obsolescence

Unexpected cost increases from supply disruptions and price volatility in general are two issues of particular concern for manufacturers. Unexpected cost increases may force them to raise their product prices or miss profit targets. Volatility in general makes it more difficult for firms to manage their costs, their inventory and their cash-on-hand. Volatility of prices has been cited as a reason for automotive manufacturers to avoid using magnesium, for example (Urbance, Field et al. 2002). Financial hedging is often used by firms dealing with a volatile commodity market, but is not risk-free and additional tools should be considered (Hayenga 1979; Nelles and Ruegemer 2009). Campbell (Campbell 1989) suggested that copper companies moved towards a more specialized business model to deal with copper market condition volatility.

Increased material scarcity could lead to higher prices, higher volatility of prices, higher frequency and magnitude disruptions in supply and increased environmental and social costs leading to increased public scrutiny and regulations. Such impacts should motivate firms towards actions that reduce scarcity or at least their exposure to scarcity.

Historically, the trend for metal prices and price volatility has not been one of increasing material scarcity, although there are indications that increasing environmental costs are not properly being captured. Slade suggested that many commodity prices would follow a U-shape, having decreased over much of the 20th century because exogenous technical changes had pushed prices down despite decreasing ore grade and ore quality (Slade 1982; Slade 1985). The decrease in natural resource prices had been observed despite increasing public scrutiny of environmental costs and increasing regulations leading to increasing internalization of these costs (Slade 1992). Brunetti et al. found that metal price volatility was related to the stock-consumption ratio and that a tighter metals balance led to higher volatility (Brunetti and Gilbert 1995). However metal price volatility had shown no tendency to increase between 1972 and 1995, rather there had been periods of relatively tighter metal balances and periods of higher stocks. A longer time frame may be worth examining, especially given the volatility in markets in the past decade and a half.

Despite the lack of trend of increasing scarcity when measured by price and price volatility, there are indications that not only is there more scrutiny on the environmental and social costs of scarcity, but at least for petroleum, those costs are increasing as a result of increased depletion of

petroleum resources (Cleveland 1993). These environmental and social concerns may make scarcity worth examining for firms, since they could lead to a poor corporate image and may be a leading indicator for future increasing in price and price volatility.

Research that examines sustainability and industry concerns has been performed in the field of Industrial Ecology (Frosch and Gallopoulos 1989; Ehrenfeld and Gertler 1997; Esty and Porter 1998). Case studies have shown that firms that are eco-efficient can both cut costs and have a positive impact on the environment. Eco-efficiency is often defined by the amount of environmental impact generated or avoided, specifically waste produced, reused or recycled. In the classic example, multiple firms have been co-located in an industrial park in Kalundborg, Denmark so that the waste products from one firm can be used by another as an input (Gertler 1995). By finding customers for their waste products, savings are achieved in avoided cleanup costs, and by using waste products, firms can save on their raw material costs. One of the goals of examining industrial symbiosis, the cooperation among firms that leads to innovative use of waste and overall reduced environmental impact, is to demonstrate the benefits of such strategies (Chertow 2007).

This work fits in with the industrial ecology field in that it examines sustainability from the perspective of private interests. This research will complement the existing research in that it will specifically address sustainable consumption of materials and scarcity in particular.

2.4.1 Responses, Outcomes and Strategies

Manufacturers must deal with many changing conditions and uncertainty, of which changing materials availability is one variable. Responses are any action or set of actions that manufacturers take as a result of changing scarcity conditions. Outcomes are changes to the market conditions that occur as a result of the responses taken by individual firms and participants in the market. A strategy is a plan and possibly a set of steps taken to prepare firms to respond more quickly to increasing scarcity or to set firms up so that they can mitigate the likelihood of facing conditions of increasing scarcity.

Dealing with risk of disruption and uncertainty within the supply chain is a topic addressed by a growing literature intended to drive more robust and resilient supply chains and is not new to firms and supply-chain managers (Lee, Padmanabhan et al. 1997; Sheffi 2001; Simchi-Levi, Snyder et al. 2002; Pickett 2003; Rice and Caniato 2003; Kleindorfer and Saad 2005). In the context of identifying broad strategies for the supply chains, knowledge, planning, and flexibility were listed.

These strategies apply generally to all types of supply-chain management risks and are not specific to the risk of materials scarcity.

When a manufacturer faces increasing scarcity, it may have to respond by temporarily assuming the responsibility for the increases in cost, possibly even accepting some losses, or passing on the increases in cost to the consumer.

Research in the area of dealing with uncertainty and changing market conditions include alternative areas for firms to respond. One option for firms is to change their pricing and marketing strategy to deal with new conditions (Hayenga 1979). Another option is to use financial tools including hedging to protect firms from changing prices (Schwartz 1997; Christian 2006). Firms can also use inventories or stockpiles to protect themselves from uncertainty in both demand and supply (Pindyck 1994).

In this work, I will first suggest additional strategies, especially in the area of technological tools. The strategies are developed with a case analysis of a historical event leading to supply scarcity of a material: cobalt. These strategies will include:

- improving production secondary material collection to save on material costs, reusing when possible, and otherwise selling it as new scrap

- substituting high cost material for a lower cost material

- changing product design in order to reduce use of high cost material

- securing and using more old secondary material from end-of-life products

I will then examine recycling, which includes improving scrap collection and using more scrap, in detail.

2.5 Research Question: Addressing Gaps in the Literature

The concept of resource scarcity has evolved over the past two centuries. Malthus' model, while simple, was important, in that it formalized the concept that the scarcity of natural resources limits economic growth. Following Malthus' paper, many economists and scientists have explored this concept. Factors such as the existence of varying levels of quality of ore, technological progress, substitution options and environmental costs have been considered within the framework of market forces that can and in fact, do, encourage innovation.

While manufacturers rely on a steady supply of natural resources, in particular material resources, they are not generally concerned for resource scarcity except during periods of crisis (ex: oil crisis). Manufacturers are somewhat removed from the day-to-day decisions being made about resource management at both the primary level (mining and extraction) and the secondary level (recycling).

Some work has been done to try to reframe the issue of scarcity in terms that directly interest manufacturers, specifically costs-savings. However, the limitations to natural resource use discussed in the context of manufacturer concerns are often directed to limitations of our environment to absorb the waste products from extraction and processing.

The earlier work leaves a gap in the area of manufacturer concerns for resource scarcity. This raises a simple overarching question which is: should firms care about resource scarcity? Or more specifically, are there financial implications for manufacturers who do not consider material availability when making decisions about material use and material selection?

The answer to this question is: probably, yes. Knowing that resource scarcity has financial implications is not sufficiently helpful to manufacturers. Manufacturing decision-makers need to know: (1) what strategies can be implemented by firms in the manufacturing sector? (2) what are the financial advantages to strategies that mitigate the impacts of scarcity? (3) when should such strategies be used?

This research will seek to answer these questions by addressing in detail a specific aspect of these questions:

How does *increasing scarcity* impact *manufacturer concerns*? What are *strategies* that manufacturers can pursue and that retard increasing scarcity? What are the *cost advantages* to *manufacturers* of such strategies when implemented early?

For the first question, I will need to 1) develop what it means to experience increasing scarcity in a material system and 2) define a number of metrics that can be used to measure some of the wide range of manufacturer concerns. For the second question, I wish to examine strategies that can be implemented at the manufacturing level and am particularly interested in those that not just mitigate the impacts of scarcity, but also can have an impact on increasing scarcity. While responses to increasing scarcity can be implemented at any point in time or for any number of materials, strategies are plans that take time to develop and should be established before and not after crises in materials availability occur. Of the strategies that are identified, recycling is examined in greater detail. Thirdly, I examine the financial advantages on the cost-side beyond

what conventional price signals would dictate. Price, expenditures and variability of price are examined but revenues are not. I examine the value of these strategies within a given materials-market context and how the context matters in determining the value of a strategy. By including a consideration of delays in real material systems, examination of technological tools for inclusion in manufacturer strategies, rather than simply as responses to market conditions are encouraged. By examining scarcity and the dynamics of material systems and increasing scarcity, additional value to the proposed strategies may be identified.

3 Historical Case Studies: Effects of and Responses to Scarcity

Historically, supply chains have been impacted by specific examples of materials availability during the 20th century. This section examines two such cases: cobalt and palladium. The cobalt case is presented in more detail first, to better understand how materials availability has influenced supply chains and to suggest how to identify vulnerability to such risks.

3.1 Decreased Availability of Cobalt in the 1970's

The price of cobalt has always been volatile. In fact, from 1966 to 1976 and from 1980 to 2002, the year-to-year price changes of cobalt were as high as 41%. However, even these levels of variability were small compared to the shock felt between 1977 and 1979, when prices increased 380%. The price spike occurred following a rebellion in Zaire, a country which at the time constituted only 0.009% of global GDP (U.N.S.D. 2006). In response to this price swing, products, production technologies, sourcing routes, and even national policies were changed. Information on historical events and data for the cobalt crisis were taken from (NRCan 1886-2004; U.S.G.S. 1932-2006; Adelman 1978; Blechman and Sloss 1985).

3.1.1 Background: cobalt sources and applications

To many, cobalt sounds like an exotic metal with limited practical value. However, cobalt is used in a broad array of products including aircraft engines, turbines, magnets, and cutting tools. In the early 1970's, 40% of world land-based cobalt reserves were located in Zaire. Consequently, Zaire and neighboring Zambia controlled about 2/3 of world production. The major mines were located in the southern Shaba province. The Benguela railway, which passed through Angola, was the main cobalt export path. During this period, the U.S. was the main world cobalt consumer and produced no primary cobalt domestically. One single dealer, African Meta Corps (AMC), supplied all Zairian cobalt to the U.S.

3.1.2 Political events surrounding the Cobalt Crisis

Following World War II, the U.S. recognized the strategic importance of cobalt and began a stockpile. The actual stockpile inventory at the end of 1973 was of 63Mlbs; the U.S. yearly consumption was 18Mlbs. That same year, the U.S. decided to decrease its stockpile goal by selling cobalt to U.S. consumers.

Political instability around Zaire became of concern in 1975, when the Benguela railway was closed due to a civil war in Angola. Although a longer route had to be taken and consumer concern led to increases in consumer stocks, the supply disruption of cobalt from the downstream viewpoint was limited because of sales from the U.S. stockpile.

Continued uncertainty in the region led AMC to limit its shipments in 1976 to 125% of previous 15 months shipments. The U.S. government, concerned with cobalt availability, decided to restock and set a new stockpile goal of 85.4Mlbs. Moreover, there was an increase in aircraft engine and drilling demand. Still, prices from 1975 to end of 1976 only rose from $8800/t to $11880/t.

In May 1978, insurgents from Angola took over parts of the Shaba province. They cut the main power line to most major mining facilities. About 200 of the 2500 European expatriates employed as mining contractors were killed and the remainder were evacuated.

Overall, the insurgents were in Zaire for about 2 weeks. Electrical power to the mines was lost for a total of 5 days. Due to flooding and the evacuation of most expert contractors, the mines in the area were slow to restore operation. Despite all of these issues, Zaire managed to produce *more* cobalt in 1978 than the average yearly production during the years 1975 to 1977.

However, during this same time period, there was a global economic upturn that led to increased demand for many primary commodities, including cobalt. This concern for supply shortages, along with real delays in transporting cobalt out to Western countries, led to speculation. In February 1979, the price of cobalt hit $55000/t with dealer prices reported at $99000/t. Prices remained high until 1982 (see Figure 7).
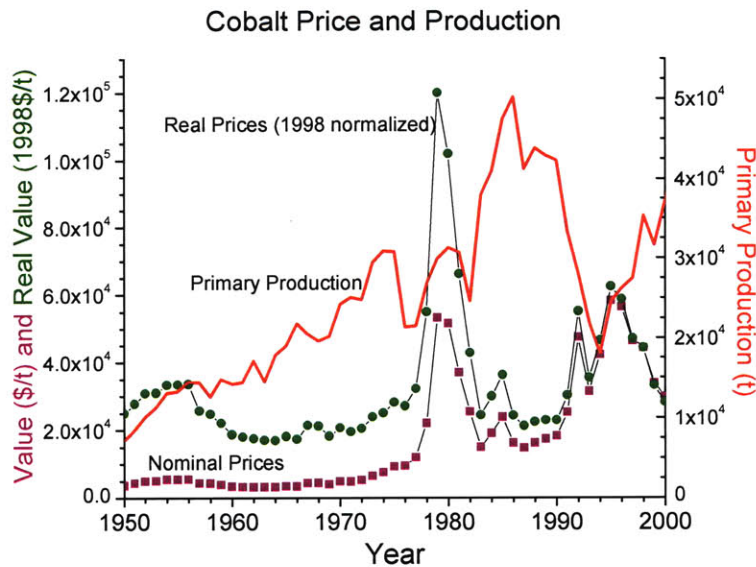
Figure 7: Cobalt average yearly prices and primary production: 1950-2000 (U.S.G.S. 1932-2006).

3.1.3   Outcomes of the Cobalt Crisis

During the period of high cobalt prices, interest in reducing the world's vulnerability to cobalt price volatility led supply-chain stakeholders and consuming country governments to act. Emphasis here will be on private responses.

3.1.3.1   Upstream Responses

Short-term upstream efforts concentrated on shortening the lead times that had increased due to the political disturbance, leading to the use of air transport. Longer-term efforts in Zaire were aimed at stabilizing and expanding existing mining operations. Zambia increased its production capacity by adding to its refining capacity and by improving recovery techniques (see Figure 8).

U.S. mining companies considered domestic mine resources, but did not increase domestic production. However, both Zambia and Australia dramatically increased their primary production capacity reducing the importance of Zaire's mining of cobalt. Such changes meant that by 2004, Zaire only accounted for 31% of world mined cobalt.
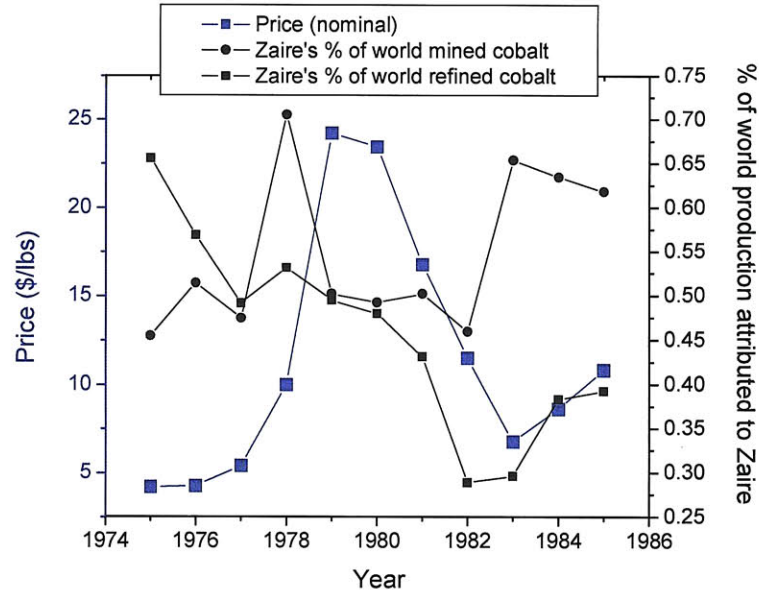
Figure 8: Cobalt prices and changes in Zaire's market share of cobalt supply (U.S. Geological Survey 1932-2006).

3.1.3.2   Downstream Responses

Component and product manufacturers also reevaluated their production options in light of the price increases. The specific changes in cobalt consumption patterns are outlined in Table 1.

Substitution to lower-cobalt-containing alloys occurred quickly in the magnet industry in applications with limitations on weight, size and energy (U.S.G.S. 1932-2006). Reducing cobalt use in superalloys was difficult because of limited substitutes and an increased demand for jet engines. In the short term, cobalt consumption in the transportation industry increased, with only some substitution to nickel-based alloys. A key change in cobalt use occurred with the development of a recycling process for scrap superalloy, resulting in a doubling of cobalt recovery after 1978.

Some substitution to iron-based and nickel-based alloys also occurred in cutting tools; however, net machinery end-use of cobalt increased slightly. Cobalt consumption in ceramics and paints also dropped because substitution in these applications was straightforward.

Table 1: Changes in cobalt uses from 1975 to 1981 (Blechman and Sloss 1985).

Cobalt Consumption End-Use	1975-1977 average		1978		1979-1981 average	
	Quantity (Mlbs)	%	Quantity (Mlbs)	%	Quantity (Mlbs)	%
Transportation (superalloys)	3.5	30	4.6	23	5.8	36
Electrical (magnets)	4.4	20	4.6	23	2.8	17
Machinery (cutting tools)	2.9	17	3.3	16	3.0	19
Paints	2.7	16	3.8	19	2.1	13
Chemicals	1.6	9	2.2	11	1.7	11
Ceramics	1.8	10	1.6	8	0.6	4
Other	0.5	3	0.3	1	0.2	1
Total	17.4		20.4		16.1	

Overall, as prices rose, the supply chain responded through:

- materials substitution and development of new technology,

- source relocation,

- hoarding and rationing,

- supply mode changes, and

- recycling

3.1.3.3 Government responses

The governments of the Western world also played an important role in influencing market stability. They controlled defense stockpiles, land use for potential mining and armies for stabilizing the affected region.

Governments first responded to the invasions by deploying foreign armies to the affected region, at the request of Zaire (Odom 1993). During the first invasion, Moroccan armies with Egyptian and Saudi backup and French airlifts aided Zaire's own armies. The concerns of the Moroccans

appeared related to fears of communism spreading while the concerns of the French appeared related to France's economic interests and interest in having a role as Africa's guardian. During the second invasion, French and Belgian armies were deployed, but only after the beginning of an expatriate massacre. During the second invasion, the Europeans' main focus was the safety of the expatriate community, many of whom were French and Belgian. Indirectly, various foreign governments, such as the U.S., provided arms to the Zairian government to fight the rebels.

In the U.S. there was the possibility of increasing cobalt production domestically and the U.S. government provided legislation to facilitate this. The U.S. redefined the Idaho wildlife area, allowing for cobalt mining at the Blackbird mine, putting environmental concerns aside for market concerns. The U.S. also passed legislation to allow U.S. commercial seabed mining of cobalt-containing nodules by 1988. Neither of these two options were ever exercised due to future restoration of Zaire cobalt supplies, making the U.S. supplies uneconomic to extract.

The U.S. also held defense stockpiles as a back-up source for short term disruptions that threatened the safety of the country. These stockpiles were not intended as a commercial stock of cobalt but were large enough to supply U.S. commercial cobalt consumption for about 2 years. Because of the cost of keeping these stockpiles, during the period before the crisis, when cobalt prices were low and cobalt supply was not yet of serious concern, the U.S. government had released and sold about 20Mlbs of cobalt for commercial uses. When cobalt became of concern again, the U.S. government decided to restock, although there was enough for more than two years of U.S. cobalt consumption at 1973-1979 average rates of consumption, including non-defense consumption.

3.1.4 Conclusions on the Cobalt Case

Cobalt was selected for this case study because it is an important example of the resulting extent of the outcomes of material availability disruptions. Outcomes from market instability-derived availability problems extended from price increases to product changes requiring substitution to newly developed materials. The extent of the outcomes appears to have been exacerbated by the high global dependence on production from a single region, Zaire's Shaba province, and by the importance of cobalt for crucial defense applications leading to increased concern, hoarding, and speculation.

The relevance of this study of materials availability is highlighted by each of the outcomes of the disruption.

- increased costs

- source relocation

- materials substitution and development of new technology

- supply mode changes

Increased costs were incurred in the transportation industry where there was increased demand for commercial airplanes and lack of substitutes. Needs to reduce costs were obtained by tapping into new sources in the form of increased recycling. Cobalt-intensive magnetic materials were substituted by new magnetic materials, allowing the electrical industry to reduce their cobalt needs. Cobalt refineries were moved from Zaire to neighboring Zambia to insulate parts of the supply chain (especially foreign employees) from the political instability.

The events surrounding the supply disruption highlight some factors that influence materials vulnerability to market instability. Three issues increased the effect of the disruption:

- poor geographic distribution of sources

- monopsony market conditions and

- lack of substitutions for an important applications, in this case defense-related applications

 A large aspect of the price spike was based on speculation, related to the fact that Zaire alone controlled such a large part of the global primary cobalt market.

The U.S., the largest consumer of cobalt, depended on a single supplier for all its Zairian cobalt. This supplier's decision to impose allocation limitations on sales, which they maintained from May 1978 to July 1980, and increased lead times for delivery of supplies, affected the whole U.S. cobalt market. This increased the impression of cobalt shortages and encouraged commercial holding of cobalt stocks, creating additional market pressure.

Cobalt's importance in defense applications and lack of substitutes in those applications increased pressure on the U.S. government to increase the defense stockpile at a point in time when supply for commercial uses of cobalt was already low. The government's actions added to the uncertainty in the market even if no cobalt purchases for the stockpile were made between the time it increased the stockpile goal, in 1976, and the beginning of price drops in 1981.

The factors that influenced cobalt vulnerability were indicators of the possibility for market instability. Actions by various players in the cobalt supply chain were able to both reduce and increase the negative effects of the supply disruptions.

- Upstream supply chain efforts to find new sources of cobalt were not particularly fruitful. Imposed allocations by the sole Zairian cobalt supplier only increased market uncertainly and possibly extended the length of the disruptions.

- Downstream supply chain efforts were generally positive. Consumption of primary cobalt was decreased by material substitution and increased recycling.

- Although, the U.S. government held stockpiles of cobalt and was an important second source of cobalt, it could not continue supplying the U.S. market in the long term. The sales of cobalt from the stockpiles between 1973 and 1976 only artificially kept cobalt prices down. The government's decision to stop sales from the stockpile and restock in 1976 resulted in a sudden decrease of domestic supply and increase of demand, resulting in a sudden change of the cobalt market.

- Supply-chain managers' decisions to change transportation path improved lead times in the short-term.

- The US government was also a dominant (potentially fickle) consumer. When demand from this dominant consumer increased during the crisis, the supply chain could not respond and prices climbed.

3.2 Decreased Availability of Palladium in the 1990's

The case of palladium is similar to the case of cobalt and is only briefly discussed to demonstrate that the concerns raised in the cobalt case are not unique to a single historical event. Stakeholders in the platinum group metal (PGM) supply chain experienced palladium shortages in the late 1990's.

In 1997 Russia produced 43% of global palladium. At the same time as Russia cut its shipments of palladium by about two thirds, global demand skyrocketed, especially in the automotive industry (38% annual growth). As a result, demand far outpaced supply of palladium (U.S.G.S. 2009) and real prices quadrupled over the three-year period between 1997 and 2000.

This dramatic price increase led to equally dramatic changes in demand: demand in 2002 was almost halved from 1999 peak levels (Johnson Matthey Precious Metals Marketing 2008). 2007 demand remained below 1999 levels, despite relatively healthy growth (see Figure 9).

While all industries that use platinum experienced the same higher prices, some experienced much larger changes in their yearly spending rates than other industries (see Figure 10). While real prices increased by almost 4 times, demand for palladium in the automotive industry also grew and total spending rate for palladium by the global automotive industry in 2000 was estimated to be almost 7 times greater than the 1997 spending rate. For jewelry, the 2000 spending rate was about 4 times greater, about the same as the price increase, and in dental applications the 2000 spending rate was just 2.3 times greater than the 1997 spending rate.
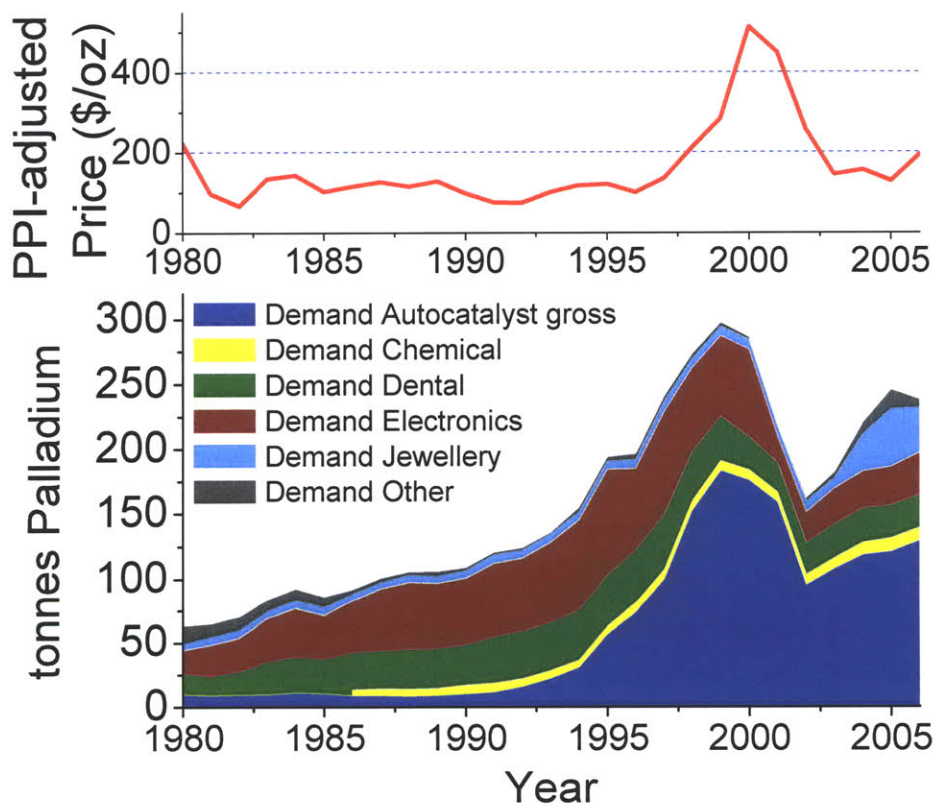
Figure 9: Historical palladium demand response as a result of price increases (Johnson Matthey Precious Metals Marketing 2008).
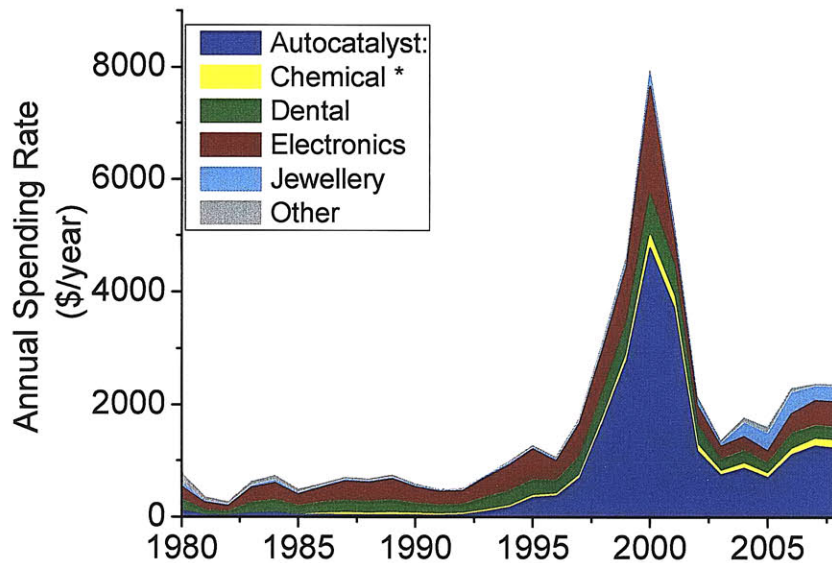
Figure 10: Palladium indsutry-level spending rate.

3.3 Case Study Conclusions: Costs of Increasing Scarcity and Strategies that Mitigate the Impacts of Scarcity

The cobalt and palladium cases exemplify increasing scarcity due to supply concentration. In both cases, a large percentage of world supply of a given metal depended on a single country's production and global markets were severely impacted when local supply interruptions occurred.

The responses to the material price excursion reveal the difficulties that firms can suffer in the face of resource scarcity, as well as the complexity of the resulting firm responses. These historical examples highlight the need for better consideration of the consequences of unexpected materials scarcity for firms reliant on their upstream material suppliers. Manufacturers' strategies in the face of price increases require time to implement and therefore reacting only *post facto* to increasing prices is a poor mode of managing risk. While this retrospective demonstrates that resource scarcity can significantly impact the firm, it also underscores the importance of the tactical questions that such firms should consider: (1) What and how critical are the risks for increased material scarcity, (2) How to make the best use of current information to assess the gravity of resource scarcity risks and (3) How to respond to increasing scarcity.

Suggested strategies from these case studies include recycling, substitution and reduced material usage. These three actions are also considered important towards improving long term material availability and environmental sustainability (Gordon 1987; Ayres 1997). This work shows that actions that mitigate risk of short term increased scarcity can also lead to improved long term material and environmental sustainability.

4   Forms of Information to Screen for Increasing Scarcity

While historically, material prices and price volatility have not shown a strong increasing trend, concern still exists for manufacturers. The historical case study describing events within the cobalt supply chain during the mid to late 1970's demonstrated that materials availability can affect a number of aspects of supply chain operation, on which manufacturers depend. It is expected that material availability problems could result in any or all of the outcomes observed in the historical cases.

As mentioned previously, the literature on supply chain management suggests that supply-chain managers must know their supply chain [15, 16]. In the case of materials availability, this includes not only monitoring metrics of risk, but also to foster the existence and exchange of information to ensure accuracy of those metrics. Armed with information, managers can identify how and when to modify their supply-chain practices.

The first key challenge is to identify those elements within their own supply chains which may be vulnerable. This section will begin to address this question by examining the usefulness of a range of metrics which have been proposed to provide insight into the vulnerability of existing materials markets. The following is a review of metrics that have been used when discussing future materials scarcity. These metrics have been categorized and framed here as additional tools for manufacturers to aid in their materials selection process. Given the past literature focus on global social welfare, these metrics are not specifically tied to manufacturer concerns.

4.1   Defining Metrics

The problem for those attempting to ascertain resource scarcity is the complexity of a materials economy. Reducing this complexity to a manageable set of indicators has been an ongoing effort. While a variety of simplifying abstractions have been employed to successfully tease out certain insights about resource scarcity, no single approach retains the generality necessary to cover all possible presentations of "scarcity." The history of mercury serves as an example of this shortcoming. In 1972, mercury was identified as becoming critically scarce (Meadows, Meadows et al. 1972). However, through the intervention of market forces, by 2004, mercury had a static depletion index (reserve base) approaching 200 years (U.S.G.S. 1932-2006). Nevertheless, business decisions must continue to be made. This section examines how careful application existing metrics can provide insights to guide a firm's strategy.

The most fundamental question of metric construction is "what does it mean to be '*scarce*'?" When estimating the scarcity of a resource, there are a host of competing rates, which can also be viewed as "*drivers of availability*". Metrics must somehow assess the evolution of these rates against the amount of extracted and as-yet unextracted resource (see Figure 1). Based on the literature and the preceding case analysis, the authors propose two mechanisms that result in materials scarcity:

- *institutional inefficiency*: failures by markets, firms and governments can result in transitory resource unavailability

- *physical constraints*: the amount and quality of a resource is physically determined and ultimately limits resource availability

These perspectives on the mechanisms of scarcity provide a useful scheme to categorize metrics that have emerged over time in the literature. The cobalt case illustrates scarcity from purely institutional mechanisms. More conventional notions of scarcity, as discussed previously in the section on Scarcity Literature, can be traced at least as far back as the writings of Thomas Malthus (Malthus 1798). In his presentation, scarcity arises from physical constraints, occurring when extraction exhausts resources. In the early 19th century, economist David Ricardo refined this notion of physical constraints, based on the observation that resources exist in different levels of quality. As such, scarcity is not a consequence of exhaustion, but instead derives from the increasing difficulty and cost of access (Ricardo 1821, first published 1817).

4.1.1 Institutional inefficiency metrics

An example of institutional inefficiency was the cobalt crisis of the late 1970's[8] when a rebellion in Zaire shut down production of mines in the main cobalt producing area of the country. Institutional inefficiency leads to supply disruptions that may be significant to individual firms and specific markets, even if the aggregate source is sufficient to satisfy world demand. An example of a type of institutional inefficiency is a government-imposed quota preventing imports of an otherwise globally available material. Institutional inefficiency has also a technological component and can play a role in the dynamics of materials leverage points.

Interestingly, few reports have been found that considered the aspect of institutional efficiency and materials availability. A single chapter of Chapman and Roberts' book on metal resources is

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[8] Cobalt has always been a material with a volatile price. In fact, from 1966 to 1976 and from 1980 to 2002, the year-to-year price changes of cobalt were as high as 41%. However, even these levels of variability were small compared to the shock felt by the market in the late 1970's. Between 1977 and 1979, the price of cobalt increased 380%, climbing from $5.20/lbs to $25/lbs ($11440/t to $55000/t). The price spike occurred following a rebellion in Zaire (now the Democratic Republic of Congo) prevented all supplies of Zairian cobalt from reaching world markets.

devoted to the political aspect of materials availability (Chapman and Roberts 1983). It suggests that increasing scarcity could result in an increase of the frequency of small supply disruptions. Developed nations have already extracted a large portion of their natural resources (especially Europe) and are imposing increasingly stringent environmental regulations that limit further exploration. As a result, it was predicted that future known metal sources would be increasingly concentrated in developing nations and the concentration of sources in a few, possibly unstable countries could lead to more significant disruptions.

Institutional inefficiency leading to disruptions of materials leverage points is an aspect of scarcity that is very much applicable to a firm-level perspective. This mechanism of scarcity may have been largely ignored in resource availability literature. Moreover, the technological component of institutional inefficiency, although it increases the complexity of the scarcity question, is a component that may be dealt with at a firm level and not just a policy level.

As the cobalt case study demonstrates, short-term problems, even in isolated areas of the world, can result in global disruptions to the supply of a material. Some scarcity metrics that derive from notions of institutional efficiency are outlined in Table 2.

The most broadly-cited measures of vulnerability to institutional inefficiency focus on concentration within the supply chain, at either the national (Chapman and Roberts 1983) or firm level (McClements and Cranswick 2001).

In the cobalt case, the geographic and industrial structure of supply and demand affected material availability. Generally, the geographic distribution of reserves depends on geophysics, past depletion, and present exploration. Consequently, resource distribution is uneven and, in most cases, extraction is concentrated in a small number of countries. In the face of uncertain external factors (such as political events or natural disaster), concentration makes a resource more susceptible to institutional inefficiency and supply disruptions (Chapman and Roberts 1983). Likewise, oligopsonistic markets are more vulnerable to fluctuations in demand, leading to market volatility.

An examination of the availability of secondary sources yields another perspective on supply chain concentration. In the cobalt case, recycling became an important supply source. Recycling rate can be an indicator of the importance of scrap as a resource (U.S.G.S. 1932-2006). Thus, higher recycling rates can be an indicator of lower vulnerability.

The ability of a supply chain to modify availability through secondary sources is ultimately limited by access to such materials. The recycling efficiency rate (RER) or recovery rate metric provides insight into this issue (Ruhrberg 2006). Unfortunately, RER is difficult to measure and data must be derived from modeling such as material flow analyses.

The final metric of institutional inefficiency listed in Table 2 is the market price of the commodity of interest. As a number of authors have indicated, price is one of the best measures of scarcity insofar as the market embeds many of the issues outlined above (Cleveland 1993). However, from the perspective of informing supply-chain strategy, price is not a leading indicator; while price will ultimately be the trigger that initiates supply-chain changes, effective response strategies must already be in place.

Table 2: Measures of institutional efficiency.

Metrics and Indicators	Description
Geographic Structure based on Supply (%) (Chapman and Roberts 1983)	Distribution of reserve size in top countries Assumption: supply diversity increases efficiency
Geographic Structure based on Production (%) (Chapman and Roberts 1983)	Distribution of production in top producing countries Assumption: supply diversity increases efficiency
Institutional Structure based on Production (%) (McClements and Cranswick 2001)	Distribution of control by most important company Assumption: supply diversity increases efficiency
Institutional Structure based on Consumption (%) (McClements and Cranswick 2001)	Distribution of applications and companies that consume a given material, identification of new uses of the material Assumption: demand diversity increases efficiency
Recycling Rate (%) (U.S.G.S. 1932-2006; Ruhrberg 2006)	Scrap consumption divided by total consumption Assumption: reliance upon recycled resource increases efficiency; greater confidence in supply
Recycling Efficiency Rate or Recovery Rate (unitless) (Ayres, Ayres et al. 2003; Ruhrberg 2006)	Old scrap consumed divided by total material at end-of-life Assumption: reliance upon recycled resource increases efficiency; greater confidence in supply
Economic Metric: Market price ($) (Chapman and Roberts 1983)	Time trend and volatility of price. Assumption: efficient markets

4.1.2 Physical constraint metrics

The outcomes to supply chains arising from institutional inefficiency in the cobalt case could also have occurred from physical constraints (Chapman and Roberts 1983). In this section, metrics drawn from literature will be briefly discussed, but their interpretation will be made through the case study which follows.

4.1.2.1 Malthusian Metrics

The direct approach to measuring vulnerability to geophysical limits is to compare how much there is with how fast it is being consumed. These metrics attempt to balance a notion of the total amount of a resource that is available against the rate at which that resource is being consumed. Table 3 includes Malthusian-inspired metrics from the literature. The metrics are divided into two broad categories (static or dynamic) depending on the degree to which they treat the varying nature of the many interrelated rates (see Figure 1).

The static index of depletion is an estimate of the years to exhaust a material supply based on present consumption rates and one of the four estimates of supply: reserve, reserve base, resource or resource base. The dynamic index of depletion is a simple extension that includes changing consumption rate, for which expected consumption is derived from historic data. Any given material with a low depletion index is considered more vulnerable than one with a high index of depletion.

The simplicity of Malthusian metrics is a major advantage: depletion is related to how fast a non-renewable resource is consumed. Moreover, the required data is generally readily available.

The depletion indices metrics assume a decreasing supply base for non-renewable resources. However, new discoveries, improved technology and increased recycling have contributed to supply increases in the past. Taking this into account, one can classify materials with a rate of supply growth less than the rate of increasing consumption as vulnerable (Malthus 1798; Gordon, Bertram et al. 2006). It has also been argued, especially for oil, that resource scarcity will occur when production peaks with Hubbert's peak for oil and oft cited example (Hubbert 1962).

Table 3: Measures of physical constraint including static and dynamic Malthusian metrics and Ricardian metrics.

	Metrics	Description
STATIC	Static Index of Depletion (years) (Meadows, Meadows et al. 1972; MMSD 2002)	Time to consume supplies at constant consumption rate: Supply/(present consumption rate); $d_s = Supply/ C_{present}$. *Assumptions: consumption rate constant; discovery and recycling rates negligible*
DYNAMIC	Exponential Index of Depletion (years) (Meadows, Meadows et al. 1972; MMSD 2002)	Time to consume supplies at constant exponential growth of consumption rate: Supply/(projected consumption), where future consumption can be modeled as having exponential growth; $d_e = \frac{1}{r} \ln\left(r \frac{Supply}{C_o} + 1 \right)$, where r is rate of growth. *Assumptions: consumption rate exponential; discovery and recycling rates negligible*
	Relative rates of discovery and extraction (unitless) (Malthus 1798; Gordon, Bertram et al. 2006)	Ratio of rate of discovery to rate of consumption. *Assumption: recycling/reuse and substitution negligible; improvement in extraction technologies negligible*
	Time to peak production (years) (Hubbert 1962)	Time until this forecast peak is reached: based on models of future rates. *Assumption: rate of net consumption (demand less substitution) will grow faster than rates of discovery, technological improvement and recycling/reuse*

RICARDIAN	Average ore grade (%) (Chapman and Roberts 1983; Ayres, Ayres et al. 2003)	Concentration of metal in a given ore body *Assumptions: efficient markets in factors and capital; technological efficiency; accessibility effects negligible*
	Cost ($) (Barnett and Morse 1963; Chapman and Roberts 1983; Cleveland 1993)	Sum of technical costs (machines, fuel, labor, etc.), environmental costs, political costs, commercial costs (marketing, insurance, stock dividends) Assumptions: efficient markets in factors and capital; technological efficiency
	Economic Metric: Market price ($) (Barnett and Morse 1963; Chapman and Roberts 1983; Cleveland 1993)	Relative price, time trend. Assumption: efficient markets

One criticism of Malthusian metrics is that, since many of the parameters are based on historical data, the effects of new technologies that may increase demand or improve efficiency are not considered. Additionally, the choice of defining supply as the reserve or resource appears arbitrary without an understanding of the technology and economics of extraction.

4.1.2.2 Ricardian Metrics

Malthusian metrics generally ignore variations in the quality of a source, which are tied to the level of effort required to obtain additional material. From a Ricardian viewpoint, scarcity should occur long before physical exhaustion as high quality sources will be preferentially consumed and, future availability would decrease with increases in the difficulty of extraction (Barnett and Morse 1963). Ricardian metrics of global availability are presented in Table 3.

The ore grade is a physical measure of the quality of supply (Chapman and Roberts 1983): in general, the lower the ore grade, the more earth will be displaced, energy will be expended, and waste will be generated to extract the resource. Unfortunately, ore grade does not entirely capture the accessibility of the supply; an ore body at the surface of the earth's crust is more accessible

than one underground. Moreover, extraction from certain minerals is more difficult than from others (oxide minerals vs. sulfide minerals).

A more informative measure of quality is the cost of extraction. Increasing extraction costs indicate the changing nature of the available resources and would be expected to correlate with increasing vulnerability. Barriers to using cost as a metric are lack of public data and the subjectivity involved in defining analytical scope. Due to the difficulty in obtaining complete cost data, reports have focused on energy, labor, or capital costs (Chapman and Roberts 1983; Cleveland 1993). These simplifications can weaken the utility of cost as a metric of scarcity.

Metal prices are sometimes used for analyzing physical constraints. From a business perspective, price may not provide adequate notice to manage risk, especially when considering taking actions such as increasing recycling, materials substitution and dematerialization.

4.2 Limits of Metrics

In summary, the limits of using metrics for identifying risk of scarcity can be illustrated with an example of two materials, one with low consumption growth such as lead and one with fast consumption growth such as copper. With the static depletion index based on reserves, consumption rate is assumed constant. The static depletion index of lead is 2/3 that of copper. Therefore, this metric indicates that there are higher levels of risk for scarcity associated with lead (see Table 4). However, the dynamic depletion index based on reserves, which assumes that the historic consumption growth rate will continue into the future, indicates that risk for copper scarcity is as high as that for lead.

Table 4: Comparison of metrics for copper and lead (U.S.G.S. 1932-2006).

	Copper	Lead
Static depletion index based on reserves for 2004 (Reserves/primary consumption rate, years)	32	21
Growth rate	4.4%	1.3%
Dynamic depletion index based on reserves (years) $d_e = \dfrac{1}{r} \ln\left(r\, \dfrac{Supply}{C_o} + 1 \right)$	20	19

Interestingly, both lead and copper have experienced significant price excursions in the past few years, with a four-fold increase in copper prices and a five-fold increase in lead prices between 2003 and 2007 (see Figure 11). The low 2004 depletion indices may have played a role in the subsequent price excursions, but there are definitely other factors to consider. For example, gold, with a static depletion index of 17 years, and platinum, with a static depletion index of 300 years, both saw their price essentially double in the past 5 years.
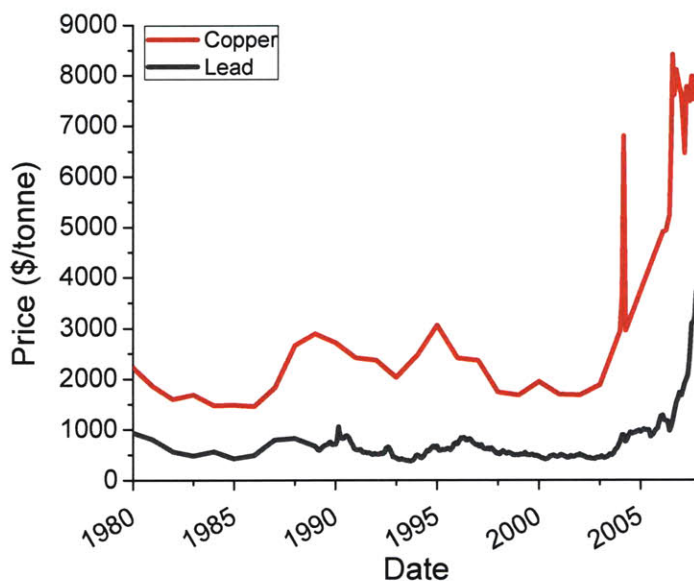
Figure 11: Prices for lead and copper from 1980 to 2007 (USGS and www.metalprices.com).

The question that arises in the use of metrics is what values indicate a need for action? Unfortunately, the real answer to that question derives from the complex interaction of the characteristics of known and unknown resources, the evolution of future demand and production technology, the effectiveness of secondary recovery, and changes in cost, price and the elasticity of substitutes. The development of such models includes the research described in this document

5 Building a Simulation Model

The results of the historical case study indicated that system characteristics (supply concentration in one region), system changes (supply scarcity), and actor behavior (government and private firms) affect system performance. It also showed that system changes towards increased scarcity led to responses that largely depended on characteristics of the different industries that used cobalt, in particular, their dependence on cobalt. For example, the magnet industry substituted their cobalt-based alloy materials for a new and less expensive substitute material that used less cobalt but was only able to do so because the research had been done on the new materials before the crisis had started. On the other hand, the defense industry had few alternatives to using cobalt and with this concern in mind, the US government focused on increasing defense stockpiles.

In some cases, these responses helped reduce scarcity and, in other cases, they probably worsened the crisis. I wanted to be able to analyze the effect of such responses on system performance. I believe the best way to accomplish such an analysis is to define system performance metrics and to measure them using a model that can project certain system attributes over time and into the future. The system attributes that need to be included are primary supply, recycling, demand and price feedback dynamics. Moreover, one of the desired criteria in building the market model was to have the model reflect the behavior observed in the market that can affect manufacturers downstream.

In summary, my modeling strategy is to model how I believe markets behave in general and how prices and costs are determined endogenously within this market framework and then to use this model to test firm strategies. Markets do not always perform efficiently and inefficiencies such as implementation delays, disruptions, and poor decision-making by market actors are to be included in the model. In 5.2, the assumptions about the structure of a materials market will be described in more detail.

Many models have been built to examine resource scarcity. A few were discussed in the literature section (section 2). Techniques that have been used include analytical modeling, econometrics, optimization and simulation. Some of the most important work in the field of resource scarcity uses analytical modeling, including, the seminal work of Hotelling in 1931 (Hotelling 1931). Econometric models require access to historical data and have also been important to examine areas such as price cycles and trends (Labys, Lesourd et al. 1998), recycling drivers (Slade 1980; Blomberg and Söderholm 2009) and the effect of technology on extraction rates (Cleveland and Kaufmann 1997). Gordon et al. built an optimization model to examine the long term effect of

copper depletion and the transition towards backstop technologies and substitution materials (Gordon 1987).

For this work, a simulation technique, system dynamics, was selected. System dynamics is a numerical simulation technique that uses a system of interdependent non-linear first order differential equations to represent a complex system. System Dynamics modeling can address questions that may not be possible to model with a closed form model. It provides a framework that is especially suitable for understanding inefficiencies, inhomogeneous behavior among different actors and delays. It also provides a framework to track material and information flows separately over time.

A system dynamics model of a material system was built using platinum as a case study. The system dynamics modeling will be supported by econometric regression modeling that will focus on individual platinum market sectors separately. For example, regression modeling will be used to examine demand and supply elasticity to price. Historical data will be used to build a model to reflect the observed real-world behavior of the platinum system.

Systems with complex feedbacks such as material markets and the supply chain have been studied previously using a simulation method called system dynamics with ordinary differential equations.

One of the best-known system dynamics model was in the area of global resource scarcity. Meadows et al. examined whether and how limited resources could impact future economic growth (Meadows, Meadows et al. 1972). They determined that the greatest concern would be under scenarios where there is both rapid growth and long delays in signaling scarcity.

Another notable work in the area of resource scarcity was done by Sterman et al (Sterman and Richardson 1985). They pointed out, in the context of a modeling study of global oil reserves, that the greatest concern for physical exhaustion is not so much that it could occur, as, that it could occur unexpectedly due to overestimation of recoverable resources. Sterman and Richardson noted that overestimation of resources could result in inefficient allocation of exploration effort, overvalued lease tracts and complacency in the development of substitutes & recycling infrastructure.

System dynamics has also been used in the area of supply-chain management, especially in understanding the bullwhip effect (Angerhofer and Angelides 2000).

Urbance et al. from the MIT Materials Systems Laboratory modeled the magnesium material system using system dynamics (Urbance 2001; Urbance, Field et al. 2002). The model of the magnesium system was used to simulate magnesium prices as a result of increased interest in

magnesium by the automotive industry. An observation derived from the model was that while increased magnesium interest by the automotive industry would occur if the magnesium market became more stable and the magnesium price decreased, an increased demand by the automotive industry would result in a magnesium price increase and potentially destabilize the market. Unless the structure of the magnesium market changed, it was unlikely that magnesium could replace steel at the prices desired by the automotive industry. Rather than predict that magnesium prices would increase or decrease, the model used by Urbance et al. identifies barriers to the entry of magnesium in the automotive industry as a result of the structure of the magnesium and automotive markets.

The following sections will (1) introduce the platinum material system which will be used as a case study, (2) describe the modeling approach, the model structure and its mechanisms, (3) describe the data incorporated into the model and (4) describe the process used to calibrate and set up the model.

5.1   Use of a Case Study: Platinum

The market model was built by examining a specific material market and using it as a case study for understanding scarcity concerns for manufacturers. By using a case study, it is possible to calibrate the model's behavior against actual historical data but still examine alternate scenarios and conditions that should provide broader insights into other materials systems.

Platinum was chosen for this study of resource scarcity. It is representative of many other metals in that it is recyclable, is sold on commodity markets, and possesses properties that make it industrially valuable. Yet, it is a unique system that is in some ways easier to model than many other materials. Extensive data is publically available and given that the platinum market is dominated by a few large firms, the data is easily collected. Also, platinum is generally recovered to primary platinum quality and so this allows for simplification when modeling the recycling sector: secondary platinum can perfectly substitute for primary platinum.

5.1.1   Motivation for selecting platinum from a scarcity perspective

There are three aspects of the platinum market that make the platinum system particularly interesting for this study.

The first is the high concentration of platinum supply measured on both a firm and geographic basis. Primary supply of platinum is concentrated in South Africa (75% of production, 88% of

reserve base) (U.S.G.S. 2005) (see Figure 12). Five companies (Anglo Platinum, Norilsk Nickel, Implats, Lonmin and Inco) control most of the supply (Hagelüken 2005).

The second is the potential for a large increase in demand for platinum if proton exchange membrane fuel cells become a key component for reducing greenhouse gas emissions in the transportation sector. PEM Fuel cell technologies typically use platinum to catalyze the electrochemical reaction that produces electricity. Estimates of platinum requirements for a typical fuel cell car range between 15 and 100g/car, significantly more than the platinum used for a typical catalytic converter (~5g/car) (TIAX and Carlson 2003). Presently, the known substitutes for platinum in PEM fuel cell applications perform very poorly relative to platinum. Moreover, potential substitution options are other platinum group metals, such as palladium, which are mainly mined alongside platinum.
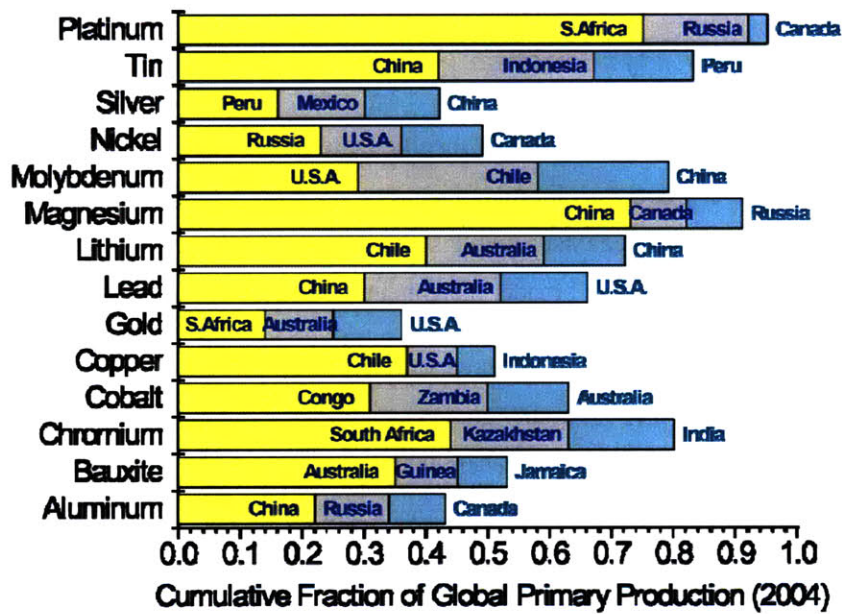
Figure 12: Country distribution of primary production (U.S.G.S. 2005).

The third concern is that cost of extraction is more susceptible to energy price increases than that of most other metals because of typical platinum ore grades. Platinum ore grade is 3 orders of magnitude lower than copper, nickel, tin, zinc or lead (see Table 5).

Platinum reserves relative to primary production are much larger than those of other metals (Reserves/Production in Table 5). Geophysical supply of platinum is abundant relative to demand for the metal.

Table 5: Comparison of metrics of scarcity for metals. References are: Ore grade (Ernst 2000), price (monthly average for October 2007, www.metalprices.com), energy (Simapro, Ecoinvent database), Reserves/Production (U.S.G.S. 2005), Recycling Rate and Recovery Rate in US from USGS Recycling Circular 1998/2000, data for 1998 (U.S.G.S. 2009).

Metal	Ore grade (wt %)	Price ($/tonne)	Energy (MJ/kg)	Reserve/ Production (years)	Recycling Rate in US (%)	Recovery Rate in US (%)
Magnesium	70-95% MgCO$_3$, brine 3% Mg	2938	257	Very large	33	39
Aluminum	35-50% Al$_2$O$_3$	2391	201	157	36	42
Iron	30-65% Fe	645	12	112	41	52
Lead	4-8% Pb	3227	21	21	63	95
Zinc	2-4% Zn	2881	85	23	27	19
Copper	0.2-5.0% Cu	7773	64	32	32	66
Nickel	1.5% Ni	30,748	195	44	36	
Tin	0.5% Sn	15,023	324	23	22	75
Cobalt	0.4% Co, byproduct of Cu, Ni, Ag	65,725	132	134	32	68
Silver	0.006% Ag, byproduct of gold and base metals	415,080	Not available	14	32	97
Platinum group metals	0.0003-0.002% PGM, sometimes a byproduct of Ni-sulfide ores	42,331,189	196,000-846,000	332	16	76

5.2 Overview of the Dynamics in Material Markets

As mentioned above, the modeling strategy is to attempt to capture the key market behavior and then to use the model to test firm strategies. The importance of market forces and prices in determining long-term material availability has previously been emphasized by many who have addressed this issue (Barnett and Morse 1963; Slade 1992; Simpson, Toman et al. 2005). It has also been noted that market forces may not always lead to optimal mineral extraction, especially where geological information is inaccurate or incomplete (Pindyck 1978). Incorporating the effect of market forces is a key aspect of the modeling strategy.

Figure 13 depicts broadly how I view a material market where primary and secondary resources are perfectly substitutable for each other (ex: platinum).
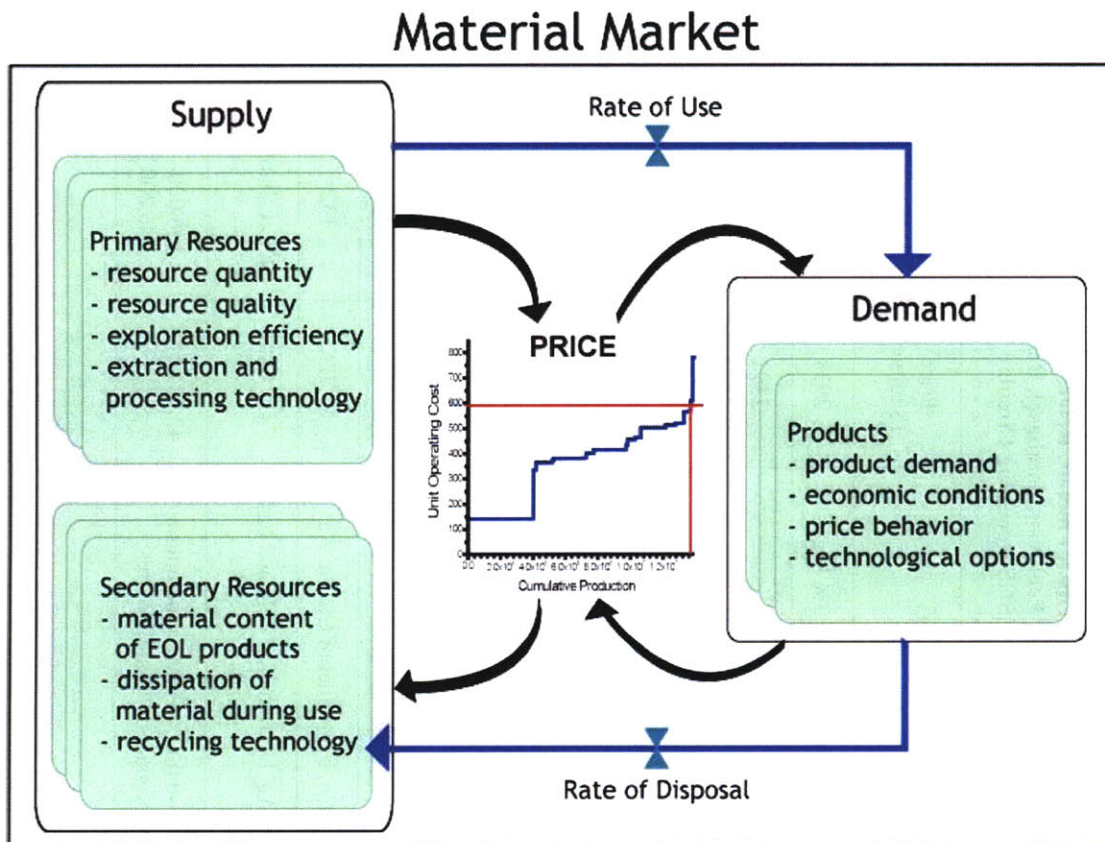
Figure 13: Model Structure Diagram. Three sectors are used to describe a material market: primary and secondary supply, price and demand. The key information desired to describe supply and demand is also listed.

There are three key sectors in a material market: supply, demand and price. Material flows from the supply sector to the demand sector (represented by blue arrow with a valve labeled "Rate of Use").

This material flow is the amount of material sold and used. When products reach their end-of-life, they are disposed of and become secondary resources (represented by blue arrow with a valve labeled "Rate of Disposal"). Information about the amounts produced and offered on the market, the costs of production and the amounts purchased (represented by black arrows from the supply and demand sectors to the price sector). Price then informs the supply sector which must decide how much to produce in the next time period (represented by a black arrow from the price sector to the supply sector). Price also informs the demand sector which much decide how much to plan on purchasing in the next time period (represented by a black arrow from the price sector to the demand sector).

In the model, changes in price occur when there are imbalances between supply and demand. The supply curve is modeled by aggregating the supply from individual suppliers subdivided by region, each willing to offer a set quantity of material at a given price (Tilton 1977). Supply increases with increasing price, all else being equal. Gross demand is a sum of the demand from manufacturers of consumer goods or parts for consumer goods. Demand decreases with increasing price all else being equal.

The evolution of supply and demand are not just based on price, but also on a number of other factors such as resource quality and ability to extract the resource over time, economic conditions, demand for products that use the material and the amount of material needed to produce a given product over time. The time factor is important to emphasize here and the factors listed should be thought of as evolving over time. Evolution of technology has been especially important in the past in changing material system characteristics.

5.2.1 Dynamic Behavior of a Material System Described using System Dynamics Terminology

To build the system dynamics model, the above market structure diagram was deconstructed to identify stocks, flows and feedback loops. The following section uses terminology specific to system dynamics and the vocabulary may be unfamiliar to the readers[9]. Figure 14 is a system

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[9] System Dynamics Terminology: (sometimes it is easiest to use an example to explain the terminology, refer to Figure 14 for the examples)

Stock (depicted with a box): Represents a level, or amount of material, ex: material resources

Flow (depicted with a line and valve): Represents a rate of change of a stock of a material. ex: extraction rate

Causal Link (depicted with a curved arrow): Links two variables that are related by cause and effect.

Positive Causal Link (depicted with a curved arrow and a + sign): ex: an increase in demand causes price to increase

dynamics stocks and flow diagram of the model of the platinum market. The following is a description of the diagram using system dynamics terminology.

Primary supply is limited by how much ore is available and known and how easily that ore can be extracted (Bp: balancing or negative loop). Price and primary supply are related by three loops, B1, R1 and B4. First, mining companies will increase their production capacity when prices rise and their potential profitability increases but by increasing their mining capacity, these mines will be increasing primary supply and when primary supply increases, all else being equal, the price can then decrease. This is represented by the balancing loop B1 because the initial increase in price leads to a chain of effects that then balance the initial increase with a decrease in price following delays. This does not mean that the decrease in price will offset the initial increase in price, rather it means that there will be some decrease that may be of different magnitude to the initial increase. In particular, the causal link between price and primary production capacity occurs following a significant delay due to the high capital costs and potential regulation limitations for building new mines. In the shorter term, mining companies wish to maintain cash flow to cover costs, maintain capacity utilization, avoid labor force size changes and satisfy investors (Mikesell and Whitney 1987; Tilton, Eggert et al. 1988; McIsaac 2008). This is represented by the reinforcing loop R1: when prices increase, cash flow increases, mines reduce production by extracting lower quality ores and supply decreases which reinforces the initial price increase. Finally, it is important to note that increasing primary production leads to increasing depletion of primary resources and all else being equal, higher costs of extraction and higher prices (B4). This effect can be dampened with improved technology of extraction.

Demand and price are related by a balancing loop, B3. Following a price increase, demand decreases and when demand decreases, all else being equal, price will decrease. There can be long delays before manufacturers are able to find substitutes when price increases, as depicted by the hash marks on the causal link arrow that goes from price to demand. Also represented in the figure

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Negative Causal Link (depicted with a curved arrow and a – sign): ex: an increase in supply causes price to decrease

Delay (depicted with a double hash mark on a curved arrow): the average amount of time for the variable at the end of the causal link to respond to a change.

Balancing Loop (depicted with a B): The causal links form a loop that leads to goal-seeking behavior. For example: an increase in price leads to a decrease in demand which then leads to a decrease in price.

Reinforcing Loop (depicted with an R): The causal links form a loop that leads to reinforcing behavior. For example: increasing consumption leads to increasing disposal when those products reach end-of-life which leads to increasing supply of secondary which leads to decreasing price which leads to increasing demand and increasing consumption.

is an exogenous factor: economic growth. In many applications, the demand for platinum is derived from the demand for the products that use it. The economic market conditions, unrelated to the platinum market, can exogenously affect demand.

For platinum, which is recycled to a form that is indistinguishable from primary platinum, the supply is the sum of primary and secondary materials. Secondary supply is related to price by two loops, B2 and R2. The balancing loop, B2, describes how increasing price leads to increasing collection of end-of-life products. However, increasing price also leads to decreasing demand and in the long run, less material available for recycling (R2). With less material available for recycling, supply of secondary decreases (Br).
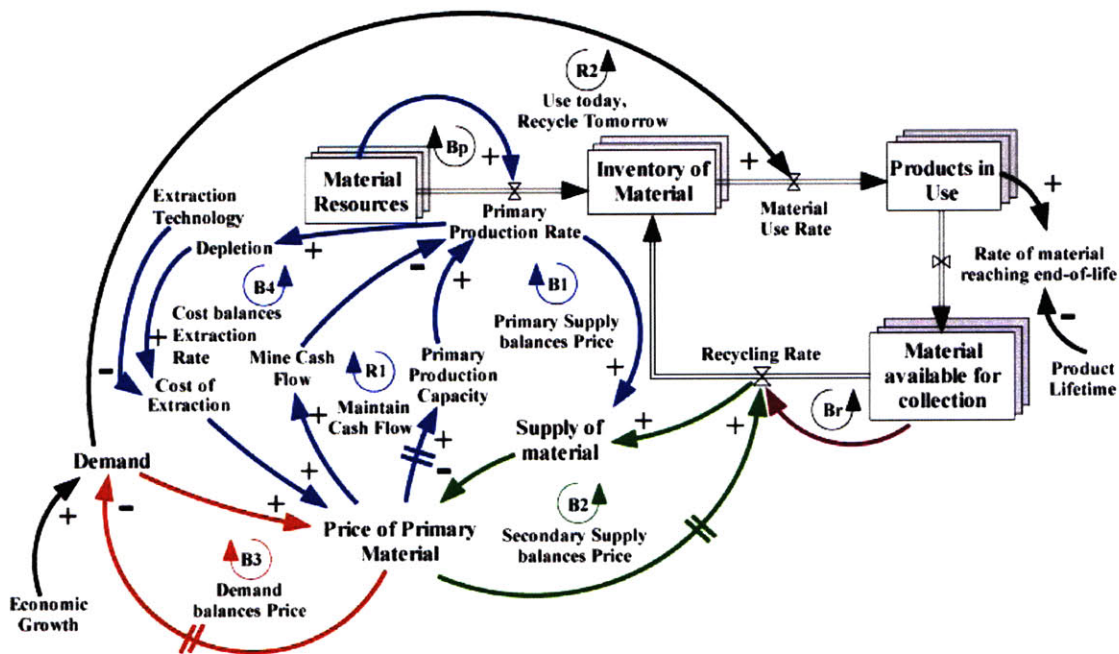
Figure 14: A system dynamics causal loop diagram summarizing the key feedbacks in the model structure. Each arrow represents a causal relationship between two variables. Boxes represent stock variables and arrows represent flow variables.

The feedback-loops that describe the mechanism by which price will tend towards an equilibrium price are the balancing loops B1, B2 and B3 that govern supply and demand. If price does increase, supply will increase and an increase in supply will depress price. On the other hand, demand will decrease and the decreased demand will also depress price.

It is important to note that although supply and demand are governed by balancing loops, delays and the reinforcing loop R1 can make it difficult for the system to reach equilibrium state. Instead of reaching equilibrium, systems governed by balancing loops with delays can experience oscillatory behavior as it chases an equilibrium state (Sterman 2000).

Finally, my approach to model-building was to start small and, when possible, to use previously developed frameworks. Where appropriate, this will be noted in the model descriptions that follow.

The following is a short description of the general behavior of market actors who will be considered and how such behavior will be modeled. It is not a comprehensive discussion of supply and demand theory.

5.2.2 Actors in a Material Market

The market dynamics depend on the behavior of individual market actors. To build the model, I tried to answer the following questions: who are the market actors that matter and how do they behave given what they know about the material system? This section briefly describes the key market actors and their role in the material system while the next sections go into more detail on market actor behavior, how the material system affects the decisions of market actors and how those decisions affect the material system.

The main market actors are:

- primary material suppliers

- secondary material suppliers

- product manufacturers

- consumers

- investors

- market-maker

While there are many individual market actors, the model aggregates the actors into groups whose average behavior is captured. The primary materials suppliers are aggregated based on the type of ore that they mine. The secondary material suppliers, product manufacturers and consumers are aggregated based on the type of platinum-using product that they recycled, produce and buy, respectively. The investors and market makers are each treated as a group. The main benefit of aggregating is that it reduces the computational and data requirements for the model, yet still allow the model to capture different behavior of elements of the market. However, aggregation doesn't

capture the behavior of subsectors with each category; essentially the model only captures the behavior of the average actor.

Primary material suppliers are the mining and extraction companies located at the upstream end of the supply chain. They tend to be well aware of the importance of material availability because, to a large extent, they determine short and mid-term supply of material by deciding how much to extract, which ore bodies to extract and how much to spend on exploration and extraction technology research.

Each mining company can own a number of mines. Each mine has an associated cost of mining, a given type of ore body and given size. In some cases, two different mines that are located adjacent to each other can mine a single ore deposit. Although these two mines may be owned by different companies, the quality of the ore body that is mined will likely be similar and the political conditions under which they operate will be similar (taxes, government agreements...). For any given material, there can be half a dozen or more mining companies and a few dozen mines. As mentioned above, I have selected to aggregate mines according to ore body characteristics.

Recyclers are secondary material suppliers. These actors collect material from landfills or from consumers and are limited to collecting products after they have reached the end of their useful life. There are varying qualities of secondary material, including relatively pure, clean scraps and highly alloyed, mixed scraps. For example, while copper cables are made of high purity copper, electronic circuit boards contain copper that may be difficult to separate from the many other materials. Recyclers' costs are a function of the type of product they recycle. Recycling companies tend to be local and there can be dozens of recyclers in a given state. I will aggregate recyclers by the types of products that they handle since within each product category, the costs of recycling are similar and the costs of recycling are generally much lower than the costs of primary extraction and therefore the actual value is less important.

Material demand is derived from product demand: product manufacturers decide which materials to purchase depending on consumer demand for products. Product manufacturers are aggregated according to the type of product that they produce. Manufacturers are able to substitute materials if conditions change (ex. prices, desired properties, and new material options). However, substituting a material may involve changing manufacturing processes and may require new equipment and technical knowledge. In the model, the difficulty to change use patterns is treated as a delay.

As with many other commodities, and especially with precious metals, platinum is sometimes purchased as an investment tool. Investors will be defined here as actors who purchase platinum,

hold it and then sell it in the same conditions as when they first purchased it. There are also many investment products related to platinum (please see (Christian 2006) for an introduction for non-traders to commodity investment products and strategies, including platinum). Also, many actors participating in the platinum supply chain (primary suppliers, manufacturers, for ex.) make investment decisions to hedge their positions on specific contracts. These types of investment products and decisions will not be discussed here. In the aggregate, it will be assumed that investors are trying to make a profit on their platinum purchase, but will not always succeed.

Finally, the material market, such as the London Metal Exchange (LME), helps sets price. In the model, the market-makers set price based on inventory levels, and mining and holding costs.

5.2.3 Equilibrium Supply-Demand Model

Figure 15a illustrates the price construct with supply and demand in a competitive market. This illustration aggregates the behavior of multiple suppliers and multiple consumers and shows that in general, the quantity of a commodity offered by suppliers increases with increasing price and the quantity demanded by consumers decreases with increasing price. The equilibrium price is defined as the price at which the quantity of a commodity offered by suppliers and the quantity demanded by consumers is the same.

Supply and demand curves can experience structural shifts as illustrated in Figure 15b, where a demand increase is represented by a shift of the demand curve to the right. A model that would aggregate consumers' behavior would identify the shifted demand curve as:

$$D_{original} + (Q^{f}{*} - Q^{i}{*})$$

When such a demand increase occurs, a new equilibrium price can be defined. At the original equilibrium price, there is now a higher quantity of product demanded. However, suppliers will only supply this higher quantity for a higher price. In a well-behaved system, shortages in supply and excess demand will lead to a convergence of the price to a new equilibrium price that would reflect the increased demand.
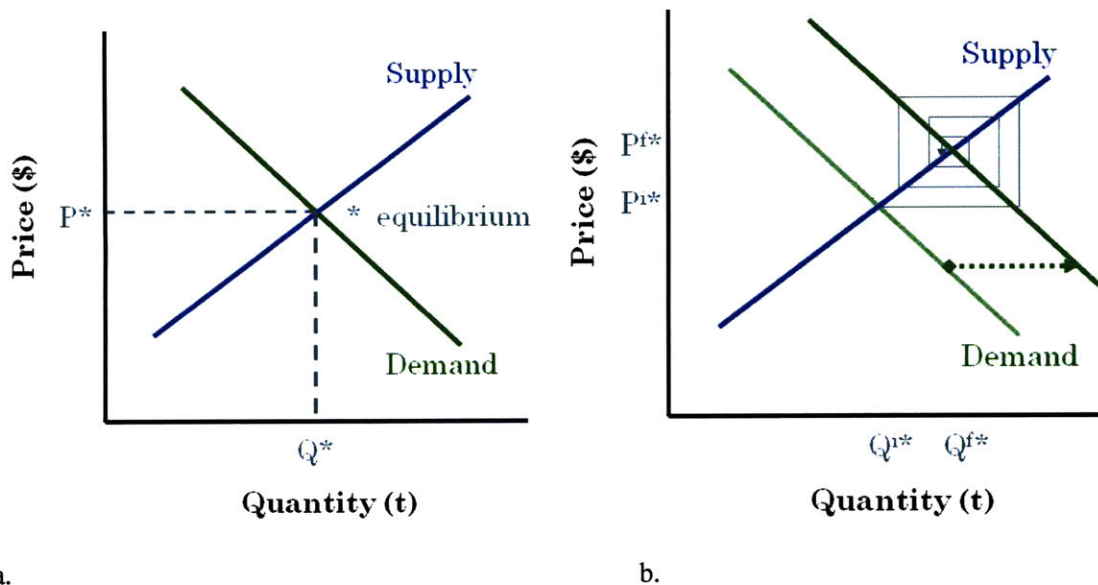
Figure 15: Classical depiction of dynamics of supply and demand. a. At any point in time there is an equilibrium price that corresponds to where the supply and demand curve cross. b. Structural shift of demand and supply: if there is an increase in demand, the price, initially P^i*, is expected converge to the new equilibrium price P^f* in a well-behaved system.

The supply and demand curves are theoretical constructs that can be determined for a real system at a given point in time or for a given period in time. The supply curve is constructed from the production capacities for each producing mine and the respective costs of production. The demand curve is constructed by determining how much manufacturers that use the material purchase and at which point the price becomes high enough for them to substitute away from the material or for them to change production strategy.

The rates of change in supply and demand as a result of the price feedbacks determine the overall behavior of the market. In the next sections, it will be suggested that the model should separate multiple individual firm decisions in order to add flexibility and constructive detail to the model. Incorporation of such mechanisms into the model could improve the understanding of future risk of scarcity. For one, the many possible factors that can lead to a structural shift in demand and supply can be examined.

5.2.4 Dynamic Supply

In the classical depiction of supply, a rightward shift of the supply curve indicates a supply increase and a leftward shift indicates a supply decrease. The following are some reasons for a structural shift of material supply:

- changing capacity,

- changing technology of mining, extraction and processing of materials,

- changing factor costs (labor, equipment, energy…),

- changing prices of byproducts (most ore bodies contain more than one mineable resource),

- perception of future price changes,

- loss or addition of supplier.

The classical supply curve as depicted by a smooth line is only a representation of the theoretical supply at a given point in time. More realistically, the supply curve is generally not a straight line as it represents the aggregated supply from multiple suppliers, each willing to offer a set quantity of the material at a given price (Tilton 1977).The supply curve is therefore roughly depicted as a step function of different suppliers as shown in Figure 16a.
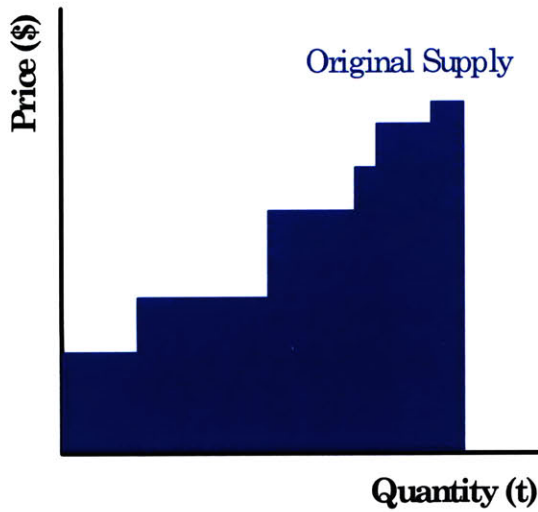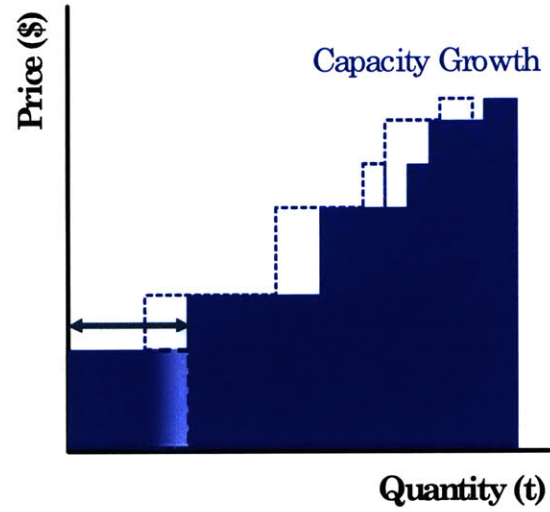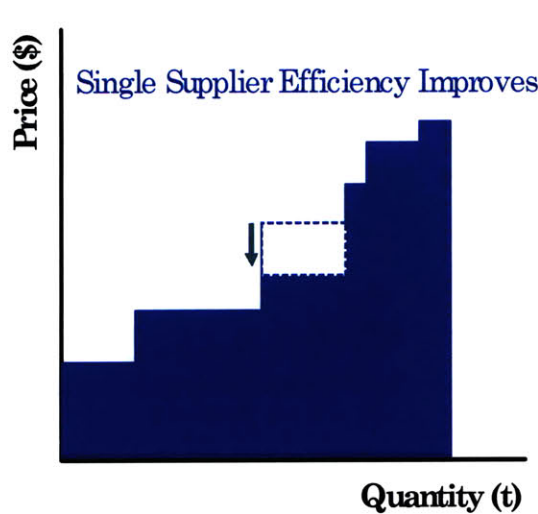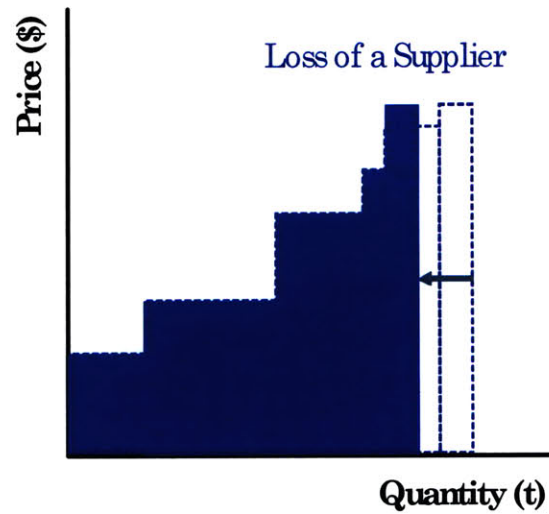
Figure 16: a. Rough schematic of supply curve broken down into the various suppliers willing to offer material at different prices. The supply curve shifts when b. a supplier increases capacity; c. a supplier improves efficiency and therefore reduces its cost; d. a supplier exits the market.

A shifting supply curve can more accurately be depicted as one where changes occur to one or more of the suppliers, rather than a curve that shifts smoothly to the right or the left. A few examples are depicted. In Figure 16b, capacity increases for a given supplier either because the supplier becomes more efficient and able to produce more or because the supplier invests in added capital. In Figure 16c, a supplier reduces its costs and can therefore sell at a lower price. In Figure 16d, a supplier goes bankrupt, or political disturbances cause a supplier's shipments to be stopped.

In the first two cases, supply increases, while in the last case, supply decreases. The shifting of the supply curve is governed by decision rules that determine costs and capacity over both the short and long terms.

A number of scarcity scenarios can be examined by modeling the supply curve as one that results from different production strategies of individual firms. For example, one can compare the risk of scarcity for a monopoly, an oligopoly or a competitive market. Moreover, a supply curve shift that occurs as a result of the loss of an individual supplier could potentially produce different results from shift that occurs as a result of an improvement in mining technology efficiency.

5.2.4.1 *Primary supply decisions*

Primary supply results from the decision of mining, extraction and raw material processing companies to produce and sell metals and minerals. The decisions to produce and sell will be based on price, costs and the amount of resources available (Figure 14 loops B1, R1 and Bp).

5.2.4.1.1 Resources limit supply: how do primary suppliers identify resources?

Resources are distributed unevenly within Earth's crust and ultimately limit the long-term supply of non-renewable materials that can be extracted from Earth. The greater the present extraction rates, the less remains of primary ore for future extraction.

The location and quality of resources is only known if there is available technology and money spent to discover and characterize them. For most metals, extensive geological studies have identified the economic viability of resource extraction depending on present and expected future technology and prices. However, there is significant uncertainty in the studies, especially for minerals that are considered less economically viable. The model must have an exogenous variable that describes the initial conditions of resource distribution, termed cumulative supply.

Cumulative supply captures the total supply of a non-renewable resource over all time as a function of price (given a technological capability and cost factor set), rather than the supply over a certain period of time as a function of price (Tilton 2003). As with supply, cumulative supply increases with price. Knowledge of the cumulative supply curve would aid in the analysis of risk of scarcity in that it would provide a set of initial conditions for the geological context of resource availability. Given that the cumulative supply is not known, the model will use the best available data and make assumptions about future discoveries.

Knowledge about the distribution of known resources depends on spending for exploration and the technology available for exploration. Spending for exploration varies based on the potential

profitability of mining. Spending tends to increase during periods of high profitability unless the size of reserves is already large enough that it is expected to satisfy many years of projected demand (Barnett and Morse 1963). Improvements in technology have decreased exploration costs and made it possible to explore increasingly remote areas and depths greater than 2km below the surface and beneath the oceans.

Mining companies must characterize the discovered ore bodies. Characterization involves determining the volume and distribution of a given ore body and the types and concentrations of minerals within the ore body. Characterization helps determine the cost of extracting each tonne of metal.

The known data regarding the quality and quantity of reserves being mined today and in the past can be used to estimate the profitability of ore bodies that will be mined in the future. Using grade as a cost metric, the model will use data on how grade influences cost and how grade changes as ore bodies are depleted. Cumulative supply as a function of price can be estimated from cumulative supply as a function of ore grade (see Figure 17). The curve describes the sum of different supplies that can be extracted over time and the varying quality of resources and spread between the highest and lowest quality ores.
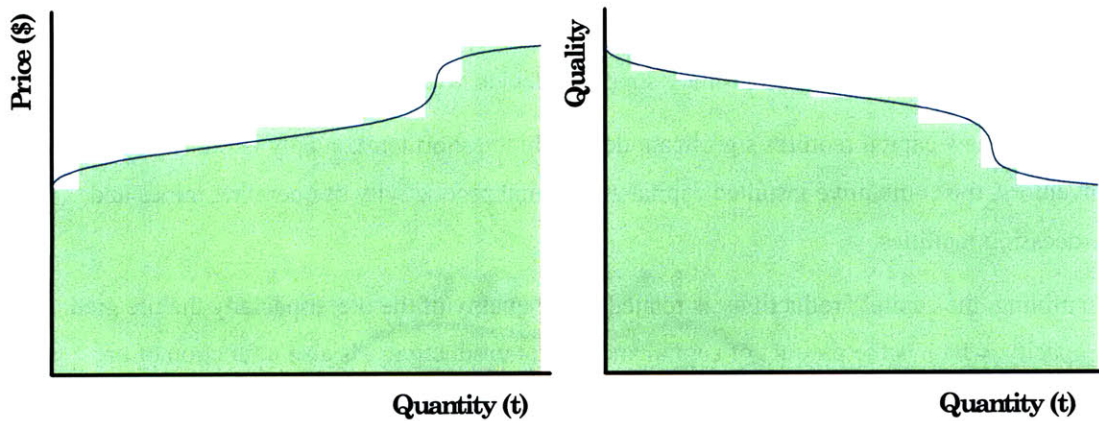
Figure 17: Schematic of cumulative supply based on price and based on quality (ex. ore grade).

5.2.4.1.2   Capacity decisions: how do primary suppliers decide how much capital to invest?

Mineral resources and our ability to access and process them determine the long-term supply of primary materials. The capital invested into mining and extraction and the capital productivity determine the supply of primary in the midterm. Each primary metal supplier must determine how much capital can be raised and decide the capacity to build. Mining and extraction companies have two options to increase capacity: expand an existing mine/processing facility or build a new

mine/processing facility. The capital and time required to build at a new site is much larger than that required to expand an existing one. There are however, limitations on the expansion of an existing mine, but generally fewer limitations for expanding a processing facility. The limitations of mine expansion can be related to geological and safety reasons, such as the ability to build tunnels right on top of each other without compromising the structural stability of the tunnels. The limitations for processing facility expansion are likely space or labor-related.

Companies must also decide whether to maintain current capital, since capital degrades over time. The degradation of the mine ore body or a changing political and economic condition may lead a company to decide to halt new capital investments in a given site.

Essentially, companies decide to invest based on the future expected return on investment (or profitability). The expected profitability depends on the expected costs of extracting a mine's reserves and the expected price. Future costs and prices are often estimated from determining the quality and quantity of the mine's ore relative to other operations and from analysis of past trends.

If the expected costs of mining are attractive relative to the expected prices and if present facilities are profitable and have capital to invest, then companies make a capital investment. Once the investment is made and the capital is installed, supply increases. This can be a large step-wise increase, depending on the production size of the new site relative to the total market supply.

5.2.4.1.3   Cash flow: how do primary suppliers decide how much to produce?

Installing new capital requires significant delays. In the short term, supply is limited by the stored inventory, the cumulative installed capital and capital productivity of operating mines and processing facilities.

In mining, the capital productivity is related to the quality of the ore, especially the ore grade. Capacity, which is the product of capital and capital productivity, is also a function of ore quality. Ore quality varies for different mineral deposits and within each mine. In fact, for a given mine, there is a distribution of varying grades of ore. To a certain degree, mining companies choose which ore grades to mine by deciding which parts of the mine to work first.

Once capital is invested, mining companies generally wish to maximize the utilization of their capital. Moreover, in developing countries, mining companies seldom can or want to make major labor changes. Effectively, each supplier will try to maintain their cash flow in the short term and generally continue utilizing their capital as long as variable costs and inventory costs are covered. The attempt to maintain cash flow helps ensure costs are covered in periods of low price. Mining companies can cover costs during periods of low price by decreasing unit costs and targeting ores

that are of higher grade. Higher grade ores lead to increased capital productivity and essentially higher metal extraction rates. The unfortunate potential effect of this loop is that increased production leads to increased supply and can further depress price.

From the processor's point of view, their production is in large part dependent on the amount of ore mined and they are more flexible in their capacity utilization. Many processors either are owned by the mines or charge a toll to mines and are therefore not particularly affected by prices.

5.2.4.2 Secondary supply decisions

Secondary supply results from the decision of recyclers to buy and process end-of-life products and sell the metal. Recyclers decide how much to collect based on price and the amount of secondary available for collection (Figure 14 loops B2, R2 and Br).

5.2.4.2.1 Material available for recycling: which materials are available for recycling?

There is a limited amount of secondary metal available for collecting: metal in products reaching end-of-life and metal in landfills. The amount depends on past demand, product lifetimes and past recycling rates. If growth of demand has been fast, then there will be less scrap available relative to total demand. For example, the amount of platinum from automobile catalytic converters that can be recycled today depends on how much platinum was used in the automobiles about 16 years ago, the average lifetime of the car. The amount of metal in landfills will be greater if past recycling rates were low and large amounts were disposed of. In the model, landfill waste mining is not implemented, although it is an option that can be made available to recyclers. This is because landfill waste mining is not practiced today.

5.2.4.2.2 Material collected for recycling: how do secondary suppliers decide which products to accept for recycling?

For any given metal, a supply curve of secondary metal can be constructed. Just as with primary metals, secondary metals from different sources have different associated costs of recovery. In the case of secondary metals, the different sources are the different types of products that reach end-of-life and their location in either urban or rural areas, near or far from recycling facilities.

The cost of recycling depends on the metal concentration and on the way it is incorporated in a given product (for example, alloying). Similar to the case of mining, the higher the concentration of the metal in the product, the less costly it is to recycle. For example, it is cheaper to recycle pure platinum jewelry than platinum used in a computer. Factors such as metal alloying can also impact cost because it often results in higher energy requirements for recycling.

The location of products, whether in rural or urban areas or distance from recycling facilities, determines the cost of transportation and collection. The waste collection from rural areas requires more transportation than from urban areas and is therefore more costly. Certain uses of platinum also involve the dissipation of the metal into the atmosphere, and that platinum becomes near impossible to collect.

Recyclers will therefore target the higher quality, lower recycling cost products first. As prices increase, the amount of material collected for recycling increases: recycling facilities have more incentive to separate out the material whose price has increased, there is more incentive to collect more distant and lower concentration products and recycling facilities are more likely to stay in business.

Recycling facilities require less capital investment and can more easily expand their existing facilities than mines. It is easier to increase recyclers' capacity, therefore, scrap material collection rates can respond more quickly to price increases than primary metal mining can.

5.2.5 Dynamic Demand

Derived demand is a term used for material demand. Manufacturers buy materials to produce a consumer good. Consumers themselves do not generally care about the materials used to produce the good as long as the good has a set of desired properties.

In the classical depiction of demand, demand decreases with increasing price for all elastic products. A demand curve shift represents demand changes as a result of factors other than price:

- changing economic conditions

- changing technology such as the development of substitutes or new products requiring less of the given material

- changing prices of substitutes

- changing preferences

- perception of future price changes

- changing regulations (ex: environmental)

When examined in detail, the demand curve, like the supply curve is made up of numerous actors, and in this case manufacturers of consumer goods or parts for consumer goods are those who directly demand materials. Each of these stakeholders is willing to buy a certain amount of material at a given price; hence the demand curve can be roughly depicted in a similar way to supply as shown in Figure 18a. Here too, the demand curve can shift when changes occur with one or many of the material consumers.

The demand curve can shift over time when changes occur in one or many of the manufacturers that use the material. For example, demand of most consumer goods tends to drop when there is an economic depression leading to an overall shift of the demand curve as shown in Figure 18b. The overall shift of the demand curve for all manufacturers can also occur if a new environmental regulation is put in place to control use of the material, effectively increasing the cost of using that material for all manufacturers. New technology, new materials or the decrease in the relative price of a substitute can all lead to substitution and essentially the loss of demand from a given manufacturer with a resulting shift of the demand curve as shown in Figure 18c. There can also be increased or decreased demand of a given product leading to increased or decreased demand of the material by one or a few of the manufacturers (see Figure 18d).
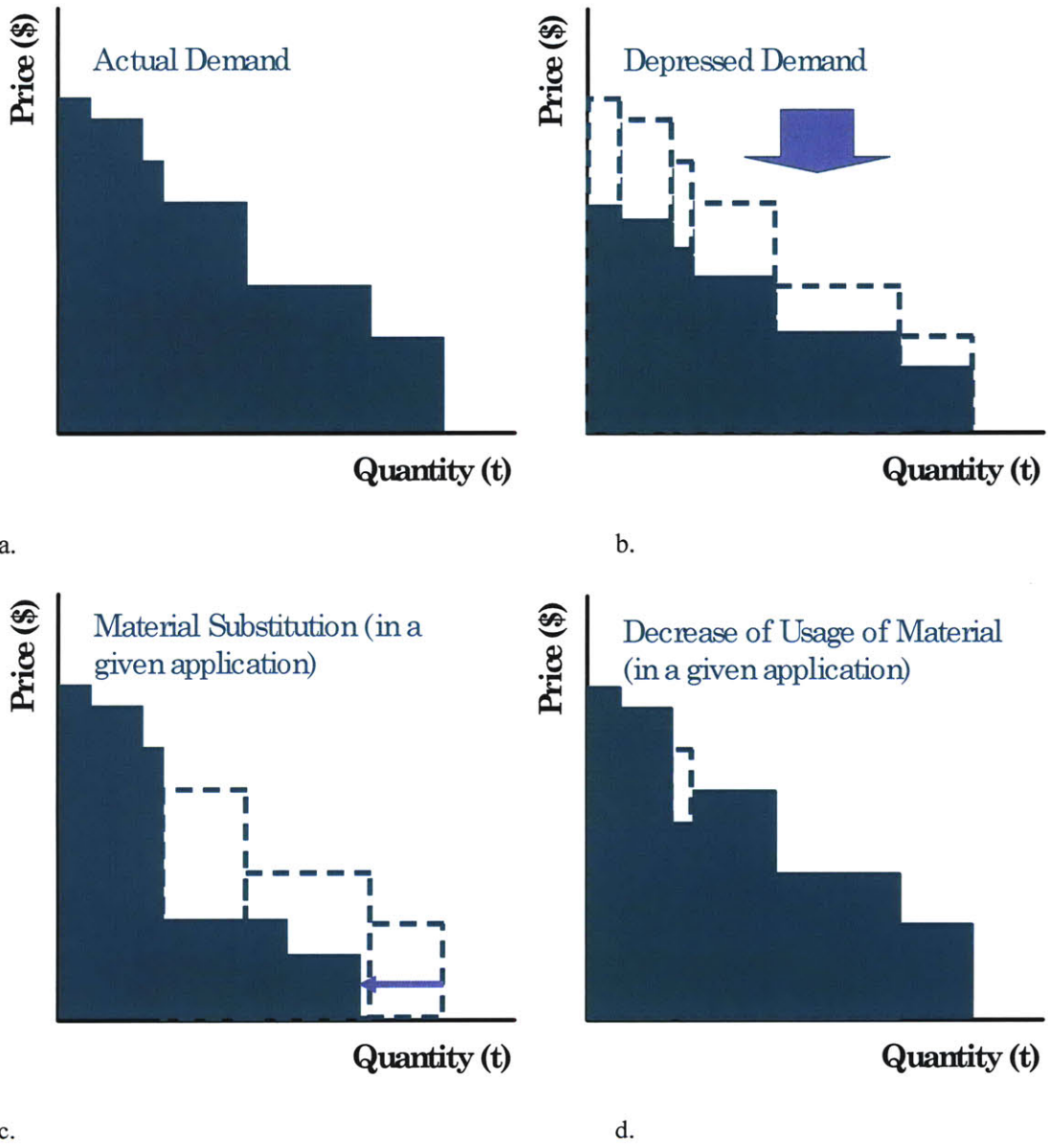
Figure 18: a. Rough schematic of demand curve broken down into the various manufacturers willing to buy material at different prices. The demand curve shifts when b. there is an economic depression that reduces demand for products in general; c. material substitution occurs in a given application effectively erasing demand for a the material in that application; d. less material is needed to make a given product.

5.2.5.1 *Demand decisions: how do manufacturers decide which material to use and how much to buy?*

Demand and price are related by a balancing loop (Figure 14 loop B3). Except in cases where environmental concerns discourage use of certain metals, the demand for different metals decreases with increasing price.

As prices increase, manufacturers seek alternatives either by finding ways to use less of the given material: by making a material substitution or by developing new technologies that make the old products obsolete. Such changes take time and for different products, the incentive to change requires different price increases. In other words, the price elasticity of platinum for the automotive converter catalyst is different from the price elasticity of platinum for jewelry. New technologies, economic growth and in the case of platinum for auto catalysts, increasing environmental regulations can also lead to changes in demand. For example, over the past 34 years, platinum use in vehicles has increased from a combination of increasing sales of vehicles and increasingly stringent environmental regulations for automotive tail pipe emissions.

Material demand is modeled so that it responds to price based on its price elasticity and the delay time to find alternatives. There is also an exogenous growth rate factor that represents economic growth leading to increased product demand.

5.2.6 Non-industrial demand for platinum: investments and speculation

Physical platinum is sometimes purchased as an investment product. One especially popular form of physical platinum investment is purchases of platinum coins issued by national mints such as the U.S. Mint, Royal Canadian Mint, Perth Mint of Australia, Pobjoy Mint of England, etc. It is suspected that there are also bars of platinum stored in vaults in banks around the world, but especially in Zurich (CPM Group 2007). Platinum-based financial tools are also available for individuals and firms wishing to hedge and/or speculate on future prices. Hedging is a very powerful tool that is used by many companies that produce or use platinum. However, commodity markets are subject to speculation leading sometimes to a worsening of a crisis, as seen with cobalt in the mid-1970's.

Investment demand and speculation both influence commodity prices. Understanding investors' and speculators' behavior is not always straightforward and has been made more difficult since the internet has made it possible for people from very different backgrounds to participate in commodity markets. The reasons for investing in platinum and for using platinum financial tools are often influenced by the economic, cultural and political climate (Christian 2006). Historically, gold was the precious metal of choice especially for investors in Asia. Recently, platinum and palladium have become more popular. Economic or political uncertainty can lead to increasing participation in commodity markets, especially precious metal commodities.

For modeling purposes, investment demand for physical platinum was considered. Investor behavior was modeled such that as price increases, investors will demand platinum, with a steeper

price slope leading to increased demand. However, as the difference between price and the marginal producer cost increases, investors sell off their platinum, with larger differences leading to increased sales. The sales overtake the purchases of platinum if the difference is very large. Net investments will influence the inventory at the market and hence price.

5.2.7 Commodity Market Dynamics: Price and Inventory

Platinum is traded both on the open market and through contracts between producers and product manufacturers. Platinum is traded globally, including on the London Metal Exchange, the New York Mercantile Exchange and the Tokyo Stock Exchange. While the amount of platinum that goes through the markets represents only a fraction of the total amount of platinum that is bought and sold daily, the market prices inform the direct contracts. So, although the prices set for the direct contracts may be different from the market price they are generally similar to the market prices.

Price is set when there is a value at which the amount that producers are willing to sell equals the amount that consumers are willing to purchase. A market-maker helps set price by holding an inventory at the market and selling and buying from and to that inventory. The goal of the market maker is to ensure liquidity. There are a number of variables to consider when trying to understand price: supply, price at which supply is offered, demand made at a price level, inventory at the market, and amount of metal traded (i.e. amount sold = amount purchased = amount traded).

The market information that is available to the general public does not always include all this data and it is therefore difficult to capture the dynamics of price from the data available. For example, data obtained on platinum traded on the NYMEX only included daily prices and inventory levels. This data had been plotted in Section 5.3.1.4. The difference between the amount supplied and the amount demanded on any given day can be used to estimate the change in inventory level from the previous closing inventory level, but no more.

Information on supply and demand can be estimated from data obtained from producers and manufacturers. For platinum this data will still only provide a partial picture of the supply/demand data unless individual investment data is also collected. For this work, primary supply data was collected from production data from financial reports of individual platinum producers but no data on secondary supply on individual investments were found. Instead, this work relied on supply and demand estimates made by two groups: (1) a platinum producer group: Johnson-Matthey and (2) a market analysis company: CPM group.

For the model, variables were defined for the amount of primary and secondary metal produced, the amount of platinum demanded, the backlog of orders (unsatisfied demand), the inventory, the cost of supply and the amount obtained by manufacturers at any given time. These variables were used to model price endogenously.

5.2.7.1 The market decisions: how is price determined?

In the model, price depends on two variables:

(1) the expected inventory coverage, i.e. how much time can the inventory that is in the platinum system can be used to satisfy demand if producers were to stop production and,

(2) the cost for the marginal producer to produce platinum. It is assumed that each producer has one cost.

In the case of platinum, where the primary metal and recycled metal have the same qualities and are perfectly substitutable, the inventory of platinum depends on the rate of primary production, the rate of secondary production, the rate of platinum purchased by industry and any actions that are made as a result of actions by speculators. When inventories are large relative to demand, price decreases. Insufficient inventory results in increasing price. Also, producer costs are taken into account, although to a lesser degree than inventory levels. In the case of platinum, the marginal producer is assumed to be a primary producer, not a secondary producer.

5.3 Incorporating Data into the Platinum Market Model

This research tries to capture the complexities of the platinum supply and demand structures through simulation modeling. The model defines separate mining regions with different ore bodies and separate platinum applications with different demand behavior. Figure 13 has been modified below to describe more specifically the type of data that will be incorporated into the model (see Figure 19).

Platinum Market
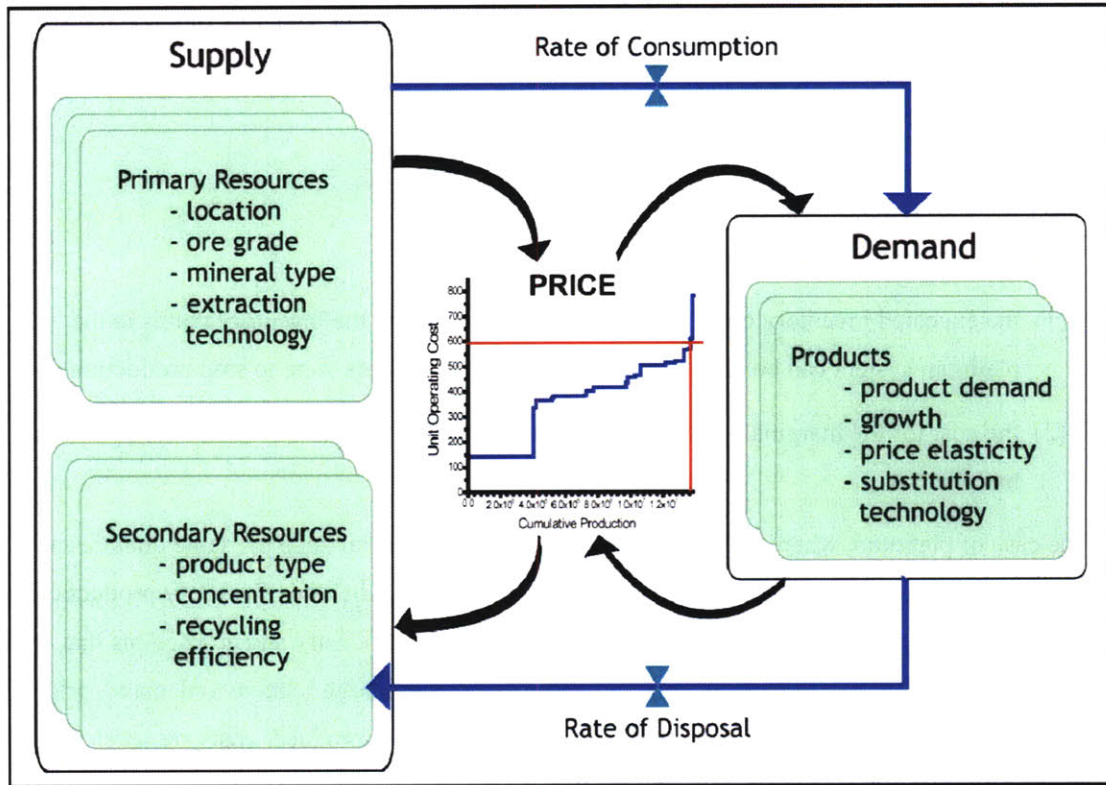
Figure 19: Model Boundary Diagram. Primary and secondary supply, price and demand are calculated endogenously by the model. Key variables that go into the model are based on historical data from the platinum supply and demand sectors.

Platinum data and information about material market behavior were used to support the model. The model used historical data to calibrate for values that were not available. Market information and data were collected from a large range of publically available data on the platinum material system. Further information was gathered by attending industry conferences and meeting industry analysts and market participants. The next sections describe the details of the platinum data underlying the model.

5.3.1.1 *Primary Supply Side*

Historical estimates for primary supply including some regional data were available from 1975 to 2008 (CPM Group 2007; Johnson Matthey Precious Metals Marketing 2008). Platinum primary supply in 2005 was 206.8 tonnes with most of the world's primary platinum (77%) produced in South Africa's Bushveld region (Johnson Matthey Precious Metals Marketing 2008; U.S.G.S. 2009). The Bushveld region is rich in platinum group metals and contains about 80% of global platinum reserves (Cawthorn 1999; U.S.G.S. 2005). Data on global secondary supply were difficult

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to obtain, except in the case of auto catalysts, where it has been reported that 24 tonnes were recovered (Johnson Matthey Precious Metals Marketing 2008).

Five mining companies dominate primary platinum supply: Anglo Platinum, Norilsk Nickel, Implats, Lonmin and Inco (Hagelüken, Buchert et al. 2006). The highly concentrated market structure of platinum is an advantage for modeling because there are fewer market actors to be modeled and from which data are needed.

Each company has a number of mines and smelting and refining operations. Data from individual mines were collected from historical company financial reports (Anglo Platinum 2007; Impala Platinum 2007; Lonmin 2007; Norilsk Nickel 2007; Northam Platinum Limited 2007; Stillwater Mining Company 2007; Johnson Matthey Precious Metals Marketing 2008) (see Figure 22 for an example of the type of data available). Cash operating cost per gram of platinum and tonnes of platinum refined data were obtained where available and incorporated in the supply curve shown in Figure 20. Unfortunately, data on costs were not found for all mines, most notably Stillwater Mines in the US, and Sudbury and Lac-des-Iles mines in Canada. The mines that are included in this supply curve account for 70% of total 2005 platinum supply.

Norilsk Nickel reported the lowest costs ($11.86/g Pt or $369/oz Pt) and produced about 23.4 tonnes in 2005. Marula and Modikwa mines reported the highest costs, but these mines had not yet reached full production capacity. The cash operating cost per gram of platinum does not take into account other metals mined along with platinum, such as other platinum group metals, gold, nickel and copper and therefore is only an upper bound measure of the cost of mining platinum.

Price in 2005 fluctuated between $2.71x10^7/tonne Pt and $3.25x10^7/tonne Pt and averaged at $2.89x10^7/tonne Pt. For most mines, the cash operating costs per tonne of platinum were below the maximum price of platinum.

Mill head grades were collected and found to vary between 1g PGM/t and 16g PGM/t. The percentage of total PGM that was platinum varied between 12 and 60% of PGM weight, with lower values for Stillwater mines and Norilsk Nickel and higher values for Bushveld region mines. To simulate the evolution of this market I need to not only be able to talk about what the supply curve looks like, but how it would be expected to change over time. Where historic data were available, mill head grade was found to have decreased with mine cumulative production over the past decade or so (see Figure 21).

USGS estimates indicate that reserves for platinum group metals are 71 thousand tonnes and that the reserve base is 80 thousand tonnes (U.S.G.S. 2007). Mines also publish their estimated reserves and resources. Although gathered data only accounted for one third of USGS's estimates, they indicate that expected PGM grades for future production from these mines are between 1g/t and 20g/t.
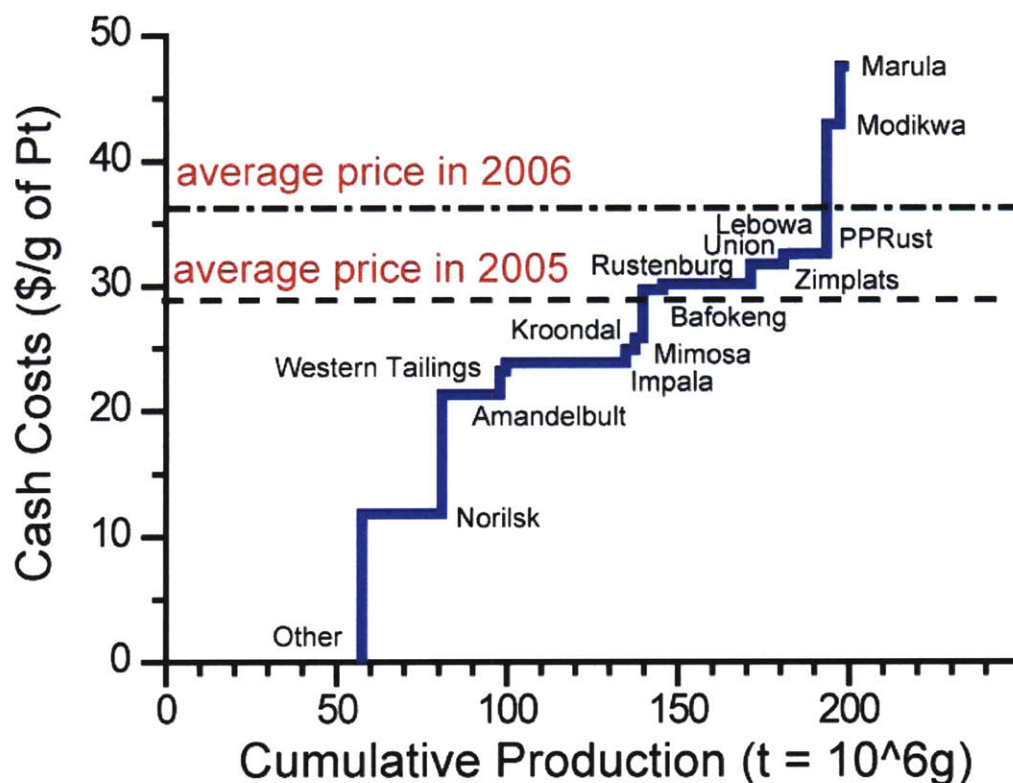
Figure 20: Platinum supply curve (70% covered, rest identified as "Others") with average 2005 and 2006 prices marked by the dashed lines (Anglo Platinum 2007; Impala Platinum 2007; Lonmin 2007; Norilsk Nickel 2007; Northam Platinum Limited 2007; Stillwater Mining Company 2007; Johnson Matthey Precious Metals Marketing 2008).
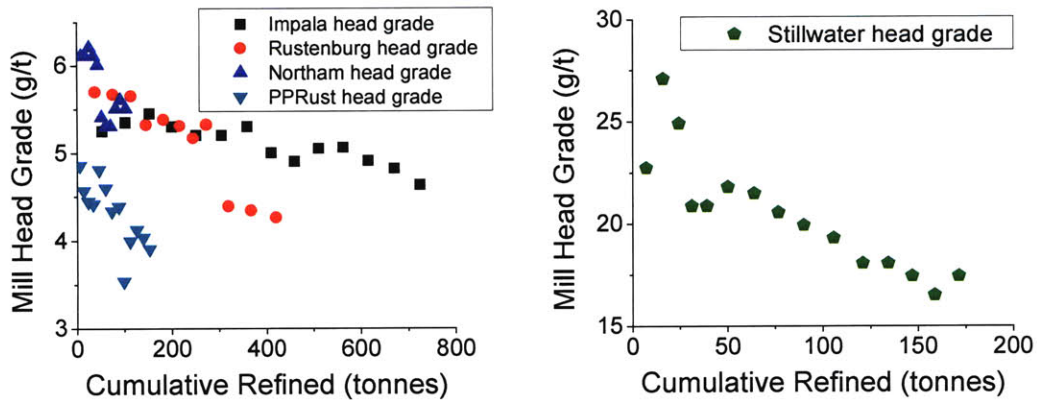
Figure 21: Decreasing trend for mill head grade (g PGM/tonne ore) over the life of four South African mines and Stillwater mines (USA).
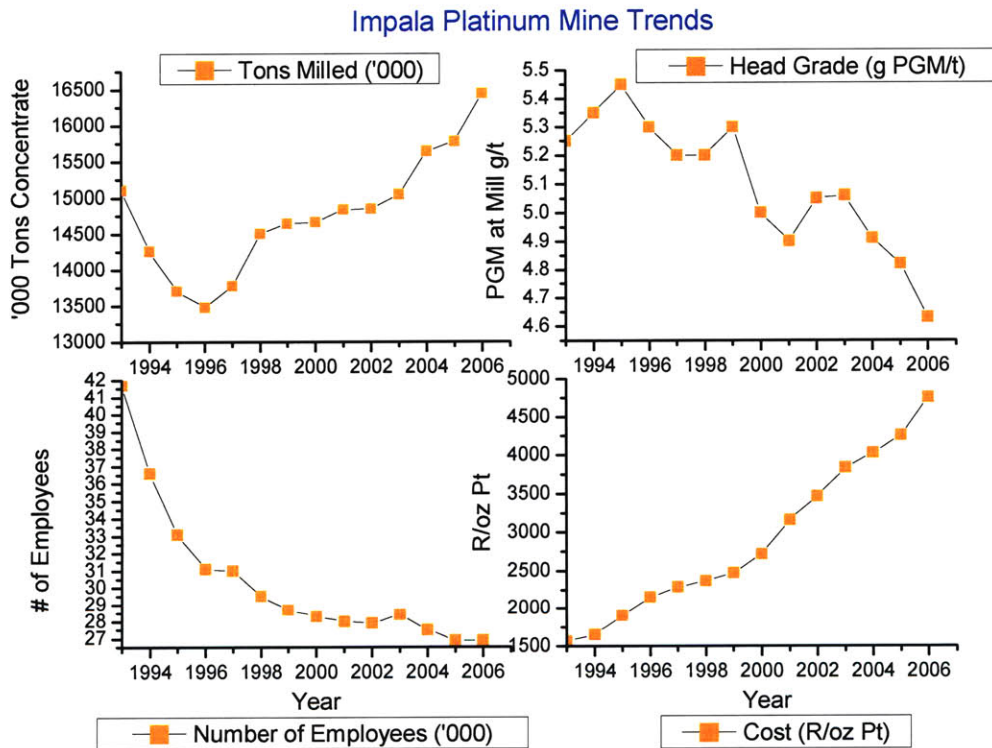
Figure 22: Data collected from Impala Mine financial reports on production and cost trends over time.

5.3.1.2   Demand Side

Historical primary demand estimates including regional and industry-level data were available from 1975 to 2008 (CPM Group 2007; Johnson Matthey Precious Metals Marketing 2008). Only recycling on automotive platinum was reported. Therefore, most of the data presented here is net platinum use, not accounting for recycling (CPM Group 2007; Johnson Matthey Precious Metals

Marketing 2008). Recycled platinum amounts were estimated by other means, as described in the next section.

Primary platinum purchases have been steadily increasing since the early 1980's. Two industries dominate primary use: the jewelry and automobile industries (see Figure 23). In particular, platinum is desired for its catalytic properties, especially for diesel engines in cars sold in Europe where auto catalysts are needed to meet increasingly stringent environmental regulations. In fact, in 2007, Europe accounted for more than 82% of world primary platinum use.

In the auto catalyst application for platinum, minimal substitution (except to other platinum group metals) has been possible and automotive platinum demand is considered relatively inelastic (TIAX and Carlson 2003; CPM Group 2007). For jewelry, where gold and silver readily substitute for platinum, platinum demand is relatively elastic (TIAX and Carlson 2003).
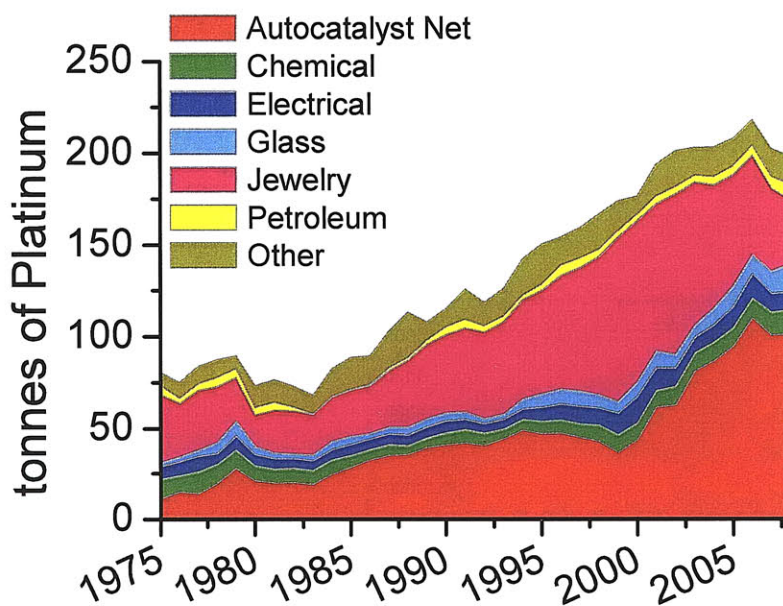
Figure 23: Global primary platinum use by industry from 1975 to 2008 (Johnson Matthey Precious Metals Marketing 2008).

5.3.1.3 Recycling Side

Except for automotive catalyst recycling, global data on historical recycling is very limited. Secondary platinum data was obtained mainly from a number of published sources (Hagelüken 2005; Hagelüken, Buchert et al. 2006; CPM Group 2007; Johnson Matthey Precious Metals Marketing 2008; U.S.G.S. 2009). The model assumes that secondary platinum is a perfect

substitute for primary platinum, an assumption that is consistent with information obtained from discussions with industry contacts at the IPMI conference.

Platinum is a material that is found in very low ore grades and its extraction requires large amounts of energy and produces large amounts of waste. Recycling platinum is estimated to only require 5% of the energy required for primary extraction (Simapro Ecoinvent Database Life Cycle Analysis), which can mean very large savings in cost if it is obtained from end-of-life products as opposed to mining (see Table 5 for a comparison of scarcity metrics for platinum and other metals). It is however not toxic and no regulations exist preventing its disposal.

Data from 1998 indicate that about 76% of platinum in products reaching end-of-life are recovered for recycling in the US (U.S.G.S. 2009). More recent data from Germany indicate that about 67% of the platinum in Germany is recovered (Hagelüken 2005).

The recovery rate of platinum is high likely due to its high price and the existence of well-structured collection infrastructure in certain platinum-using industries, in particular the direct recycling infrastructure (Hagelüken 2005). In glass production and petroleum and chemical catalysis, platinum is used in the manufacturing of products, but does not end up in the product. Recycling is usually conducted as a direct business relationship between the product manufacturer and the platinum secondary refiner, without end-user involvement. Very high recovery rates are characteristic of the **direct cycle.** Data on amounts recycled by direct recycling are most difficult to obtain because the recycled platinum does not go into the market.

Most of the losses occur in industries where platinum is part of the product sold to consumers, such as automotive and electronics. Collection of the product at end-of-life depends in part upon the consumer, and there are possibly many intermediate steps in the reverse supply chain before the product leaving the consumer ends up at the secondary refiner. Such recycling is termed **indirect cycle**.

The 1998 US recycling rate for platinum was estimated at only 17%. The present global recycling rate is likely higher because much of the platinum that is recycled is not reported, especially the material recycled through direct cycles. Based on historical growth rates of demand for platinum and estimated recovery rates from the US and Germany, it is estimated that the recycling rate for platinum is about 40% globally (calculated from simulation results). Overall, the recovery rates for platinum are higher than for many metals of lower value (price) such as aluminum and copper, but lower than for metals that are regulated because they are hazardous like cadmium and lead.

5.3.1.4   Market Data

Available market data information include nominal daily market prices, daily inventory levels at the New York Mercantile Exchange and yearly average prices that can be normalized by the yearly producer price indices. Historical average yearly price data was available from 1960 to 2008 (Kitco Inc. 2009). Daily LME prices and LME inventory volume data are available from February 1st, 1976 (Thomson Reuters 2009). Estimated platinum yearly investments were available from 1981.

Platinum data are plotted below with palladium for comparison since palladium is one of the more important substitute materials for platinum and a platinum group metal (usually one of the less expensive PGMs) (see Figure 24, Figure 25, Figure 26). While palladium is often found in the same ores as platinum and so its supply is linked to platinum's, its price does not always track platinum's price. In general, however, palladium prices have almost always been lower than platinum prices, the only exception occurring around the year 2000 when Russia cut exports due to political motivations (see Section 3.2).

Recent nominal platinum prices have reached historical highs and then crashed with the economic crisis. However, the PPI-adjusted real prices indicate that the recent price spike is the third (or fourth if the smaller 1987 spike is included) such spike in the past 50 years. The 1968 spike can be attributed to tight supply as new petroleum refineries came online (U.S.G.S. 1998). The 1980 spike corresponds to the beginning of the inclusion of platinum in the automotive catalytic converter following the passage of the Clean Air Act and speculation about platinum demand in the automotive industry (U.S.G.S. 1998; Gerard and Lave 2005). The most recent price spike was associated with very strong platinum demand, not just for manufacturing, but also for investment (physical platinum investments). The prices reached a peak as South Africa announced temporary production cuts across all South African mines (i.e. cuts that would affect more than 70% of global primary production) due to problems with the country's electricity capacity. As the electricity problem was eased in South Africa, the global economic crisis hit and platinum prices plummeted from almost $74/g ($2300/oz) to about $26/g ($800/oz) and have since recovered to about $43/g ($1350/oz) (November 2009) (Kitco Inc. 2009).
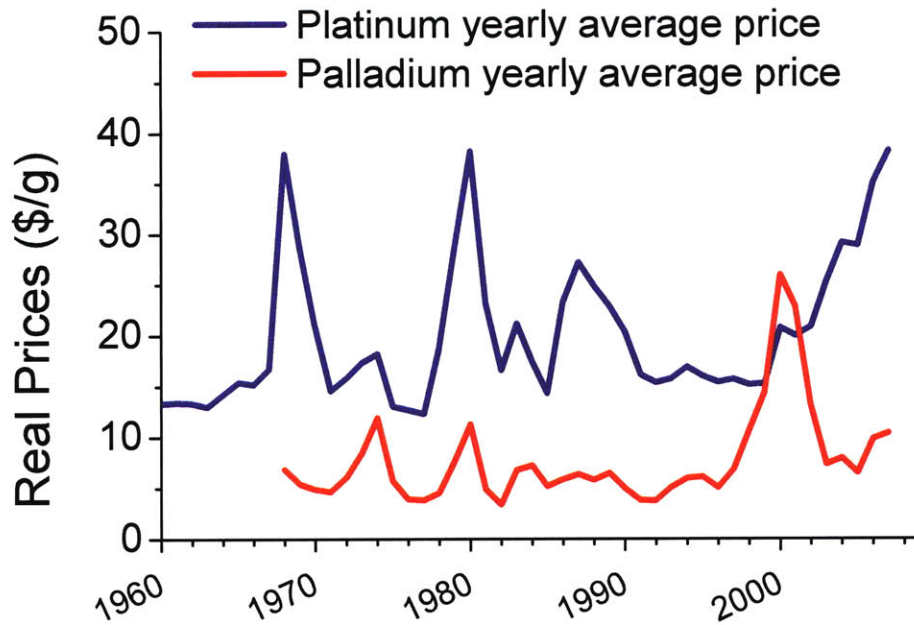
Figure 24: Average yearly LME platinum and palladium real prices (Bureau of Labor Statistics 2008; Kitco Inc. 2009).
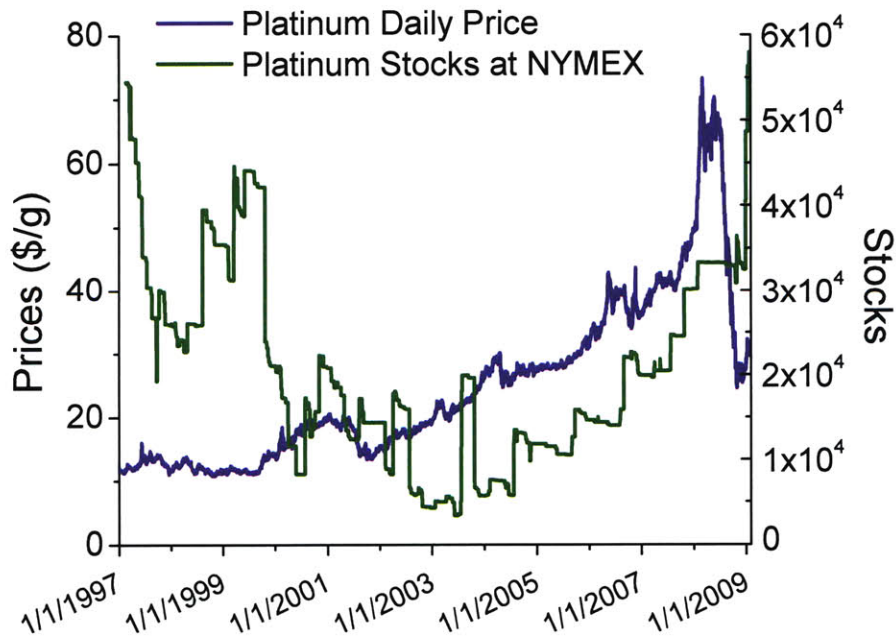
Figure 25: Daily LME platinum nominal prices and daily platinum stocks at the NYMEX (Thomson Reuters 2009).
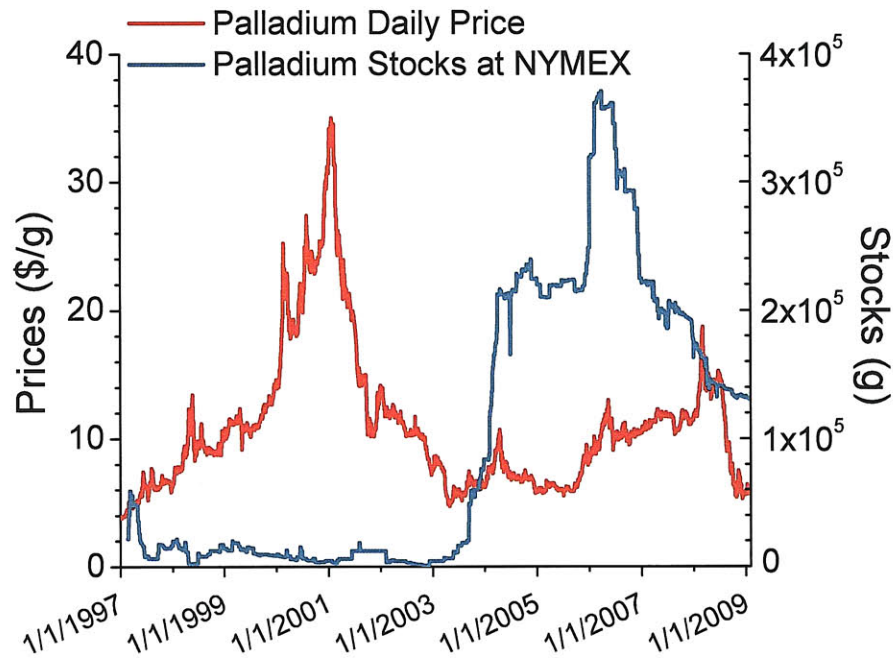
Figure 26: Daily LME palladium nominal prices and daily palladium stocks at the NYMEX (Thomson Reuters 2009).

5.4 Calibrating and Validating the Model

Model-building is an iterative process which involves

- defining a set of equations to represent the system of interest,

- testing the implications of those equations,

- validating the equations with time-series historical data, and

- reexamining and redefining a modified set of equations to represent the system.

The equations that are used for the base case model can be found in the appendix. The model structure used to represent the market actors and their behavior has been defined or described in section 705.2. This section will describe the process used to calibrate the equations and the econometric modeling used to examine market behavior numerically.

One of the reasons for selecting to do a case study of platinum was a practical reason: the availability of data. As stated in Section 5.2, data on supply, demand, price and market-level

inventory are available for the past 30 to 40 years. This time-series data was combined with economic data on GDP (gross domestic product), PPI (purchasing price index), and population for simulation model calibration and econometric modeling (University of Pennsylvania 2004; U.N.S.D. 2006; Department of Energy 2007; Bureau of Labor Statistics 2008). Where available, data on product sales were also examined (ex: automotive sales) (United States. Federal Highway Administration. Office of Highway Policy Information. 2000; Davis and Diegel 2006; Ward's Communications Inc. 2007). It is important to note here that some of the data available are estimates (especially global supply-demand data) and that there were, in the case of platinum supply and demand, data from two different sources that were compared (CPM Group 2007; Johnson Matthey Precious Metals Marketing 2008). While the two sets of data differed, they were sufficiently similar for modeling purposes. For the calibration, data was used from the source that provided more details and more years of data (Johnson Matthey) except where data was not provided.

5.4.1   Econometric modeling

Stata (Stata Corporation. 2003), a statistical software package was used to model time-series supply, demand and market data for platinum and palladium. For one series of analyses, global and regional industry-level supply and demand data were set as the dependent variables while price, GDP and population were set as the independent variables. Product sales data and substitution material price data, when available, were also used as independent variables in these analyses. For another series of data, price was the dependent variable while global supply and demand data and market inventory data were the independent variables.

Durbin-Watson analyses were run to test the likelihood of a first-order autoregression component. Autocorrelation was corrected for with Prais-Winston or Corchrane-Orcutt regression. The econometric modeling results were used to inform the simulation model, especially for the demand sector.

5.4.2   System Dynamics Simulation Calibration

The software platform used to build the simulation model was Vensim DSS for Windows Version 5.9c (Ventana Systems, Inc.). This software includes an optimization tool that allows the user to select a model variable that is to be fitted and to provide the historical data to which the model data should be fitted. The software also allows the user to set a number of exogenous variables that can be varied in the search. A modified Powell search is conducted by the software to find the set of

variables that provides the best fit. This software does not necessarily find the global optimum, but rather the local optimum given a maximum number of searches, where the maximum number of searches is set by the user.

Four series of partial calibrations were performed using the optimization tool. First, the supply and price sectors were frozen and the demand sectors were individually calibrated. Modeled primary demand was fit to historical primary demand with recovery rates set to values obtained from literature material flow analysis results. Secondly, modeled primary supply was fit to historical primary supply and the demand, recycling and price sectors were frozen. Thirdly, the modeled price was fit to historical PPI-adjusted price and supply, demand and recycling sectors were frozen, but the speculation sector was not. Finally, the modeled price was fit to historical PPI-adjusted price and none of the sectors were frozen, but rather the results from the previous three calibration series were input into the model. The variables selected for the last calibration were then used for the model base case scenario.

Model sensitivity analyses of the calibration were run by individually selecting each of the exogenous parameters that were calibrated and testing it for a range of values larger and smaller than the calibrated value. Plausibility of the model outcomes was investigated in this manner. Model changes were made and recalibration was performed a number of times to find a good fit and plausible behavior. Calibration results are presented in the Appendix.

6 Approach to Exploration with Model

6.1 Scenarios to Examine

The results of the simulation model are not attempts to predict future platinum prices. The model is designed as an experimental platform for exploring the dynamics of metal markets in the face of scarcity risks and will be used to explore a number of hypothetical scenarios. The strategy for model exploration will be to vary a parameter, such as the recycling rate, so that multiple scenarios can be examined and to gain insight into the implications of scarcity in the platinum market. These scenarios are outlined in Table 6.

Table 6: Overview of Simulation Scenarios Examined in Results Section.

Scenario Description	Parameter/Simulation Lever	Range Examined	Additional Changes
Examine Recycling Rate	Recovery rate multiplier	0.1, 0.25, 0.5, 0.75, 1.0, 1.25	none
Examine Ore Exploration	Exploration Effort	Low, Medium, High	none
Examine Recycling Responsiveness	Sensitivity of Recycling to Price	Low, Medium, High	none
			Recovery rate multiplier = 0.5
			Recovery rate multiplier = 1.5
	Recycling Delay	0.125, 2, 7, 15, 24 (years)	none
	Mine Commission Delay	1, 5.4, 10 (years)	none
	Mine Life	15, 30, 45 (years)	none
Examine Product Demand	Noise	Idealized smooth vs. Noisy	none
	Growth Rate	Zero vs. Exponential	none
	Automotive Demand	Low future demand for platinum in auto industry	none

As with any model, the platinum market model has its limitations. First and foremost, it is designed to explore a specific set of qualitative questions and should not be used to predict future platinum market prices. Despite the fact that the market model uses more than thirty years of platinum market data and has been built with input from platinum industry participants, there are many factors that are not included. For example, this model assumes that economic growth is an exogenous factor. The scenarios presented assume relatively steady future economic growth that can be either linear or exponential, but as has been experienced recently, there are economic meltdowns and runs on commodities that do not reflect evolution of the platinum supply and demand conditions.

6.2   Setting up the Base Case Simulation Scenario

Years 1 to 34 of the model represent the historical calibration period from 1975 to 2008. The parameters determined from the calibration are used going into the future for the base case scenario. For cases where exploration of variables is desired, changes are made to the model in year 34 and maintained going forward in time. Years 34 to 40 are allowed for transition time and years 40 to 90 are considered the modeling period for analysis. In the results section, year 40 will therefore be referred to as the beginning of the modeling period, or year 0.

The base case conditions for the model are as follows:

- 90 year modeling period with 34 years for calibration, 6 years for transitioning and 50 year model evaluation time frame

- 1/32nd year simulation time steps

- 8 primary supply groups (mining regions) (using data from Section 5.3.1.1)

- 7 demand groups (jewelry, automotive, electronics, petroleum catalyst, chemical industry, glass, other) (using data from 5.3.1.2)

- 7 recycling supply groups (same categories as for demand groups and data from 5.3.1.3)

- smooth exponential exogenous growth of product demand: demand changes also depend on price

- initial primary demand: 230 tonnes/year,

- initial base case static recycling rate: secondary supply/total supply = 40%

- price is inflation-adjusted to producer price index for metals and metal products

6.2.1 Future Growth and Demand

Future growth rates for products that use platinum is an exogenous factor in the model. A number of possible scenarios can be envisioned. It is possible that growth in the future will follow historical patterns. Platinum use has grown almost exponentially over the past 34 years, driven largely by a regulatory push for lower emission cars and the introduction of the automotive catalytic converter in the late 1970's. Automotive use of platinum went from accounting for less than 15% of total primary platinum use in 1975 to more than 50% in 2008 as nations around the world adopted new regulations for automotive emissions and significantly increased the size of their fleets. An example where future exponential growth for platinum could be envisioned is if new uses of platinum become commercialized and adopted worldwide, such as proton-exchange membrane fuel cell (PEM-FC) vehicles.

Future demand could also be linear, flat or even negative. Metals such as lead, cadmium and tin have had linear or almost flat growth over the past 50 to 100 years. In two of these three cases (lead and cadmium), strong regulation surrounding their use because their negative health and environmental impacts forced manufacturers either to move towards a very closed-loop system (high recycling of lead automotive batteries) or to avoid using them (lead and cadmium in electronics sold in the European Union because of WEEE regulations). In the case of tin, better substitutes or ways to use less tin for the same application were found (tin food containers replaced by stainless steel or tin-plated stainless-steel). While it is unlikely that platinum demand will decline in the future, several factors indicate a possible slowdown of demand growth. First, while platinum remains the main metal for use in automotive catalytic converters, new trends indicate a possible decrease in the amount of platinum needed per car. Technologies such as use of nanomaterials in the catalytic converters can contribute to a reduction in the use of platinum per vehicle (Mazda Press Release October 1, 2007). Changes in use patterns for petroleum as oil prices increase or as greenhouse gas emissions become regulated could lead to a decrease in the growth rate of platinum use in the petroleum industry.

For the base case scenario, product demand growth was selected to follow an exponential growth path with annual growth rates calibrated by industry from historical data. This is probably a very ambitious projection of future demand. Noise was introduced by multiplying the product demand

by a noise value at each point in time. The noise value varied between -0.3 and 0.3 and was generated by time-smoothing numbers selected by a random number generator. The numbers selected by the random number generator had a uniform distribution around a mean of 0. The noise seed for the random number generator was selected randomly.

An example of a typical noisy growth path is shown in Figure 27 and two different demand paths are compared in Figure 28. Smooth product demand growth is shown in Figure 27 and will be referred to as the idealized demand case. The noisy growth paths have fluctuations of 10% above and below the smooth demand path, similar to the level of fluctuation observed historically (see Figure 23).
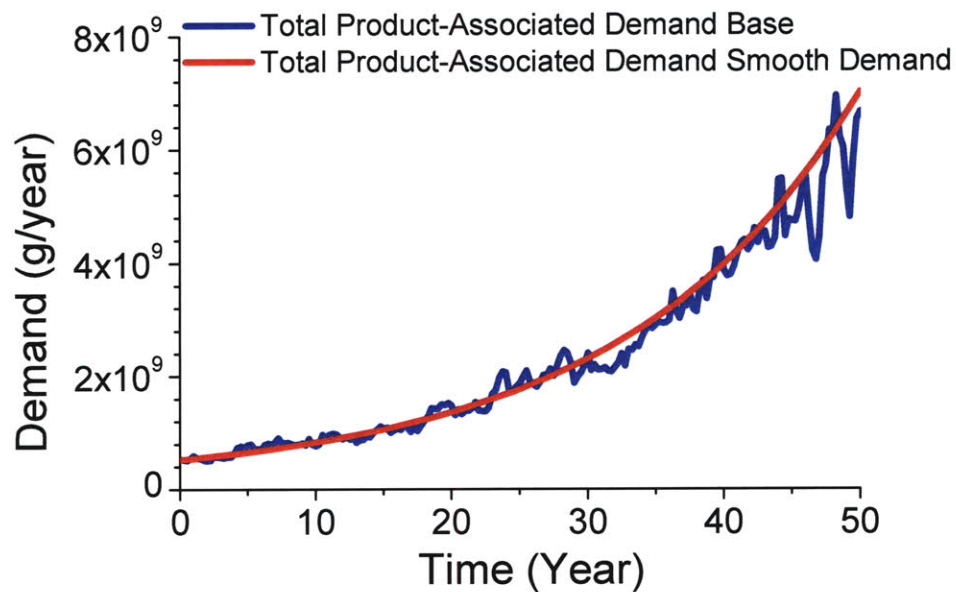
Figure 27: Typical Noisy-Demand compared with smooth demand path. The noisy demand path is the base case scenario. The smooth demand path is an idealized demand path.
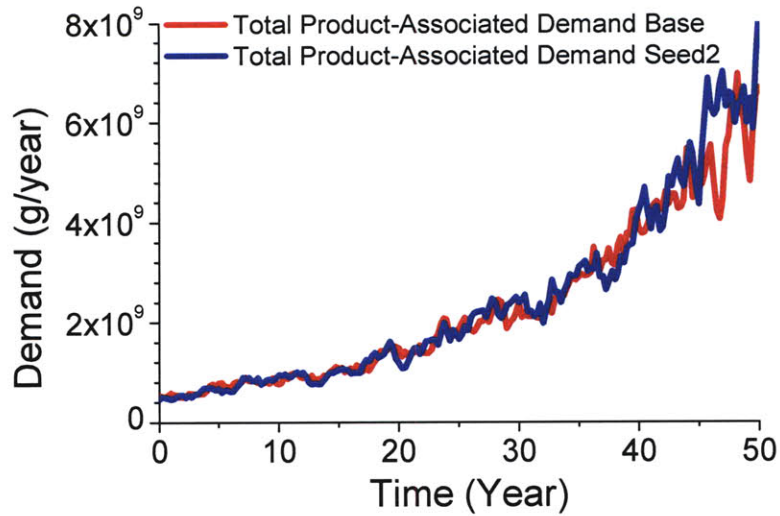
Figure 28: Two different noisy demand cases. A different noise seeds were set for each simulation.

Product demand growth rates for the base case along with additional parameters used to define the demand sectors are presented in Table 7. The values for elasticity, growth, and delay were selected by model calibration with historical data, the values for initial primary demand and product life were selected using a combination of model calibration and literature data and the maximum recycling efficiency and expected recovery rate were selected based on literature (see Section 5.3).

Table 7: Base Case Simulation Demand and Recycling Sector Parameters.

	Platinum Demand Elasticity	Product Demand Growth (%/yr)	Demand Delay (yrs)	Initial Primary Demand (g)	Product Life (yr)	Maximum Recycling Efficiency	Expected Recovery Rate
jewelry	0.55	3.17%	1	33.93 M	44	99%	90%
automotive	0.1	5.61%	15	16.28 M	18	89%	34%
electronics	0.05	1.14%	6.9	6.48 M	6	88%	30%
chemical	0.42	0.00%	11	10.03 M	5	70%	65%
petroleum	0.475	1.66%	15	3.179 M	5	70%	65%
glass	0.05	6.70%	10	1.90 M	4	98%	98%
other	1	1.98%	6.8	6.879 M	6	50%	30%

6.2.2 Sensitivity Analysis

A number of exogenous parameters in the simulation model were examined by running alternative single scenarios and sensitivity runs. When comparing single runs, the noise seed for product demand was kept consistent. In most sensitivity runs, the parameter of interest was varied uniformly across a range of interest for 200 runs and averages and standard deviations were calculated. In some cases, 2000 runs were completed to get better statistical data. Unless otherwise stated, the product demand growth noise was varied.

6.3 Measuring Effectiveness

Many different responses were observed during the 1970's cobalt crisis and some were more effective than others in reducing the impact of the increased scarcity on manufacturers. Various measures are defined here to compare the effectiveness of manufacturer responses and strategies in the model. These measures will be analyzed in the results section.

It is proposed that effectiveness should be measured by how it succeeds in reducing the financial consequences felt by firms. The measures will be used to compare different scenarios. Ways in which the firm will feel the effects of their decisions will likely be in the form of one or a combination of the following:

- increase in costs, especially material costs

- insufficient supply to meet manufacturing demand

- uncertainty of expenditures leading to cash flow issues

A number of ways to measure the effectiveness of manufacturer strategies are suggested here. These measures are taken for each simulation run and used to compare different scenarios. With sensitivity analyses, the statistical data of these measures can also be used to compare different runs. While all these variables will be easily measured in the framework of the model, they are not always easy to observe in the real world. A few notes for each variable on the availability of such data in real material systems is given along with the description of the variables, where necessary.

- average price ($/g)

- variability of price through standard deviation, coefficient of variation or difference from mean

- marginal cost of mining and extraction ($/g)

- spending rate ($/year)

- net spending rate ($/year)

- average unit expenditure ($/g)

- average net unit expenditure ($/g)

- estimated scarcity rent or net price ($/g)

- rate of resource net price appreciation (dimensionless)

The *price* of platinum modeled will be assumed to occur in a market where the prices of alternative materials and resources are constant. This is because the model considers economic growth and other factors of the global economy such as inflation as exogenous. Given that most materials are commodities that are traded on an open market, price is a well-observed measure with years of historical data available. Although manufacturing firms do not always pay the market price, but instead have contracts with material producers, the market price will inform the price set for the contracts and is a good measure of the material costs to the average manufacturer.

The *marginal cost* of mining and extraction is here defined as the cost of the highest cost producer of a given material and can be observed if the supply curve is known. In the model, the estimated variable cost is calculated based on a cost per tonne of ore milled divided by the ore grade being extracted by that producer. The capital cost is calculated based on investments made for primary production. The marginal cost of extraction for platinum is then measured as the marginal variable cost (variable cost of extracting lowest grade ore for each producer) plus average capital cost of the highest-cost producer.

In general, the supply curve can be constructed if the cost and production capacity of every producer is known. Although it is possible in the model to know the marginal cost of extraction, in reality, there is very little data available to non-primary producers on the costs of resource extraction over time. Estimates can be made from yearly financial reports gathered from all

primary producers of a resource of interest, if these are publicly available. Increasing costs to producers will likely lead to increasing prices for manufacturers that purchase materials.

The spending rate for a manufacturer is how much a manufacturer spends on purchasing a given material in any given year. It is measured as the purchases of a material times the price of the material at a given point in time, t. A system-average spending rate can also be measured.

Spending Rate$_t$ = Use$_t$ * Price$_t$

The net spending rate accounts for net revenues from selling scrap material to recyclers after use. This is possible especially for material that is used in the processing stage of manufacturing rather than in the final product. In some industries, there are take-back programs that collect products at end-of-life and the recycling of those products can also bring in revenue (but also incur costs which need to be accounted for).

Net Spending Rate$_t$ = Use$_t$ * Price$_t$ - Toll * Recycled$_t$

The average unit expenditure is calculated over a period of time as the total spending divided by the total amount of platinum purchased and used. It is in other words a weighted average material cost to the manufacturer over a period of time of interest. As with spending rates, average unit expenditures can be measured for the system as a whole, or at an industry-level. Net average unit expenditures are calculated in a similar fashion, except using net spending rate rather than total spending rate.

$$\textit{Average Unit Expenditures}_{\text{up to time T}} = \frac{\sum_{t=0}^{T} SpendingRate_t}{\sum_{t=0}^{T} Use_t}$$

Expenditures and spending rates are not generally available to the public, although they would be easily tracked by individual manufacturers.

The *net price* can be measured as the price net of marginal extraction cost (Slade 1992). The net price is also called in some literature the rental rate and is here used to estimate the scarcity rent.

Estimated Scarcity Rent$_t$ = Price$_t$ − Marginal Cost$_t$

The rate of resource net price appreciation is then defined as:

Instantaneous Rate of Resource Net Price Appreciation =

$$r_t = \frac{d\left(\text{Price} - \text{Marginal Cost}\right)\big/dt}{\left(\text{Price} - \text{Marginal Cost}\right)} = \frac{d\text{Estimated Scarcity Rent}\big/dt}{\text{Estimated Scarcity Rent}}$$

A rate of resource price appreciation can also be calculated in the same manner, without subtracting marginal cost from price.

$$\text{Instantaneous Rate of Price Appreciation} = \frac{d\text{Price}\big/dt}{\text{Price}}$$

7 Results: Examining Scarcity in a Dynamic Market with Recycling

7.1 Exploration of Base Case Scenario Dynamics

This section examines the results of the model under the base case conditions for a given demand noise seed condition. Product-associated demand for platinum is projected based on growth of demand for platinum-using products for a particular noise seed (see Figure 29). This is the expected demand for platinum based on exogenous growth in demand for products that use platinum and the demand noise. The modeled total demand for platinum, which takes into account the response to price from the industries that use platinum, is lower than the product-associated expected demand in this case. The difference between the two lines is due to price elasticity and price, as will be discussed shortly.
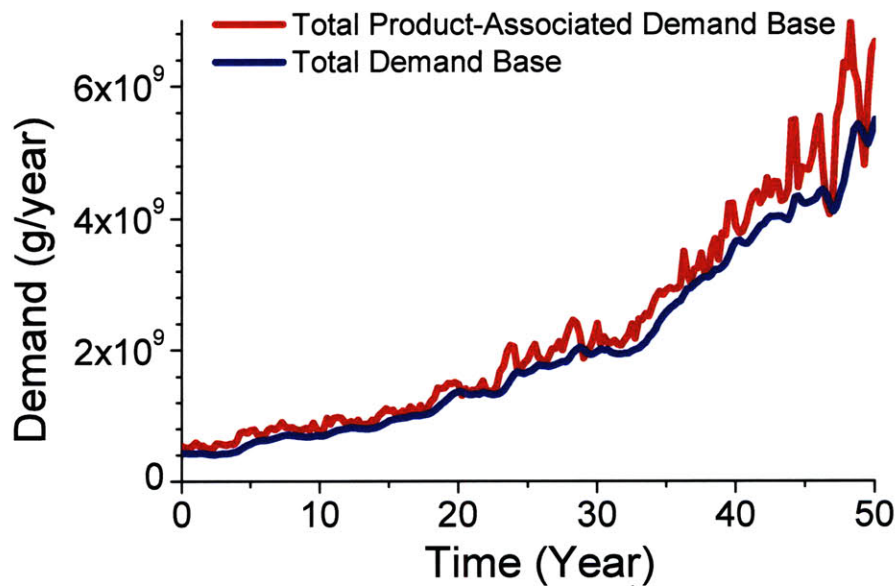
Figure 29: Projected product-associated demand for platinum based on exogenous growth rates of products containing platinum (no-response to price) (RED) and total demand for platinum (responds to price behavior) (BLUE).

Modeled price and marginal cost of primary platinum extraction are graphed in Figure 30. The marginal cost curve presents the cost of the highest cost producer of platinum at any given time. Marginal cost changes either when there are changes to the cost of extraction in a given region, or when a new, higher cost region enters the market (see Figure 31). Marginal cost increases in a step-

wise fashion in keeping with the model structure, which bins the primary supply by region and ore quality.
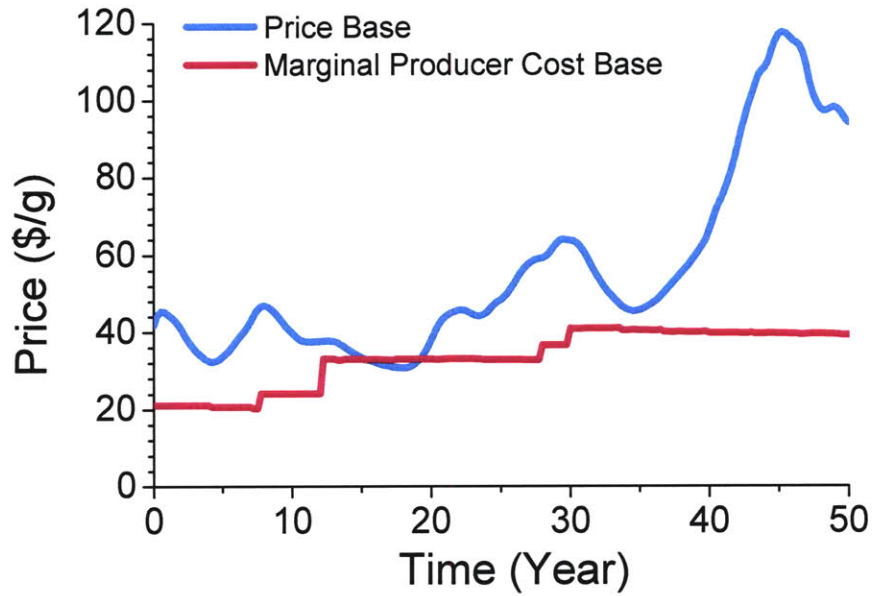
Figure 30: Price (BLUE) and Marginal Cost (PINK) as a function of time for the Base Case.
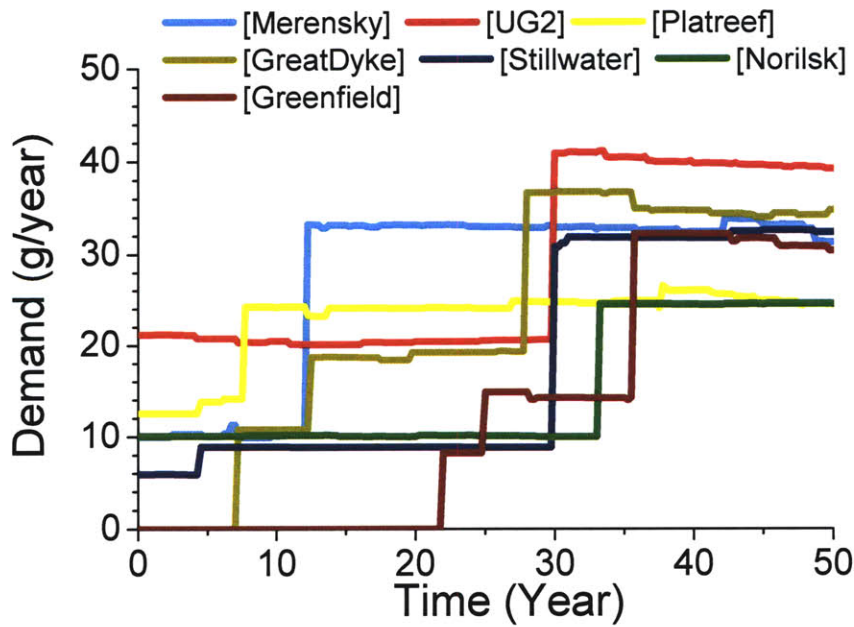
Figure 31: Marginal Cost by Primary Mining Supplier as a function of time for Base Case.

Price increases ahead of marginal cost under increasing demand for platinum. Primary metal suppliers are not motivated to open new mines and refineries unless price is expected to cover the costs to build and run the new production capacity. The new production capacity costs are increasing because ore grade depletion occurs more rapidly than technological improvements in mining, extraction and refining processing. Hence, prices first increase as demand increases but supply does not and then new mines are built when price becomes attractive.

Overall growth in demand for platinum is driven by demand in the glass and automotive industries (see Figure 32). Overall demand growth is almost exponential, which is a result of the exogenously imposed demand path for products that contain platinum. The exponential growth was observed in the historical period and is the growth rate determined from the calibration of the demand sector in the model. The use of platinum in the automotive and glass industries grows despite prices almost tripling in the 50-year modeled period. This is consistent with calibration results which showed low price elasticity in these two industries: demand for platinum in these sectors grew exponentially in the 34-year calibration period even though real prices (2005 $) varied between $13/g and $38/g. The low price elasticity in the automotive industry can be explained by the low total cost of the platinum used in a car relative to the total cost of a car and to automotive manufacturers' risk-averse behavior towards change in the catalytic converter design after having suffered from massive recalls of the converters in the 1980's (Gerard and Lave 2005). The low price elasticity in the glass industry is mainly explained by the fact that most of the platinum used by the glass industry is recovered and recycled such that the glass industry only pays the cost of the recycling for most of its platinum use.

As recovery rate is high in the glass industry, the automotive industry actually accounts for the largest fraction of growth in demand for primary platinum (see Figure 33).
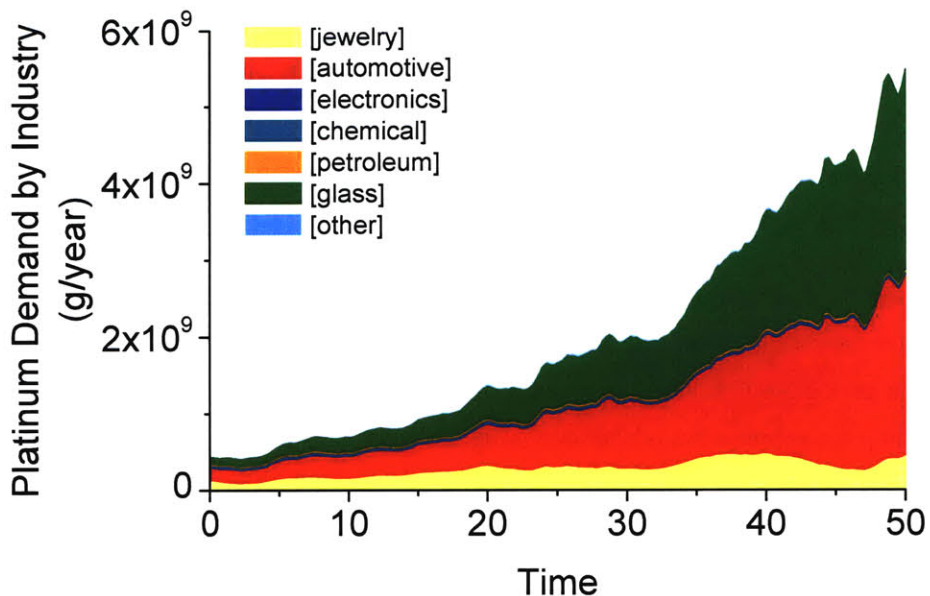
Figure 32: Stacked graph of total demand for platinum (primary + secondary) in each of the 7 demand groups. Jewelry, automotive and glass account for the majority of total demand.
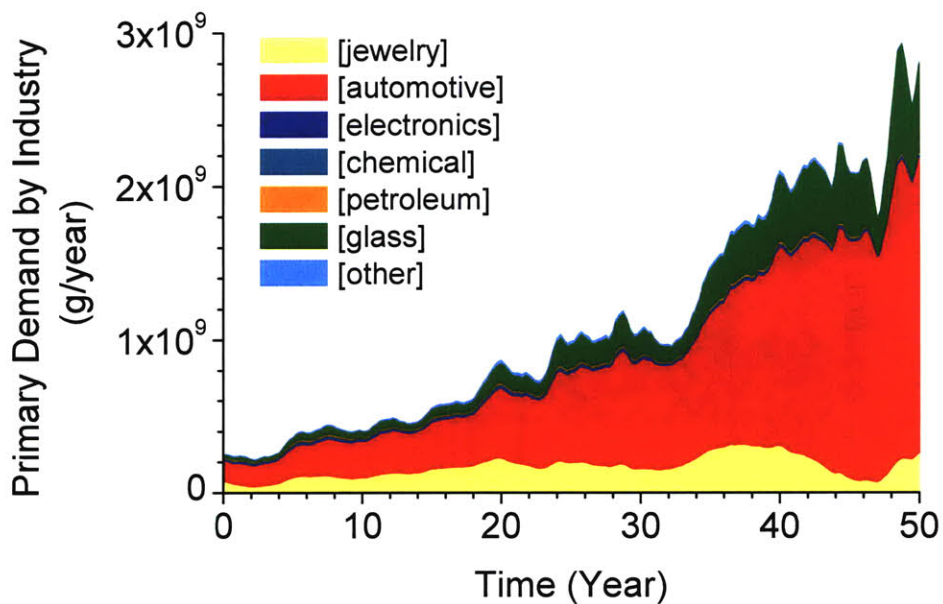
Figure 33: Stacked graph of primary demand for platinum in each of the 7 demand groups. Jewelry, automotive and glass still account for the majority of total demand.

The estimated scarcity rent or net price (see definition in 6.3) can be derived from model results as the difference between the price and the marginal cost. On average, the estimated scarcity rent for

the base case is positive, but it can also be negative (see Figure 34). It is expected, in a relatively competitive market, that the net price would be positive in the long term as suppliers that produce at costs above market price are not likely to remain economically viable. Net prices can only be negative for long periods of time if subsidies are provided to the firms that are producing at a loss. This occurs for example in commodity markets when a mining company is controlled by a government.

The net resource price appreciation for the base case fluctuates widely over time, especially in the period when the estimated scarcity rent becomes negative (see Figure 34). The average value over the 50-year period is 9.6%. Price appreciation does not fluctuate as much and averages 1.6%. A positive net price appreciation is consistent with the theoretical economic model of increasing scarcity.
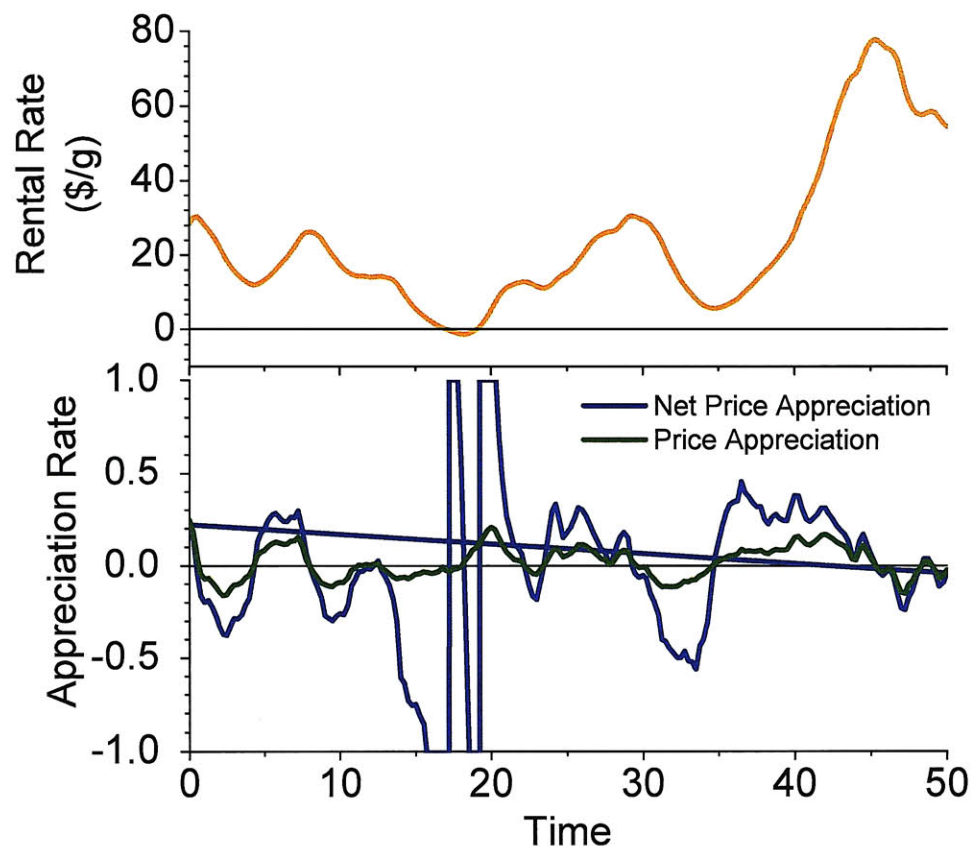
Figure 34: Estimated scarcity rent (Price – Marginal Cost) as a function of time for Base Case (ABOVE). Instantaneous price appreciation and net price appreciation (LOWER) as a function of time. Average over 50-year period: price appreciation = 1.622%, net price appreciation = 9.638%

On the supply side, 60% of demand is satisfied by primary extraction while recycling satisfies the remaining 40% (see Figure 35 and Figure 36). In the modeling period, on average, 70% of platinum is recovered for recycling. The slope of recovery rate with time is slightly positive because recovery is motivated by price and prices increase over time. The modeled recovery rate is consistent with literature on the US and Germany estimated rates, which were 76% and 67% respectively.
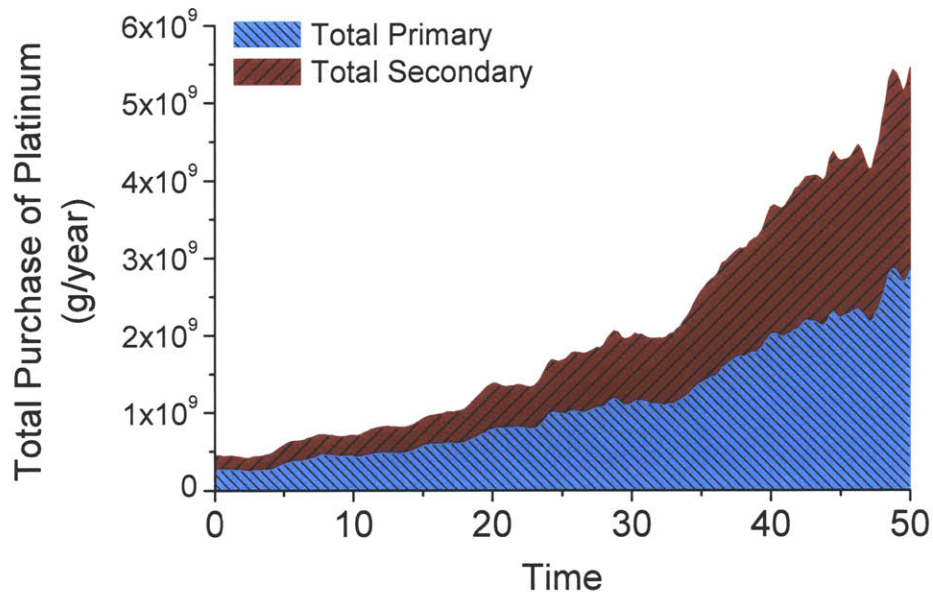
Figure 35: Stacked Primary Purchases and Secondary Purchases as a function of time for Base Case.
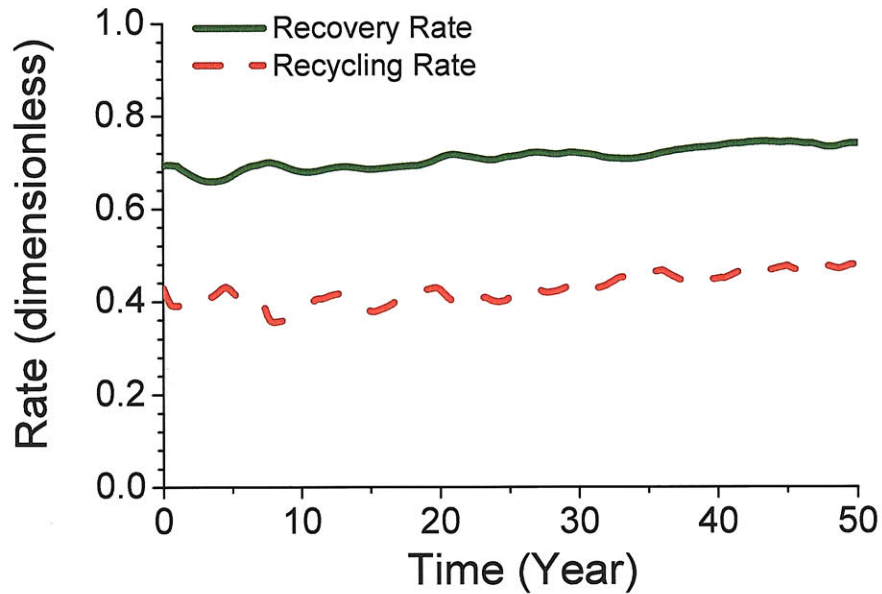
Figure 36: Recovery Rate (GREEN) and Recycling Rate (RED) as a function of time for Base Case.

The measures that were described in Section 6.3 are presented for the model base case run in Table 8 and will be used as a basis of comparison for how changes to the system effect its performance from these perspectives. In other words, these metrics will be compared for alternative scenarios in the next sections. Desirable outcomes for manufacturers include lower material price and lower average expenditures. Marginal costs of extraction may be correlated with price and average unit expenditure. The net price appreciation is a measure of the change of the estimated scarcity rent over time.

Table 8: Measures of Effectiveness for Base Case single run taken over 50-year period.

Measure	Average	Standard Deviation
Price ($/g)	55.6	24.2
Marginal Cost ($/g)	31.7	7.79
Net Price Appreciation Rate (dimensionless)	0.0963	4.27
Average Unit Expenditure ($/g)	44.1	9.09

In the next sections, I examine the effects of recovery rate and recycling rate on the platinum system and the mechanisms of primary and secondary supply that can lead to these observations. I

also examine the effect of recycling for the different industries and examine the industry-level properties that make recycling important.

7.2 Examining Recycling as a Response to Scarcity

Hypothetical recycling scenarios were simulated and the results will be presented here. An exogenous variable, defined in the model as the recovery rate multiplier, was varied between 0 and 1.5. The recovery rate multiplier is a factor that is multiplied to the recovery rate on an industry-by-industry basis.

Recovery Rate = MINIMUM (Recovery Rate Multiplier * Reference Recovery Rate, Maximum Recycling Efficiency)

When the recovery rate multiplier is equal to 1, the recovery rate is equal to the estimated present recovery level. This is called the base case recovery rate. This level of recycling can also be referred to as 100% of base case recycling. When the recovery rate multiplier times the recovery rate was larger than the maximum recycling efficiency[10], the recovery rate equaled the maximum recycling efficiency. An example of how this was implemented is shown for two separate scenarios in Table 9.

Table 9: Recovery rate multiplier example.

Scenario	Industry	Reference Recovery Rate	Maximum Recycling Efficiency	Model Scenario Industry Recovery Rate
Recovery rate multiplier = 1.2	automotive	0.34	0.89	0.408
	glass	0.98	0.98	0.98
Recovery rate multiplier = 0.75	automotive	0.34	0.89	0.255
	glass	0.98	0.98	0.735

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[10] The maximum recycling efficiency is the most that can be recovered if all products containing platinum that have reached end-of-life are collected for recycling. The maximum recycling efficiency is calculated as 1 minus fraction lost due to dissipation during use minus fraction lost due to the secondary extraction processing losses. Also see definition in the appendix.

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The system-level recycling rate was calculated at each time step as the total amount of secondary going into use divided by the total amount of platinum going into use. An average recycling rate for each scenario for the whole modeling period of 50 years was calculated as the average of the recycling rate (non-weighted) at each time step.

The system-wide recovery rate was also calculated at each time step by comparing how much platinum was recovered divided by the total amount of platinum reaching end-of-life. The average recovery rate for each scenario for the whole modeling period was calculated in the same way as the average recycling rate.

7.2.1 Observations of the Effect of Recycling with Base Case Demand

Three sample scenarios with recovery rate multiplier equals 1 (100% of base case recovery rate), 0.5 (50% of base case recovery rate) and 0.1 (10% of base case recovery rate) and the base case demand noise seed were simulated. Average price was lowest in the case of greatest recycling (the recovery rate multiplier equals 1) and highest in the case of lowest recycling (the recovery rate multiplier equals 0.1) (Figure 37). Also, at any given time, except in the first 10 years, the price was lower for the higher recycling scenarios. The resulting primary and secondary platinum use rate for the three scenarios is shown in Figure 38.
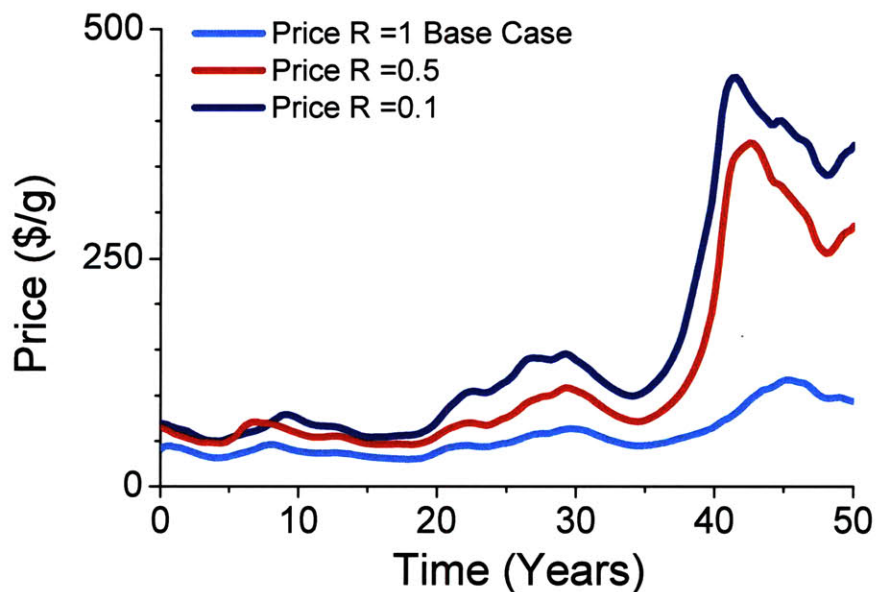
Figure 37: Price for base case recycling (recovery rate multiplier, R = 1), recovery rate multiplier = 0.5 and recovery rate multiplier = 0.1.
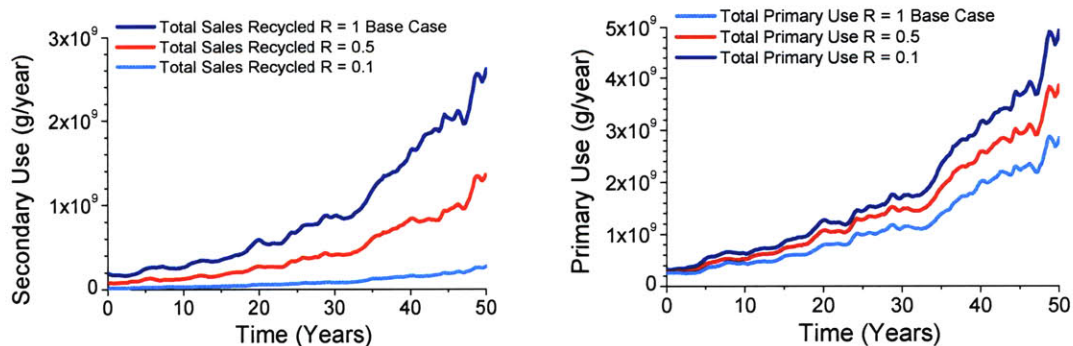
Figure 38: Total platinum secondary use and primary use for base case recycling (recovery rate multiplier, R = 1), recovery rate multiplier = 0.5 and recovery rate multiplier = 0.1.

When recycling is reduced and total product demand is maintained, the demand for primary platinum in products must be met by increased primary production. The push to increase primary production puts pressure on the exploration and discovery aspects of primary production and would be expected to lead to increased costs since lower quality ores will need to be tapped. In the base case, the cost of extraction of the marginal producer tripled from year 0 to year 50 and, in the case of R = 0.1, that cost increased by 6.8 times in the same period.

There is some response on the demand side to the increased price of platinum but, given the low price elasticity and long delay times for changing use patterns for platinum-using industries, this response is limited. There is only a 4% decrease in demand for platinum as a result from the higher prices under the 10% of base case recycling scenario (see Figure 38). The insensitivity to price exhibited in the demand of the automotive and petroleum industries is a reflection of their past performance in the face of price swings. Although there may be reason to suggest that this response may not persist, historical data provides no evidence of price responsiveness in these industries. The price responsiveness of demand will be further explored in a later section.

Figure 37 shows results from the same base case demand noise seed, which means that the product demand path is the same for all three curves. The noise seed can lead to large differences in the price even with only a 10% variation from the smooth idealized path. The sensitivity of the model results to different product demand paths was examined by varying the noise seed. Figure 39 shows this effect by plotting model results for price for 200 simulations each based on a different noise seed (i.e., different random noise in demand) with all other conditions held at base case levels. The inner lighter band represents the 50% of modeled results closest to the mean result for that time period. The next band captures an additional 75% of modeled results, while the dark outer band represents 95% of the results. From Figure 39, it is clear that the range of modeled price based on

varying noise seed while keeping all other variables constant is wide, especially at later time periods.
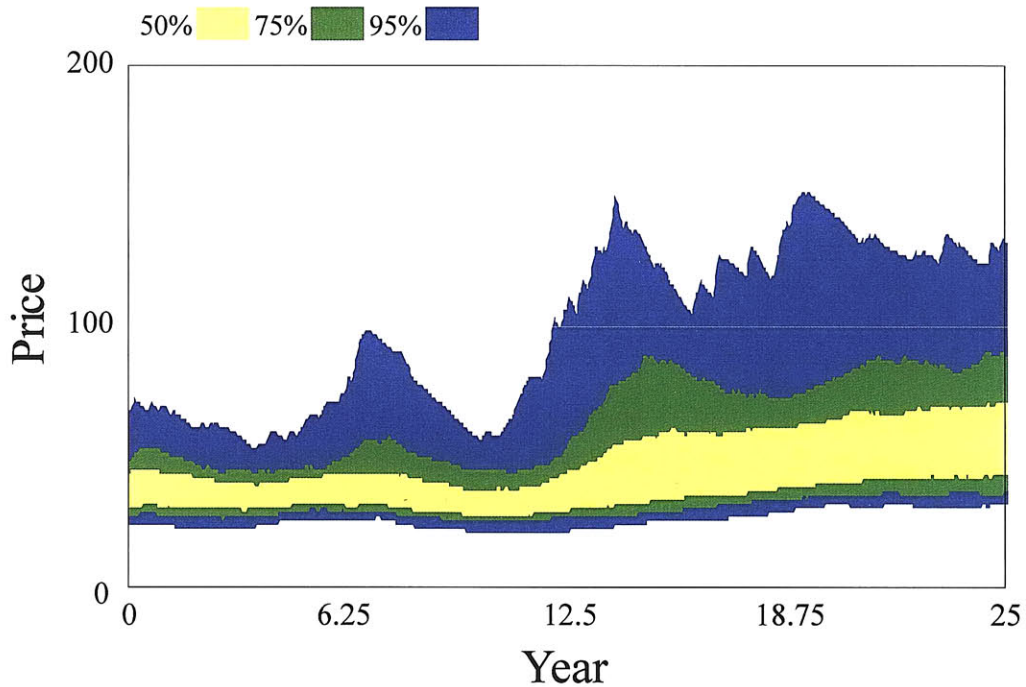
Figure 39: Confidence range on price with varying product demand noise seeds.

The sensitivity of the model results to different product demand paths was examined by varying the noise seed. The effect of recycling differences was examined by running an analysis similar to that presented in Figure 39 (i.e., 200 simulations with 200 different noise seeds) at several recycling levels to average out the effect of the noise seed and discern the underlying behavior of the model. For this analysis, six levels of recycling were compared with the recovery rate multiplier set at 1.25, 1, 0.75, 0.5, 0.25 and 0.1.

The average recycling rate, average price, maximum price, average unit expenditures overall and average standard deviation of price over time were measured for each analysis set for the 200 simulations. The standard deviation of average prices from each simulation was also calculated (see Table 10). These variables are endogenous variables. In Figure 40 the average price and corresponding standard deviation of average price (shown as error bars) is plotted as a function of the average recycling rate (not recovery rate multiplier).

Table 10: Results of 200 simulations at each recovery rate multiplier value. Demand growth is exponential.

Recovery rate multiplier	Average Recycling Rate	Average Price	Maximum Price	Average Unit Expenditures	Average Standard Deviation of Price	Standard Deviation of Average Price
1.25	0.4571	89.49	345.95	132.61	72.50	20.20
1 (Base)	0.4302	90.42	344.52	133.31	71.54	20.75
0.75	0.3246	105.19	431.97	160.76	90.90	20.43
0.5	0.2175	130.74	532.01	206.25	119.30	25.79
0.25	0.1095	158.36	615.36	252.17	144.74	28.61
0.1	0.0441	187.83	705.87	299.59	168.12	32.90
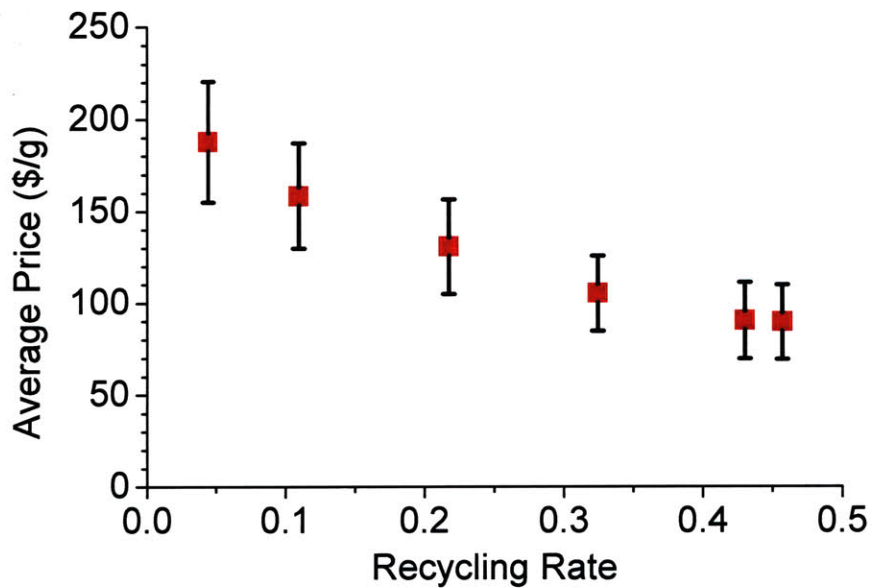
Figure 40: Price and standard deviation of price at different levels of recycling and exponential demand growth graphed.

As before, when recycling is decreased from base case level (recovery rate multiplier = 1) to 10% of base case recycling (recovery rate multiplier = 0.1), average price and average standard deviation of price increase. As described previously, ore degradation leading to higher costs of

extraction is hypothesized to be at least one of the reasons for the observed price increase with decreasing recycling.

The scenario with recovery rate multiplier equal to 1.25 is different from the other scenarios in that the average recycling rate actually doesn't increase much. When the recovery rate multiplier is greater than 1, it is possible that the recovery rate reaches the maximum recycling efficiency. In the case of platinum, the base case recovery rate is already at or close to maximum for the glass, petroleum and chemical industries (see Table 7). As a result, the recovery rate for these industries reaches the maximum and cannot increase despite a 25% increase in the desired recovery rate. The average standard deviation of price and the maximum price are actually higher than the base case scenario. It is hypothesized that when recovery rates approach maximum efficiency, there is not much room for recycling to respond to changes in price and in particular there is not much room for recycling to increase during supply shortages. This limit will be further explored when the responsiveness of recycling is examined (Section 7.2.2.2). It will be shown that operating at the maximum recycling efficiency can lead to price increasing more during certain periods than it would have had the recovery rate been just slightly lower than the maximum recycling efficiency.

A set of 2000 simulations were run with randomized recovery rate multipliers (from a uniform distribution ranging between 1 and 1.5) and a randomized noise seed. The results were reduced using the procedure described above and are presented in Figure 41. This Figure affords another way of visualizing the relationship between recycling rate and platinum price in the model. For each simulation, a different noise seed was also selected, which accounts in part for the noise in the results. Two regimes are seen: below a recovery rate multiplier of 1, the slopes of recycling rate and recovery rate vs. recovery rate multiplier are steeper than above 1. The regime change occurs because, for certain industries, the base case is the most efficient recovery rate possible and above 1, the multiplier is only affecting industries that are below maximum recycling efficiency. The price and average standard deviation of price also have different slopes in the two regimes. The slope is negative below 1, indicating decreasing price as the recovery rate multiplier increases and is relatively flat above 1.
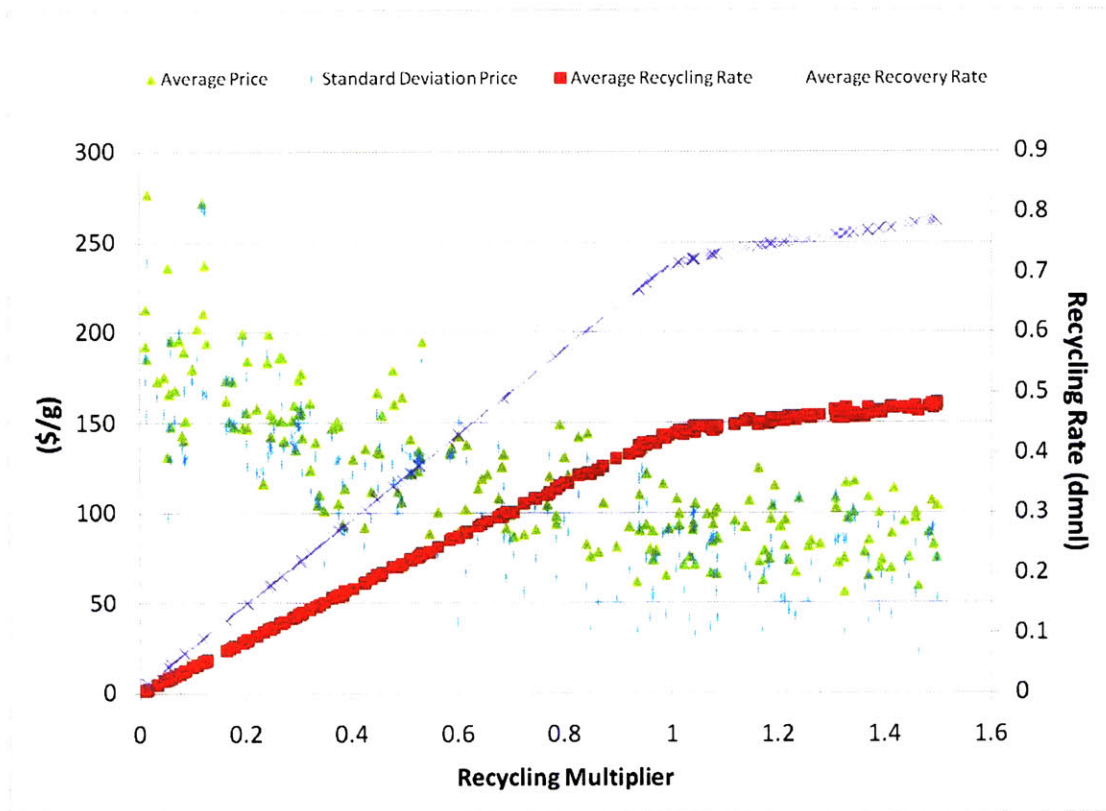
Figure 41: Average price and average standard deviation of price (left axis) and average recycling rate and average recovery rate (right axis) are plotted for each simulation run at varying recovery rate multipliers (y-axis labeled recycling multiplier) selected randomly for the sensitivity test. Demand growth is exponential (base case).

In Figure 42, price and standard deviation of price are plotted as a function of the average measured recycling rate. There is a cluster of points around 0.45 where the points representing simulation runs with recovery rate multipliers above 1 are located. The slopes of linear fits through average price and average standard deviation of price show decreasing price as the average recycling rate is increased.

The higher platinum price translates to a higher overall average unit expenditure for firms that use platinum as seen in Table 10. The higher standard deviation of price increases price uncertainty. Both (higher prices and higher price uncertainty) are undesired impacts for firms and should motivate them to gain a better understanding of the effect of recycling.

Figure 42: Average price and average standard deviation of price are plotted for each simulation run at varying recovery rate multipliers selected randomly for the sensitivity test. The results are plotted as a function of recycling rate instead of recovery rate multiplier. Demand growth is exponential (base case).

7.2.2 Recycling Behavior Mechanisms

It is hypothesized here that recycling serves two purposes in the platinum system. The first is that recycling reduces primary demand for platinum and therefore reduces the rate of ore degradation and the rate of extraction cost increase. The second is that recycling responds differently and more quickly to price than primary production and therefore can help stabilize price.

7.2.2.1 Platinum recycling reduces primary ore degradation

Demand for platinum is derived from the growth in demand for products that require platinum. It is a very expensive metal, relative to other metals, and is used mainly in products where its unique material properties satisfy a very specific need. Historical data on platinum use indicates that demand for platinum is inelastic in most sectors based on econometric modeling of platinum demand (see Appendix). Rather growth in demand for cars or gasoline has pushed growth in platinum use.

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In the modeled scenarios, platinum recycling rates have an effect on price but do not have much effect on the overall demand for platinum because demand for platinum is not price elastic. As a consequence, for every gram of platinum recycled, there is a decrease of almost 1 gram of primary platinum extraction. The dynamics of other material systems may be different. In a system where demand is price elastic, the effect of recycling on price would likely also affect total demand (which would then affect price, etc.). It is also important to note that not all material systems are able to use primary and secondary material interchangeably. For example, for copper and aluminum, contamination of the secondary material is a big concern when firms are considering substituting secondary materials for primary materials (Gaustad, Li et al. 2007).

With increasing primary extraction, there is increasing ore degradation. This trend has been observed historically in a number of the platinum mines based on the average ore grade at the mill reported in the yearly financial reports (see Figure 21). Based on these trends, the future scenarios show decreasing ore grade as well and the decrease occurs more rapidly with increasing primary extraction. The lower ore grades translate to higher costs of extraction and higher costs can be observed at lower recycling rate (see Figure 43).

Figure 43: Average Cost of Marginal Producer, Average Price, Maximum Cost of Marginal Producer as a function of recycling rate. Demand growth is exponential (base case).

Linear regression was performed on the modeled results of average price, average cost of the marginal producer and maximum cost of extraction as a function of average recycling rate. Statistical data from linear regression are presented in Table 11. For all three variables, the correlation between the variable and the average recycling rate was statistically significant. Moreover, there may be an increase in the spread of average prices at lower recycling rates. Higher rates of primary extraction (i.e. lower recycling) also result in higher estimated scarcity rents; although the rate of resource net price appreciation remains constant (see Figure 44 which only shows 200 points, although 2000 points were obtained and used for statistical analysis). The average of the average net price appreciation rate over the 2000 simulation was measured as 0.0452. It is possible to conclude that average price, average marginal cost, maximum marginal cost, and estimated scarcity rents are all correlated to average recycling rate.

The absolute values of the residuals were also examined to see if they were also dependent on recycling rate. The absolute value of the residuals for average price showed a very low R^2 value,

but the null hypothesis that there is not correlation at the confidence level of 95% could not be rejected. The absolute values of the residual for costs showed no correlation with recycling rate.
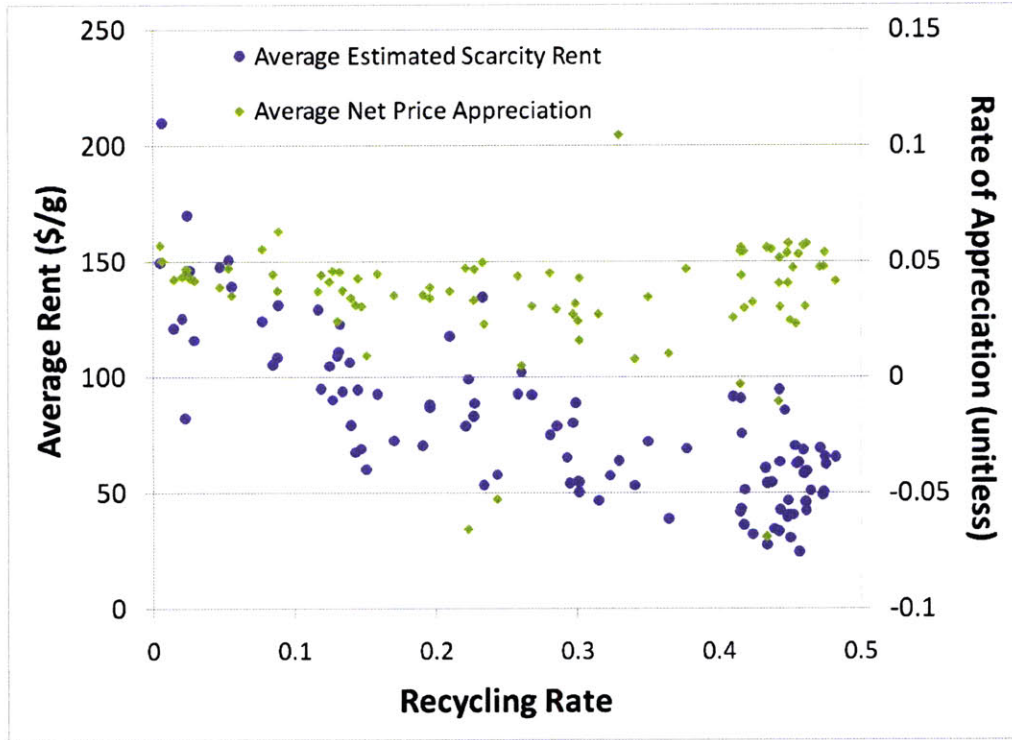
Figure 44: Average Estimated scarcity rent and Average Rate of Price Appreciation as a function of average recycling rate. Demand growth is exponential (base case).

Table 11: Results of Linear Regression from 2000 simulation runs where the recovery rate multiplier was varied between 0 and 1.5. X-variable was recycling rate for all.

y-Variable	Slope	Intercept	R²	T-statistic w.r.t. Recycling Rate
Average Price	-212	182	0.629	-58.2
Standard Deviation of Price	-219	168	0.558	-50.25
Average Marginal Cost	-42.5	60.9	0.524	-46.89
Maximum Marginal Cost	-102	117	0.351	-32.9
Average Estimated scarcity rent	-176	129	0.621	-57.2

It is possible that there will be increased exploration efforts in the future and that discoveries will change the trends observed. In that case, the increasing primary extraction will be less likely to result in increased prices. Three scenarios with varying exploration effort were examined: low,

medium and high. Three sensitivity runs were compared where the exploration effort was set and the recovery rate multiplier was varied between 0 and 1.5. The slope of price as a function of average recycling rate was measured for each sensitivity run. A lower exploration effort corresponded to a larger effect of recycling on the price, i.e. a steeper slope.

Table 12: Effect of exploration on the slope of average price as a function of average recycling rate. Slope was calculated over 200 simulation runs.

Exploration Effort	Slope of Price with Recycling Rate	R^2
Low	-267	0.6725
Medium	-132	0.4839
High	-101	0.3221

7.2.2.2 Secondary supply responds to price

In this section, secondary supply responsiveness to price changes is compared to primary supply responsiveness. Primary supply can be considered relatively unresponsive to price due to a number of factors. Primary extraction is a very capital intensive process. It takes years after discovering a potentially profitable ore body before production can begin. The process involves completing geological and economic studies as well as in many cases hurdling political barriers that in certain countries may change a number of times before a project can begin. Once the mines and processing facilities are built, there is some flexibility around how much is extracted daily, but there are capacity constraints, depending on the capital invested.

Secondary processing is less capital intensive, although it does require some collection infrastructure that may not be easy to build or change. Still, secondary supply is considered more responsive to price than primary supply, although the level of responsiveness varies by industry and end-of-life product. For the base case scenario, modeling results show that the recovery rate differs among the various industries, as does the variability of the recovery rate over time (see Figure 45). The differences between different industries will not be discussed here in detail; instead, what will be examined is how the difference in how secondary supply responds to price versus how primary supply responds to price affects the platinum system.

Two model variables characterize the sensitivity of material recovery rate to material price. The first is a sensitivity value that is defined for each industry and determines the percent increase in

recovery for each dollar increase in price above the expected market-level price. The expected market-level price has been defined as a smoothed moving average of historical price and cost of the marginal primary producer. The second variable that describes responsiveness of recycling is a variable that determines how long it takes for the recovery rate to change to the desired level. The maximum recycling efficiency also limits responsiveness, and was defined in a previous section (see Table 7).
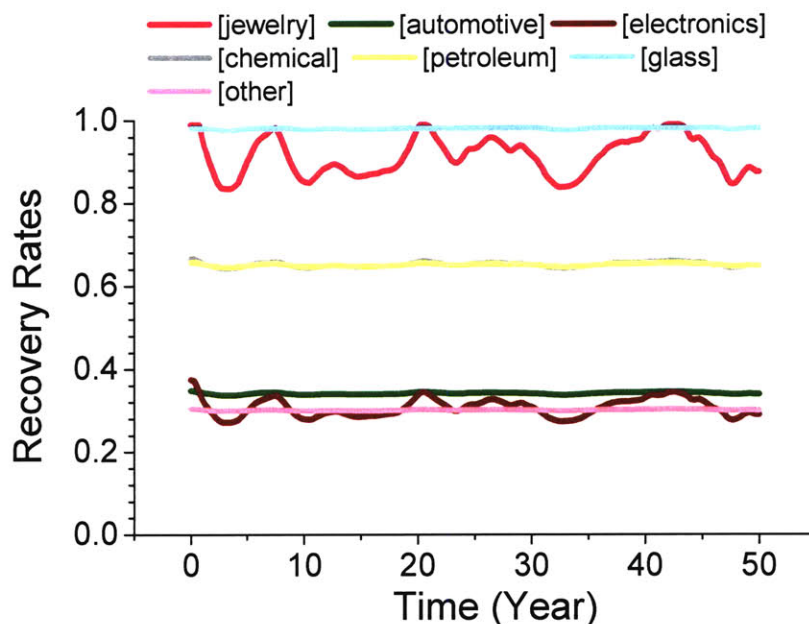
Figure 45: Recovery Rate by Industry (7 demand groups) as a function of time for Base Case.

7.2.2.2.1   Sensitivity of Recovery Rate to Price: Price Elasticity of Recycling

Three curves of price as a function of time are shown below in Figure 46. The base case has not changed and two other scenarios are compared to this case. While for the base case, the price elasticity of recycling is different for each industry and varied between 0.05 and 1, for these hypothetical scenarios the value was set at either all low (all 0.1) or all medium (all 2). All other variables in the model, including the product demand noise seed were kept as in the base case. Table 13 shows the summary results when 200 simulations with varying product demand noise seed are conducted for each elasticity scenario: low sensitivity (elasticity = 0.1), medium sensitivity (elasticity = 2) and high sensitivity (elasticity = 5) and the base case scenario. Table 14 shows the same four sensitivity scenarios as Table 13, except that the recovery rate multiplier was set at 0.5 for all the cases.
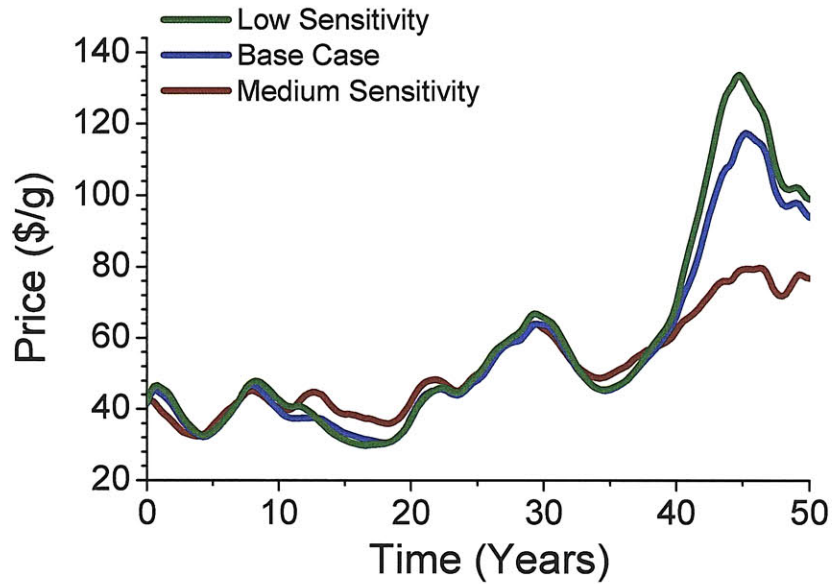
Figure 46: Three levels of responsiveness of recycling to price: low, Base case and medium recycling price elasticity.
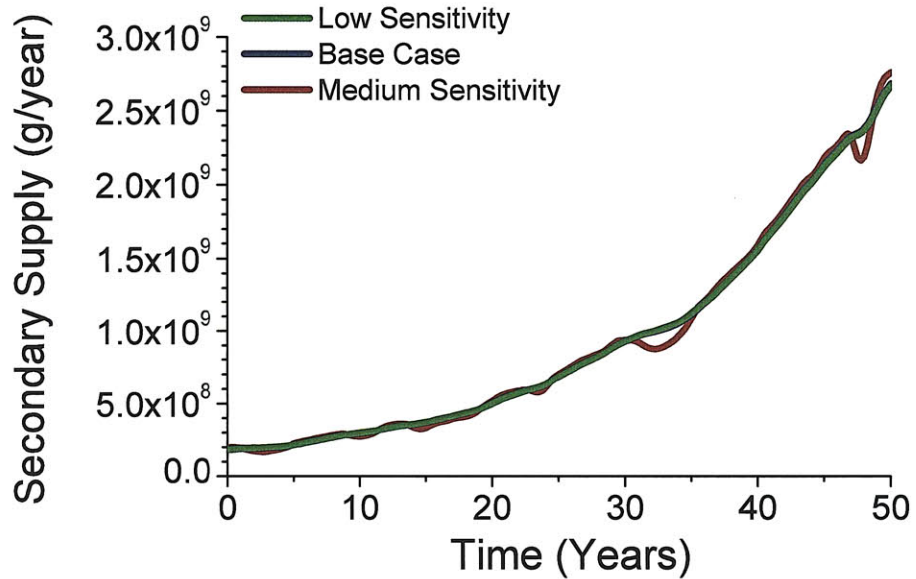
Figure 47: Total Recycled as a function of time with recovery rate multiplier set at 1 and same product demand noise seed as the base case. Three scenarios are shown: Low, medium and base levels of recycling price elasticity.

Figure 46 shows that the effect of increasing the elasticity value for recycling on price was small except in the last 10 years of the model period. With these three curves, the lowest price is observed for the highest sensitivity scenario. Table 13 and Table 14 show a similar pattern for the

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average price, where the average price increases with decreasing elasticity value for recycling responsiveness. The standard deviation of price also increases with lower sensitivity.

Table 13: Results of 200 simulations at 4 values of recycling price elasticity (total number of simulations = 4 * 200 = 800 simulations). Recovery rate multiplier is set to 1 for all scenarios.

Responsiveness of Recycling to Price	Average Recycling Rate	Average St.Dev. of Recycling Rate	Average Price	Maximum Price	Average Standard Deviation of Price	Standard Deviation of Average Price
High Sensitivity	0.4279	0.04775	68.12	180.12	36.46	13.31
Medium Sensitivity	0.4270	0.03659	80.84	257.34	54.68	17.72
Base Case	0.4302	0.03060	90.42	344.52	71.54	20.75
Low Sensitivity	0.4291	0.03096	91.74	355.90	73.49	21.77

Table 14: Results of 200 simulations at 4 values of recycling price elasticity (total number of simulations = 4 * 200 = 800 simulations). Recovery rate multiplier is set to 0.5 for all scenarios.

Responsiveness of Recycling to Price	Average Recycling Rate	Average St.Dev. of Recycling Rate	Average Price	Maximum Price	Average Standard Deviation of Price	Standard Deviation of Average Price
High Sensitivity	0.2540	0.06551	80.77	234.18	45.98	14.75
Medium Sensitivity	0.2331	0.04268	101.76	372.35	79.97	20.35
Low Sensitivity	0.2173	0.01909	132.30	526.83	120.00	25.58

Because it is easier to visualize the impact of responsiveness of recycling when the recycling rate is lower such that there is room both for increasing and decreasing the recovery rate, the following discussion will examine the high, medium and low sensitivity scenarios with recovery rate multiplier set at 0.5. In Figure 48, price as a function of time is shown for these three scenarios. In these three scenarios, the impact of changing sensitivity is greater than was seen with base case recycling level (Figure 46). The difference between low and medium sensitivity is that there is more variability of price in the low case. As sensitivity is further increased, the average price decreases overall and is more stable.

The amount recycled as a function of time provides an indication of the responsiveness of price as the sensitivity value is increased (see Figure 49). While total amount recycled grows steadily and smoothly for the case with low sensitivity, the amount recycled for medium and high sensitivity varies considerably over time in response to price changes. The ability to respond to price during short periods of increased or decreased demand is seen in the model to stabilize price in the long term.
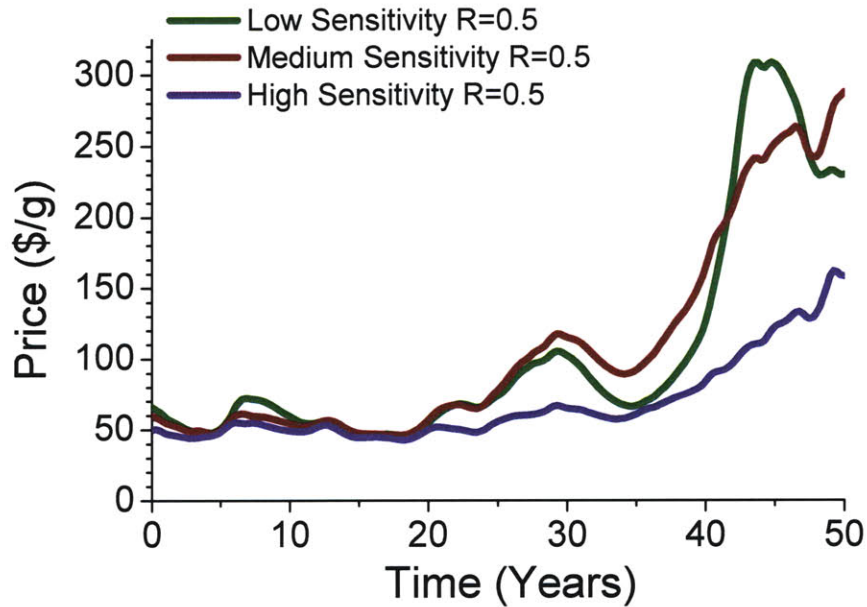
Figure 48: Price as a function of time with recovery rate multiplier set at 0.5 and same product demand noise seed as the base case. Three scenarios are shown: Low (BLUE), medium (RED) and high (GREEN) levels of sensitivity of recycling to price.

Another way to examine the responsiveness of recycling at different levels of recycling is to compare recovery rates (see Figure 50). Three recovery rate multipliers and two recycling sensitivity levels are compared. The difference between low sensitivity and medium sensitivity can be observed for each recycling level. The standard deviation of the recovery rates is higher for all recycling levels when the sensitivity is medium. Moreover, the standard deviation of the medium sensitivity cases decreases with increasing recovery rate.
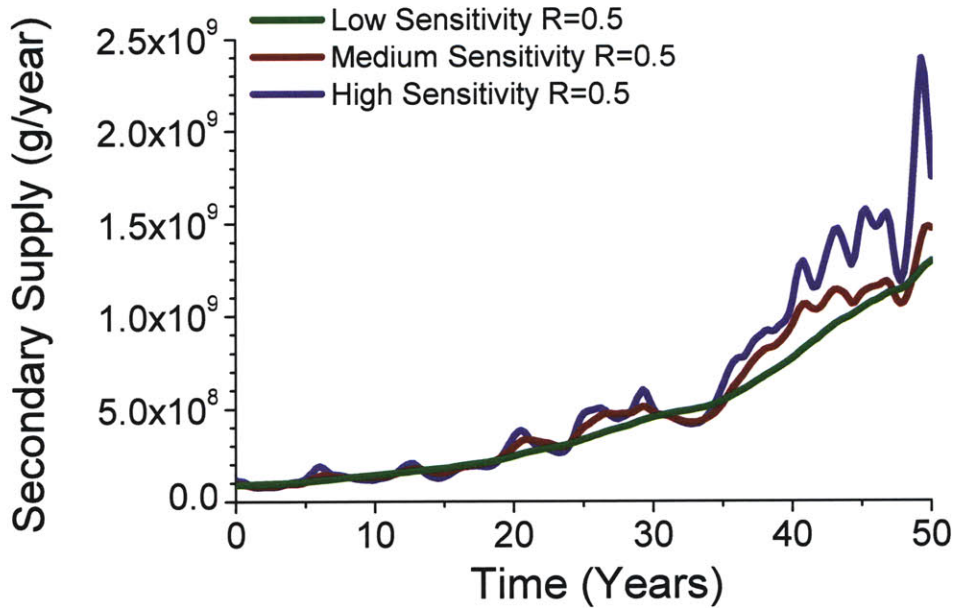
Figure 49: Total Recycled as a function of time with recovery rate multiplier set at 0.5 and same product demand noise seed as the base case. Three scenarios are shown: Low (BLUE), medium (RED) and high (GREEN) levels of sensitivity of recycling to price.
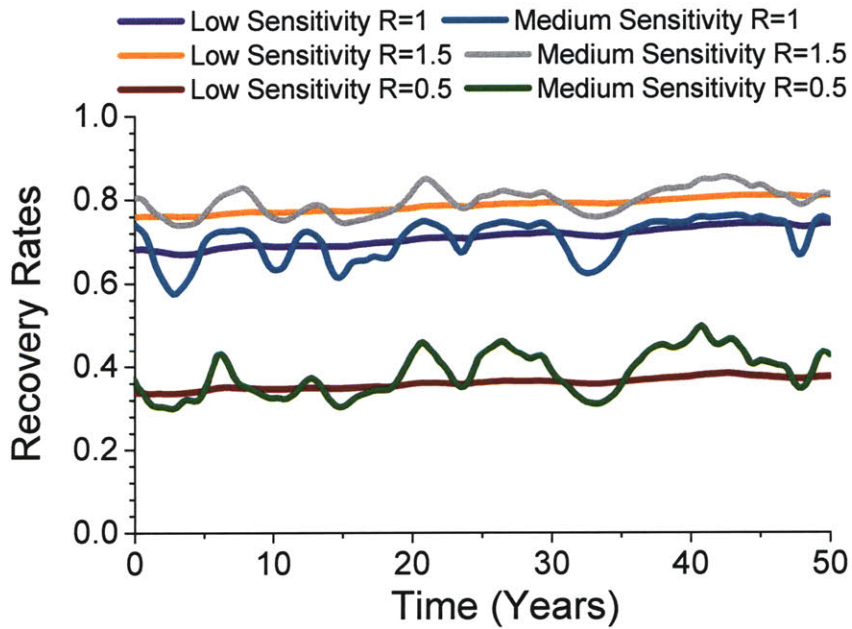
Figure 50: Recovery rate as a function of time for low and medium sensitivity values and recovery rate multipliers 0.5, 1, and 1.5.

The effect of reaching maximum recycling efficiency on recovery rate was also examined through sensitivity analysis of varying recovery rate multipliers at base case demand growth conditions and base case sensitivity of recycling to price conditions. Instead of only viewing 3 different recycling rate levels (ex: Figure 50), this type of experiment will show the trend in the recovery rate as the recovery rate multiplier is varied from 0 to 1.5. The standard deviation of the recovery rate over the 50-year period for each run and the coefficient of variation of the recovery rate over the 50-year period are plotted in Figure 51. The coefficient of variation (COV) is the standard deviation divided by the average.

There are three regimes as recovery rate multiplier is varied between 0 and 1.5: below 0.1, between 0.1 and 1, and above 1.

Between a recovery rate multiplier of 0 and 0.1, the slope of the COV is steep and negative and the slope of standard deviation is positive. In this regime, the denominator of the COV approaches zero and dominates the behavior.

Between 0.1 and 1, the slope of the COV is negative, but not as steep and the slope of standard deviation is still positive. In this regime, average recovery rate and standard deviation of recovery rate are both increasing.

Above 1, there is a step change in the average COV and the standard deviation decreases as the recovery rate multiplier increases. The average recovery rate is still increasing, although at a slower rate but standard deviation of recovery rate is decreasing. Since the average price doesn't change much in this regime, the drop in standard deviation of recovery rate is related to the responsiveness of recycling to price. In this regime, recycling is significantly limited by the fact that the recovery levels are nearing the maximum recycling efficiency.
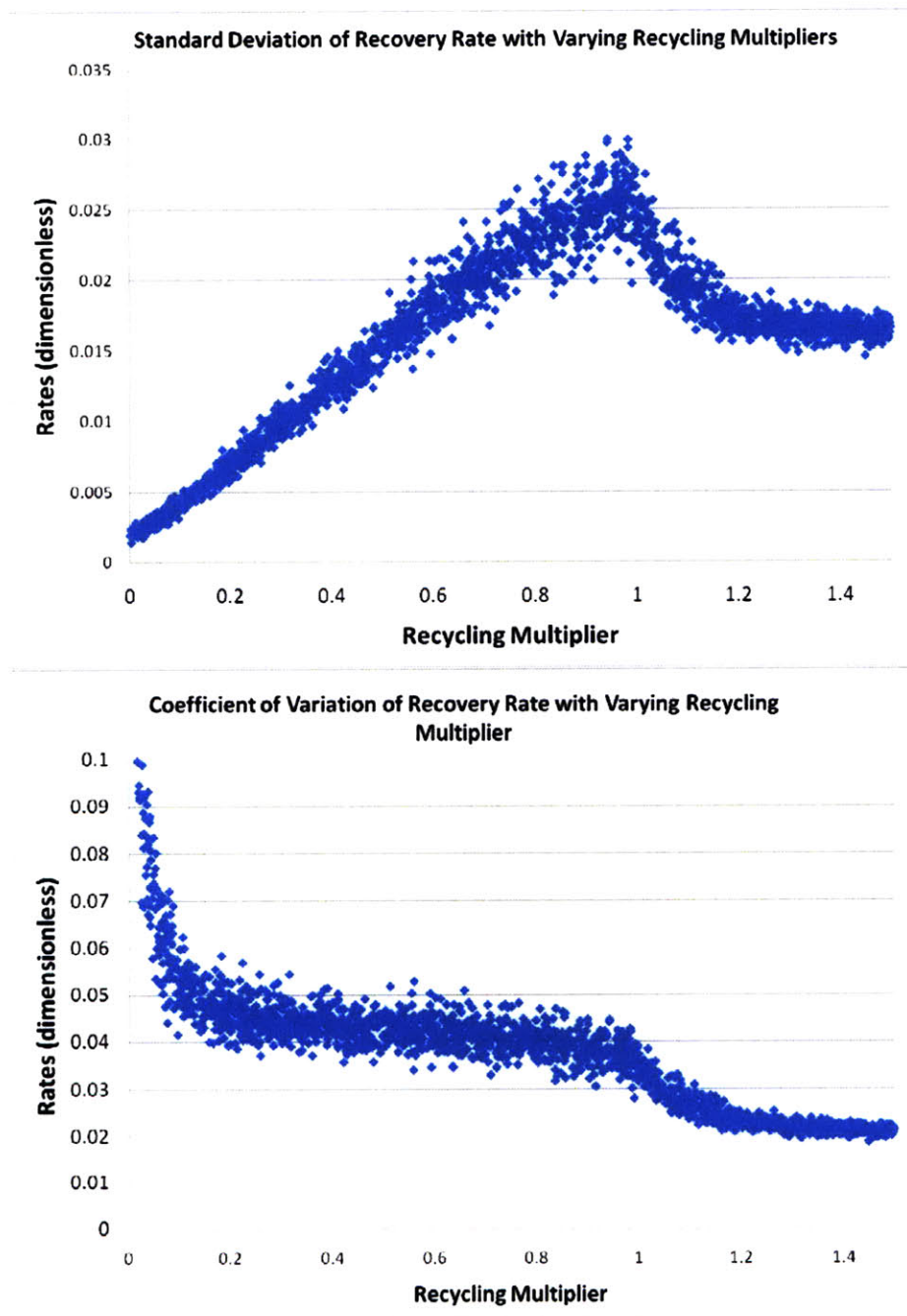
Figure 51: Standard deviation of the recovery rate over the 50-year period and the average coefficient of variation of the recovery rate over the 50-year period for 2000 simulations at different recovery rate multipliers (y-axis labeled recycling multiplier). Demand grows exponentially as in the base case scenario.

7.2.2.2.2 Recycling Delay

It is also of interest to explore the effect of the magnitude of delay for secondary supply to respond to price. This delay can be compared to the delay on the primary mining side, which is a result of

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the capital intensity of primary production. In the model, the primary supply side has a number of delays of which the time to commission a new mine is the main delay. This is a delay that describes the number of years required to start extracting platinum from a mine project after deciding to begin building.

The results with varying delay times on the secondary and primary side show how such delays impact average price, with longer delays resulting in higher average price and higher standard deviation of price (see Table 15).

Table 15: Results of 200 simulations for each delay scenario of recycling and primary supply. Recovery rate multiplier is set to 1 for all scenarios.

Responsiveness of Recycling to Price	Average Recycling Rate	Average Price	Maximum Price	Average Standard Deviation of Price	Standard Deviation of Average Price
Base Case, Recycling Delay 0.125 yrs, Mine Life 30 yrs, Time to commission new mine 5 yrs	0.4302	90.42	344.52	71.54	20.75
Recycling Delay 2 yrs	0.3879	104.99	429.50	90.93	22.45
Recycling Delay 7 yrs	0.2910	122.77	519.94	113.03	25.28
Recycling Delay 15 yrs	0.1823	127.01	532.54	118.03	23.62
Recycling Delay 24 yrs	0.1139	144.97	579.08	131.41	26.82
Commission New Mine 1 yr	0.4175	38.80	116.70	22.56	8.47
Commission New Mine 10 yrs	0.4545	243.85	823.93	200.56	16.11

In the case of delays on the secondary side, there is also an impact on the amount recycled. Longer recycling delays lead to less recycling overall. The delays on the primary side do not significantly impact the amount recycled, but do impact price.

7.2.3   Exploration of Various Demand Scenarios

The effect of recycling on average price, standard deviation of price and cost of extraction were examined for different demand scenarios. The two scenarios presented here are 1) an idealized case where product demand growth is smooth (no noise) and 2) a zero average product demand growth case (with noise).

The difference between the base case product demand and the idealized smooth product demand was shown in Figure 27. It is also important to note that, in reality, economic growth is not steady. Only with a simulation model can growth be projected to follow a steady path. In Figure 52, the difference in the price as a function of time for the two runs is shown. The smooth and continuous exponential growth of product demand results in a relatively smooth and steady increase in price as primary supply has to continuously grow and tap into lower quality ores to meet demand. Although not plotted here, marginal cost increases almost 5-fold due to degradation of ore grade.

The price increase is large but not unreasonable, at least by historical terms (the platinum real price in 2008 was about 3 times greater than the 1960 real price). The projected demand growth for this model scenario is considered aggressive and a slower growth rate or greater platinum ore discovery rate than the modeled rate would lead to smaller price increases.
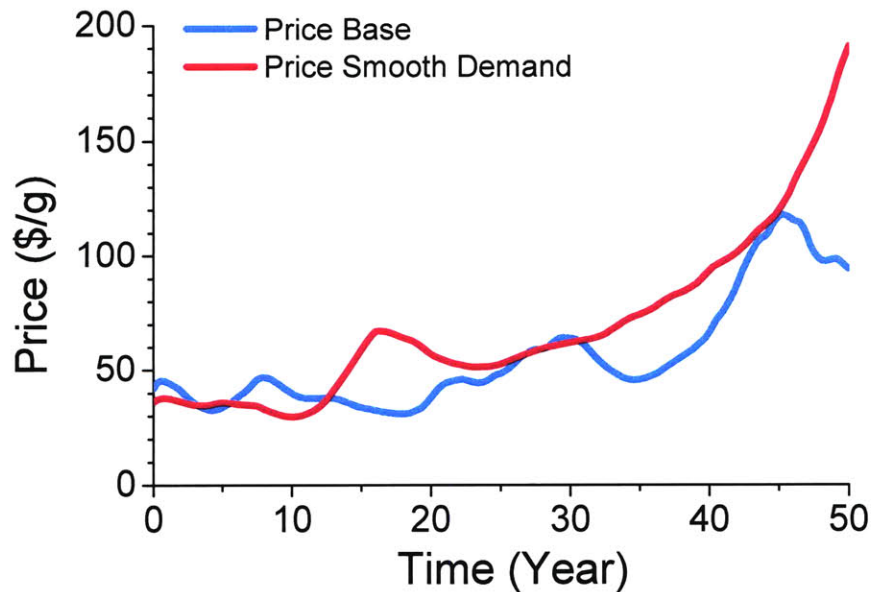
Figure 52: Price as a function of time in the base case scenario and the idealized smooth demand scenario.

With idealized growth, the recovery rate multiplier was varied in the same way as in section 7.2.1. The plot shown in Figure 53 mirrors the plot shown in Figure 42 but with smooth product demand growth for all the runs. As with the case of noisy demand, the slope of average price and average standard deviation of price as a function of recycling rate is negative, indicating that average price and average standard deviation of price decrease as recycling increases. It also shows that the better R square fit is larger due to the lack of noise in the product demand. Statistical regression results are summarized in Table 16.
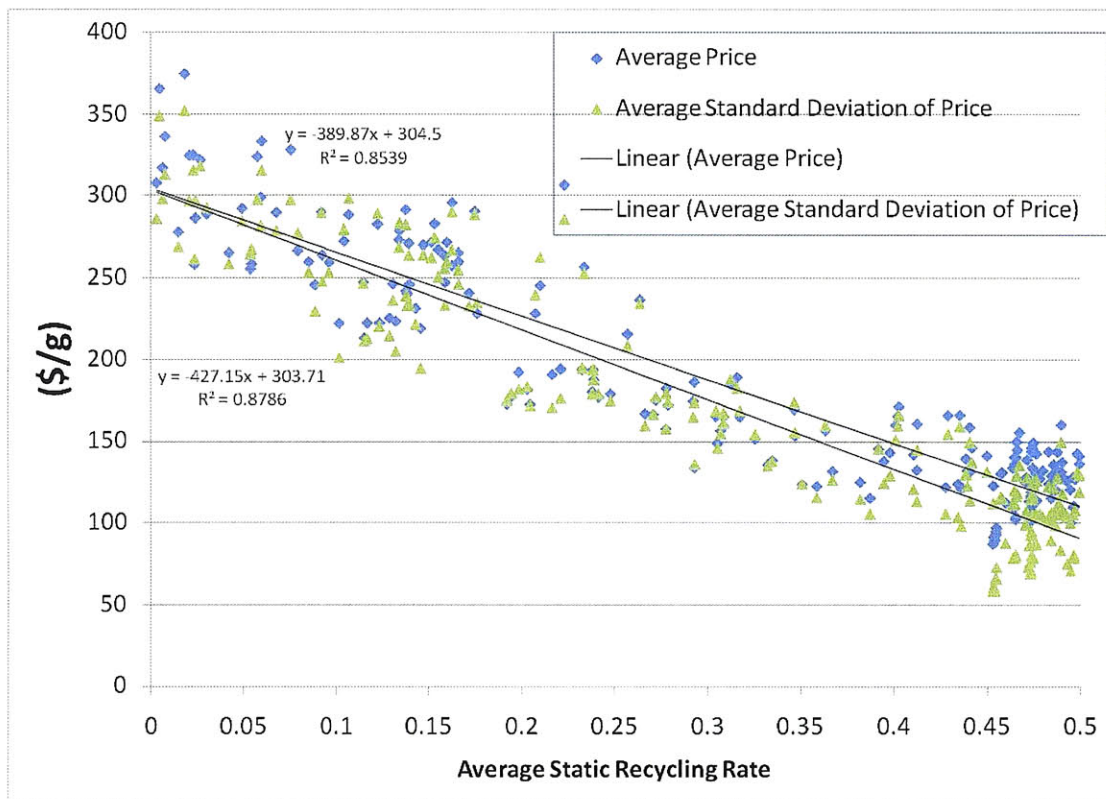
Figure 53: Idealized Smooth Growth Scenario. Average price and average standard deviation of price are plotted for each simulation run at varying recovery rate multipliers selected randomly for the sensitivity test. 200 simulation results are plotted as a function of measured average recycling rate.

In the case of zero product growth, the slope of average price is less steep than with exponential growth in demand. Standard deviation of price does not vary as a function of time (see Figure 54). The pressures on primary supply are much reduced mainly because primary supply is only needed to make up for losses in the system where recovery rate is not 100%. As a result, the cost of primary production does not change much over the 50-year period. Also, given present known reserves of platinum, no new discovery is required in the next 50 years under this scenario.

When there is no growth in product demand, recycling still has an impact on average price, but does not have an impact on the average standard deviation of price (see Figure 55). The increase in marginal cost as a result of ore degradation is the key feedback pushing prices upwards. The slope of marginal cost to recycling rate is more negative than the slope of price to recycling rate.
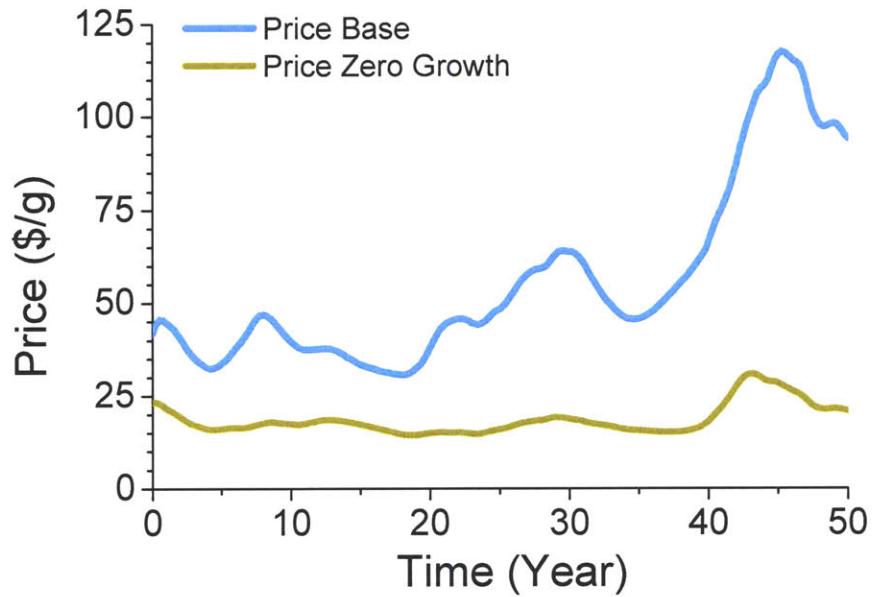
Figure 54: Price as a function of time in the base case scenario (BLUE) and the zero-growth scenario (RED).
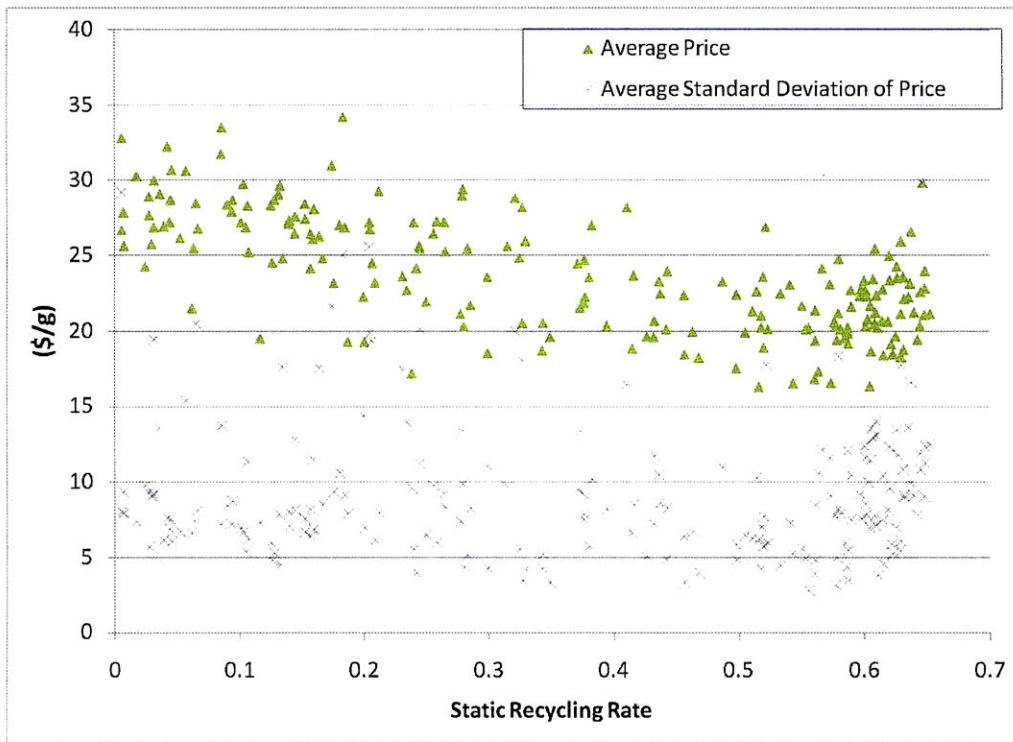
Figure 55: Zero-growth Scenarios. Average price and average standard deviation of price are plotted for each simulation run at varying recovery rate multipliers selected randomly for the sensitivity test. The results from 200 simulations are plotted as a function of measured average recycling rate.

Table 16: Results of Linear Regression from 2000 simulation runs where the recovery rate multiplier was varied between 0 and 1.5. X-variable was recycling rate for all.

y-Variable	Slope	Intercept	R^2	T-statistic w.r.t. Recycling Rate
Idealized Smooth Demand				
Average Price	-189	150	0.802	-90.0
Standard Deviation of Price	-232	139	0.831	-99.1
Average Marginal Cost	36.9	52.1	0.869	-115
Maximum Marginal Cost	117	115	0.625	-57.7
Zero Growth in Demand				
Average Price	-9.39	26.5	0.340	-32.12
Standard Deviation of Price	Mean = 0.630	no correlation with recycling rate		
Average Marginal Cost	-14.8	24.5	0.700	-68.2
Maximum Marginal Cost	-21.4	33.1	0.708	-69.6

7.2.3.1 Examination of Automotive Demand Scenarios

Automotive demand for platinum has been a dynamic demand sector over the past 30 years and may continue to be so as new technologies for cars are introduced (or reintroduced in some cases) and adopted.

In 1975, there were essentially no catalytic converters being used in the automotive industry. By 1981, the three-way catalyst had become the only technology that could economically allow car companies to meet the environmental regulations on emissions set by the EPA and by 1985, all new cars sold in the US contained one (Gerard and Lave 2005). The platinum group metals contained in each car increased from almost zero to about 3 to 4 grams.

Today, automotive companies are contemplating a number of technologies to reduce the greenhouse gas emissions from cars. The implications for the platinum system differ immensely if hybrid or plug-in electric vehicles become adopted or if fuel cell vehicles, especially polymer-electrolyte membrane (PEM) fuel cell vehicles, become adopted. For hybrid technologies, the amount of platinum group metals used per vehicle would drop. For electric vehicles the drop could potentially be to zero. For PEM fuel cells, the amount of platinum group metals used per vehicle could grow to over 15 grams per car (Department of Energy 2007).

While the model is not designed to examine emerging technologies and the dynamics involved in introducing new products to the market, it is possible to examine varying product demand paths and their effect on the platinum system.

There are many possible paths for future automotive platinum demand. Here, we examine a change in the automotive industry that occurs over a 5-year period. First, I examine the scenario where automotive demand for platinum drops to 10% of base case automotive demand at a slope of -20%/year in 4.5 years (see Figure 56). Price is plotted as a function of time for a case where the drop begins in year 5 and ends in year 9.5 and for a case where the drop begins in year 10 and ends in year 14.5 (Figure 57).

The first noticeable effect of the automotive demand decrease is a drop in the price of platinum. In the model, the marginal cost producer also partially or fully shuts down. The new marginal cost producer has a lower cost of production and the marginal cost of the system drops (see Figure 58). Note that before the decrease in automotive demand in year 5, the lowest cost primary platinum producer had 1/3 the costs of the marginal cost producer. Unless demand dropped so significantly as to no longer require primary platinum (and could be sustained with just secondary platinum), the price would not be expected to drop below the cost of this lowest cost producer.

Despite these shutdowns, over the next 10 to 20 years, the inventory levels of platinum are very high (see Figure 59) and rents are low for mines. Partially this is a result of increased recycling rates because platinum returning from vehicles reaching end-of-life will exceed the platinum needed for new vehicles for a short period of time (Figure 60).
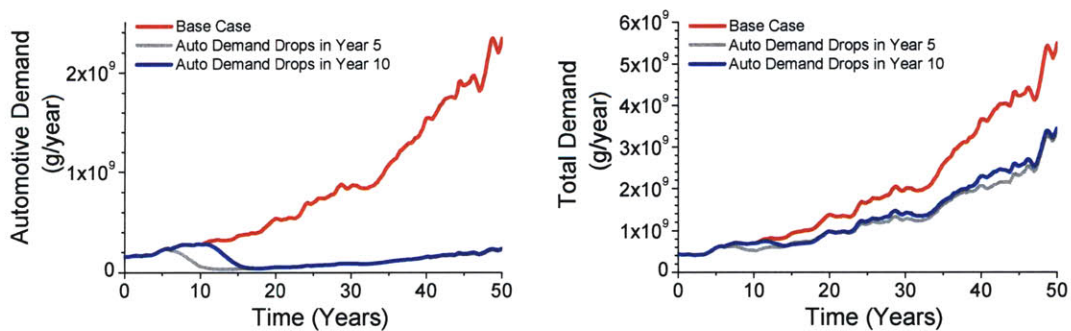
Figure 56: Base Case scenario is compared with a scenario in which automotive demand of platinum drops to 10% of base case scenario in 5 years starting in year 5 and in year 10. Demand for platinum by the automotive industry and overall for all industries is plotted as a function of Time.
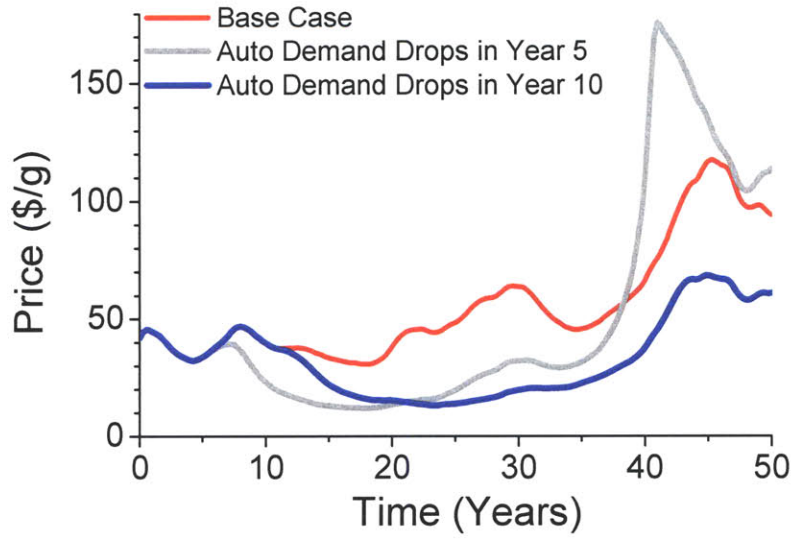
Figure 57: Base Case scenario is compared with a scenario in which automotive demand of platinum drops to 10% of base case scenario in 5 years starting in year 5 and in year 10. Price is plotted as a function of Time.
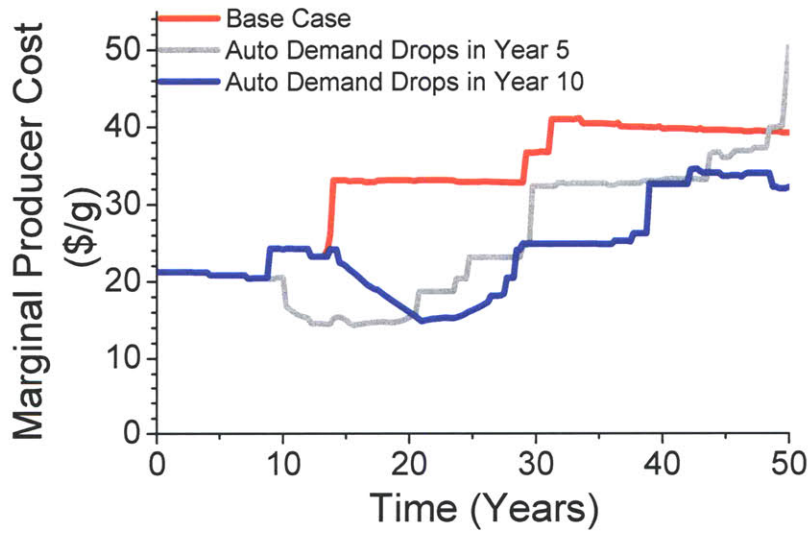
Figure 58: Base Case scenario is compared with a scenario in which automotive demand of platinum drops to 10% of base case scenario in 5 years starting in year 5 and in year 10. Marginal Producer Cost is plotted as a function of Time.
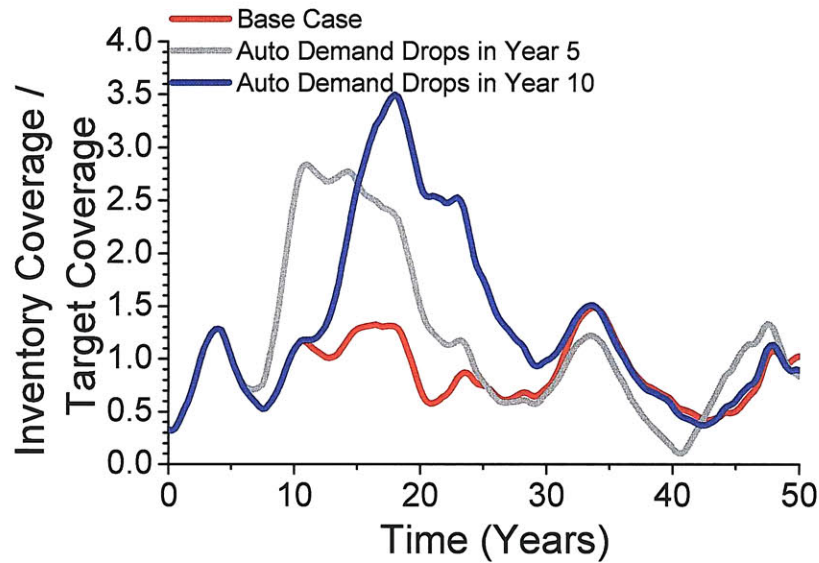
Figure 59: Base Case scenario is compared with a scenario in which automotive demand of platinum drops to 10% of base case scenario in 5 years starting in year 5 and in year 10. Inventory Coverage divided by Target Inventory Coverage is plotted as a function of Time.
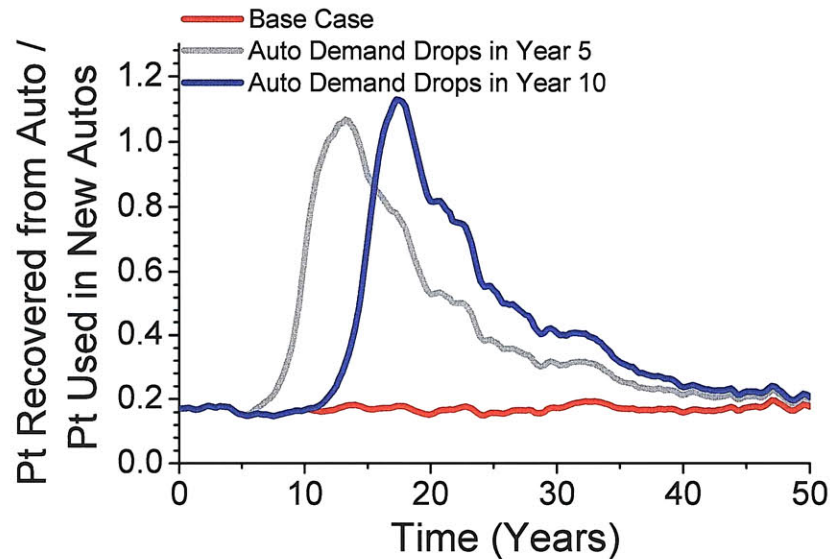
Figure 60: Base Case scenario is compared with a scenario in which automotive demand of platinum drops to 10% of base case scenario in 5 years starting in year 5 and in year 10. Platinum Recovered from Auto/Platinum Purchased for New Autos is plotted as a function of Time.

For the case where the automotive demand decrease began in year 5, price takes a sudden upward jump in year 36. In Year 35, the slope of overall demand increased (noisy demand Figure 56 right). In this scenario, the long period of depressed price led to very low exploration effort and low

primary supply expansion efforts and the supply by year 35 was tight. Recycling from auto had also almost returned to normal levels.

7.2.4   Differences at the Industry-level

Varying recycling rates does not affect all industries in the same way. Some of the differences among the various industries that use platinum will be investigated in this section. The differences observed are a result of the different demand patterns and recycling infrastructure across the industries. Table 7 listed the exogenous variables that characterize each industry's response to price and recycling behavior. Note that in the model, it is assumed that all industries pay the same price for their platinum, a simplification that ignores the ability of firms to hedge in financial markets or set contracts with suppliers.

Recycling rate will be varied by varying the recovery rate multiplier. The effect of varying recycling for two types of growth scenarios will be examined: the first is exponential product demand growth with noise; the second is zero product demand growth with noise. Under the zero product demand growth scenario, the effect of the differences in growth rates among the various industries will be removed since for all industries, zero growth rate will be imposed. Overall average unit expenditures and industry-level average unit expenditures are compared.

7.2.4.1   Observations of Average Unit Expenditures

When demand for products that use platinum is increasing but price is constant, total expenditures for the industries that need platinum to make those products will increase. Such an increase does not correspond to an increase in product unit costs and will have no effect on average unit expenditure. On the other hand, when price increases but product demand is constant, total expenditures and average unit expenditure will increase unless demand is price elastic. This is also the case when price and product demand both increase

Average unit expenditures are measured for the 50-year modeling period for the overall platinum-using industries and for each industry category (see Table 17 and Table 18). The product demand noise seed was different for each run.

Table 17: Modeled Average Unit Expenditures Overall and by Industry for 200 simulations.

Recovery rate multiplier	Average Unit Expenditures	jewelry	auto	electronics	chemical	petroleum	glass	other
Exponential Growth								
1.25	132.6	95.83	135.3	97.38	83.38	97.02	144.0	91.04
1.00	133.3	97.08	135.9	98.37	85.06	98.49	144.6	93.12
0.75	160.8	110.6	164.0	115.46	98.95	115.4	175.7	106.5
0.50	206.3	136.9	210.2	144.73	120.69	142.6	226.1	126.1
0.25	252.2	165.9	256.3	175.22	144.18	170.8	276.1	146.7
0.10	299.6	200.2	303.6	207.76	170.48	201.7	326.6	173.1
Zero Growth								
1.00	20.77	19.84	21.29	21.27	21.04	21.12	21.29	20.30
0.50	24.20	22.73	25.05	25.03	24.57	24.72	25.07	23.09

Table 18: Modeled Ratio Industry Average Unit Expenditure over Overall Average Unit Expenditure for 200 simulations.

Recovery rate multiplier	Average Unit Expenditures	jewelry	auto	electronics	chemical	petroleum	glass	other
Exponential Growth								
1.25	1	0.7226	1.020	0.7343	0.6288	0.7316	1.086	0.6865
1.00	1	0.7282	1.019	0.7379	0.6380	0.7388	1.084	0.6985
0.75	1	0.6882	1.020	0.7182	0.6156	0.7180	1.093	0.6623
0.50	1	0.6636	1.019	0.7017	0.5851	0.6911	1.096	0.6114
0.25	1	0.6579	1.016	0.6949	0.5718	0.6774	1.095	0.5817
0.10	1	0.6683	1.013	0.6935	0.5691	0.6734	1.090	0.5777
Zero Growth								
1.00	1	0.9549	1.025	1.0241	1.013	1.0168	1.025	0.9774
0.50	1	0.9390	1.035	1.0342	1.015	1.0213	1.036	0.9538

Differences in price elasticity and the delay time to implement changes lead to differences in average unit expenditures for different manufacturers under a given changing price scenario. Elasticity of demand establishes magnitude of demand change for a given change in price; the delay factor establishes the rate of change. An industry with high price elasticity moves towards lower use of platinum when prices increase. An industry with long delays and high price elasticity moves slowly towards lower platinum use. An industry with low price elasticity does not change its platinum use following a change in price.

When price is increasing and product demand is growing, two industries with the same price elasticity and demand delay but different product demand growth rates will have different average unit expenditure. The industry with faster growth rate will have larger average unit expenditure. Average unit expenditure is a measure of average price but weighted by demand for platinum instead of averaged over time. The weighting of demand at later periods when price is higher will result in higher average unit expenditure. In the model, the effect of higher product growth rate on average unit expenditures was illustrated with the case of exponential growth. Increased demand in the later periods gave more weight to expenditures made in the later modeling years, a period of

higher prices. This can be illustrated by comparing the chemical and petroleum industries which both have similar elasticity, but petroleum has higher product growth rate and higher average unit expenditure.

In the model, industries with higher price elasticities and, thus, greater sensitivity to price changes, reduced demand as price increased. This can be illustrated by comparing the electronics and jewelry industries. While the jewelry industry has higher product growth rate, the price elasticity is also much larger and average expenditures are lower. The rank order of the different industries does not change when recycling is changed, just the magnitude of the unit expenditures.

When there is zero-product demand growth, the industry-level product demand growth is also set to zero. The differences among the industries are thus reduced to only two variables: price elasticity and demand delay. The industry with highest price elasticity and shortest demand delay, the jewelry industry, has the lowest average unit expenditures.

Regression was performed for average unit expenditures as a function of price for exponential product growth (Table 19) and zero product growth (Table 20). In both growth cases, unit expenditures are very much correlated to price. In the case of exponential growth, the steepest slope of expenditures vs. price is for the glass and automotive industry, two industries with rapid expected future demand growth and minimal alternatives to using platinum to meet product demand, hence low price elasticity and slow demand delays. In the case of zero growth, the most modest slopes are for jewelry and "other" products, which have the highest price elasticity or shortest demand delay, respectively. Higher price elasticity and low demand delay allow jewelers to offer other products (gold or silver) when platinum prices are high and rapidly switch back to platinum when its prices are lower. The linear fit for the jewelry industry under zero-growth scenario has the lowest R^2 value which is indicative of the flexibility of the jewelry industry to change use patterns with price.

Table 19: Slope of Average Industry-level Unit Expenditures as a function of Price where recycling is varied and product demand growth is exponential (Base case). Slope is calculated from average values measured for 200 simulations.

Industry	Slope	R^2	Demand Growth (%/year)	Demand Elasticity	Demand Delay (years)
Jewelry	1.072	0.963	3.17	0.55	1
Automotive	1.751	0.976	5.61	0.1	15
Electronics	1.140	0.996	1.14	0.05	7
Chemical	0.8785	0.991	0	0.42	11
Petroleum	1.074	0.994	1.66	0.475	15
Glass	1.899	0.968	6.70	0.05	10
Other	0.8510	0.862	1.98	1	7

Table 20: Slope of Average Industry-level Unit Expenditures as a function of Price where recycling is varied and product demand growth is zero. Slope is calculated from average values measured for 200 simulations.

Industry	Slope	R^2	Demand Growth (%/year)	Demand Elasticity	Demand Delay (years)
Jewelry	0.866	0.898	3.17	0.55	1
Automotive	1.081	0.981	5.61	0.1	15
Electronics	1.078	0.981	1.14	0.05	7
Chemical	1.040	0.987	0	0.42	11
Petroleum	1.056	0.987	1.66	0.475	15
Glass	1.082	0.980	6.70	0.05	10
Other	0.939	0.947	1.98	1	7

Changes in price are very important to industries where the correlation between price and unit expenditures is strong and the slope of expenditure as a function of price is steep. Having shown that recycling rates affect price, the analysis of unit expenditures shows indirectly that recycling affects different industries in different ways.

This analysis focused on two factors that are indicative of an industry's ability to implement changes in use patterns following changes to material availability: price elasticity of material demand and delay to implement changes in material use. These two factors reveal something about the ability of an industry to change their demand when prices change. For example, industries with readily available substitutes for the materials that they use will have higher elasticity and shorter delays than those without. Dematerialization is another method for firms to change their use patterns in the face of changing material availability. Price-responsive industries will experience lower average unit expenditures and smaller increases in average unit expenditures when perturbations in supply lead to increases in price.

There may also be benefits to the whole system if at least one or a few of the larger industries are responsive to price. Supply responsiveness was shown to improve the stability of price and demand responsiveness could also have the same effect. Historically for the platinum system, the jewelry industry is the only industry with a significant market share exhibiting price responsiveness. Jewelry platinum demand has decreased during the recent periods of supply tightness while most other industries have increased their demand for platinum. In fact, demand for platinum for jewelry, which in 1975 accounted for almost 50% of primary platinum used, only accounted for 15% in 2008 during historical peak platinum prices. Were it not for the responsiveness jewelry industry to the price increases, demand for platinum would have likely grown at a faster rate and led to higher prices.

Finally, an additional potential effect of a reduction in use of platinum in the face of scarcity is that it can lower future rates of primary ore depletion and lower future tightness of supply if the changes become permanent. Permanent changes to demand patterns were observed in the historical case study of cobalt. The effect would only be significant if the reduction in use of platinum occurs in a significant number of industries or in one that accounts for a large fraction of total platinum use.

8 Conclusions

A simulation model of the platinum material system was developed and used to explore industry-level risks in the face of future material scarcity. More specifically, this model was used to explore recycling and growth in future demand for products that use platinum and their impact on variables that can directly impact firms that use platinum.

A simple overarching question was raised at the beginning of the analysis: do firms need to care about resource scarcity?

The answer to the overarching question was: yes.

During the cobalt crisis in the late 1970's, manufacturers who responded to the change in cobalt availability cut costs by increasing recycling and substituting to available materials. In the case of platinum, the model results show that for a scenario of exponential future growth similar to the growth experienced in the past, depletion of ore leads to higher costs of extraction and tighter supply.

This research tried to answer a more specific set of questions as well:

How does *scarcity* affect manufacturers? What are *strategies* manufacturers can pursue that moderate increasing scarcity? What are the *cost advantages* to *manufacturers* of such strategies when implemented early?

The operations management literature indicates that firms are concerned about minimizing materials costs, ensuring sufficient supply to meet manufacturing demand and minimizing uncertainty of expenditures. The in depth analysis of the cobalt crisis in the 1970's presented here demonstrated that material scarcity could be tied to higher costs and unmet demand, the very same issues of concern indicated in business literature. The examples shown with the historical cases were scarcity tied to institutional inefficiency. A system dynamics model was used to examine scarcity more broadly, especially scarcity tied to the physical constraints of using non-renewable resources. Measured factors that can affect the areas of concern for firms are price, standard deviation of price, cost of extraction, estimated scarcity rents and average unit expenditures.

Simulation results showed that historical discovery rates and depletion rates of ore grade for platinum would likely be insufficient to prevent increases in extraction costs if demand for

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products that use platinum continued to grow exponentially and continued to respond slowly to price. Model results also showed that increases in extraction costs from depletion of ore grades resulted in higher prices for manufacturers. Moreover, fast growth in demand resulted in high estimated scarcity rents to encourage higher primary extraction rates. Price variability resulting when supply was unable to respond sufficiently quickly to changing demand was also a consequence of concern. Both higher prices and higher price variability led to higher expenditures for manufacturers, especially the least flexible manufacturers such as the automotive manufacturers.

A number of strategies can be implemented at the manufacturer level to better handle potential future risks of scarcity for a given material. Through the cobalt case study, recycling, dematerialization and material substitution were identified as candidate strategies. This work focused on recycling, although dematerialization and substitution were also explored briefly.

It was seen that recycling reduced the risk of scarcity mainly in two ways: 1) it put decreased pressure on exploration and discovery of new resources of lower costs and 2) it put decreased pressure on mine-building and primary supply expansion. Figure 61 is a simple illustration of the key dynamics of supply. This simplified causal loop diagram shows that price and supply form two balancing loops. For both primary and secondary supply, as price increases, supply will increase. When supply increases, all else being equal, price will decrease. Primary extraction and secondary recycling together add up to total supply. Primary extraction is limited by the size of primary resources while secondary recycling is limited by the size of secondary resources (products containing the material of interest).

Although both primary and secondary supply form balancing loops with price, the delays involved on the primary side are generally much longer than on the secondary side. On the secondary side, recyclers generally have some flexibility to increase processing capacity utilization in response to price. The number of products that are collected will increase and landfilling will generally decrease. The main limitation is the product life. Few products will be brought in for recycling if they are still functioning well.

On the primary side, mining companies are more limited in how they are able to respond to price. The existing mines can try to increase the amount of ore mined or the grade of the ore being mined or try to decrease their inventory, but often will instead try to maintain their long term revenue goals due to their high fixed costs. This results in a move towards mining lower grade ores which at higher prices become economically viable. Additions to old mines, such as the addition of a new

mine shaft require a few years to be completed. New mines take 5 to 10 years to build and start production. More importantly, before building a new mine can be considered, there is the need to increases exploration to identify resources that can be mined and this also requires many years.

Balancing loops with long delays can result in oscillating behavior (ch.17 (Sterman 2000)). When total supply is made up of both recycling and primary extraction, the behavior of price can be more stable. Also, a higher recycling rate, which is defined as a greater fraction of total supply coming from secondary recycling, reduces primary extraction and depletion of resources. The model showed that this was the case for the platinum system under exponential growth conditions, but not under the zero-growth conditions.
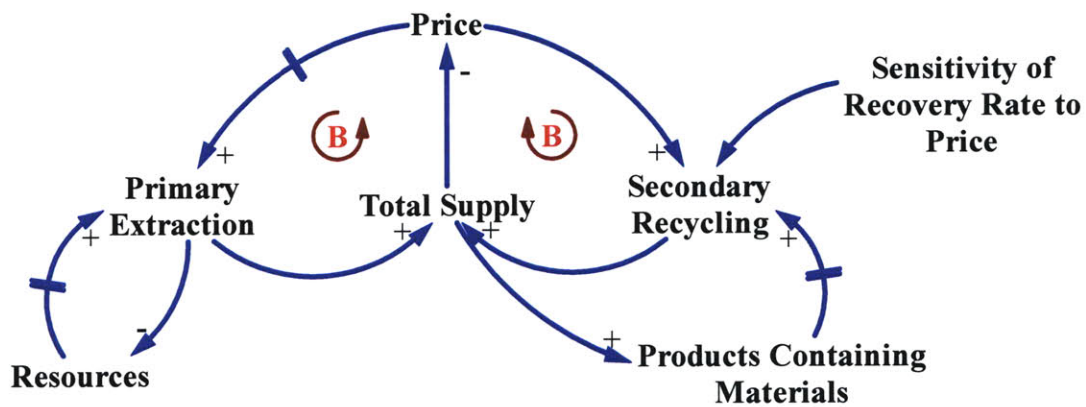
Figure 61: Causal Loop Diagram showing price and supply interactions. Long delays are marked as a cross mark on the arrow.

Finally, the model was used to explore how different industries, depending on their price elasticity and delay, responded differently to increasing and varying prices. The ability to change demand behavior resulted in reduced expenditures over the 50-year period and a reduced dependence on price, as shown with the case of the jewelry industry. It is hypothesized that the jewelry industry has high price elasticity and short delays because of the availability of substitute materials, gold and silver, because of the fact that the price of the material is a large factor in the costs of the final product.

In the end, this work has shown that at least for some materials systems, strategies to mitigate resource depletion can have value to material users beyond those previously recognized. In particular, the model indicates that recycling can lead to lower material costs and lower variability of material costs because it reduces primary ore depletion and responds more rapidly to changes in price. This is particularly true for those firms who demand is inelastic and rapidly growing.

8.1 Applicability to Other Material Systems

The insights gained from exploring the implications of materials scarcity for manufacturers of platinum-containing products can be extended to better understand other material systems as well. The platinum material system has certain common traits with many other commodities. For example, most mineral commodities have a similar structure of stocks and flows of primary supply, with exploration leading to discovery leading to mine-building and ore extraction. The secondary supply stocks and flows structure is also common with materials going into products that reach end-of-life and then are collected for recycling.

One key insight of the platinum model is that the differences in response time and response behavior of primary supply and secondary supply can lead to improved stability of price. The difference in delays between primary and secondary is a common characteristic of metals.

There are also some differences between platinum and other materials that may not be very difficult to overcome when applying the insights obtained from the platinum model to other systems.

First, the ability to perfectly substitute secondary metal for primary metal is not a common characteristic of metals, since secondary metals often contain impurities that primary ores do not have. For metals such as copper or aluminum, recyclers generally mix secondary materials with primary materials to dilute the impurities. For these materials, the maximum amount that can be recycled will not always be the amount of material in products reaching end-of-life times the recycling efficiency, but rather can be the amount of recycled materials that can be incorporated into a product. This can be viewed simply as an additional constraint on the system and would not be difficult to implement in the existing model structure. It is likely that given this added constraint, the responsiveness of recycling would be limited at lower recovery rates than for platinum, which didn't have this added constraint.

Secondly, speculation can play a key role in determining the price of platinum, since there are many small investors who hold inventories of platinum. These small investors are often not as well informed about underlying market conditions and are believed to behave in reaction to exogenous economic conditions such as the recent banking crisis. This type of investor is not as common in other commodities, except for gold and silver, where speculation plays a much larger role than in platinum. Still, new financial products developed in recent years have made it possible and more

popular for small individual investors to participate in commodity markets. It is also possible to further examine the material system with the investment sector turned off.

8.2   Recommendations for Manufacturers

Manufacturers may wish to consider whether they can improve the ways they select and use materials. This work presents a way for firms to examine their material use in the face of increasing resource scarcity.

Given that the cost to manufacturers of future changing scarcity is of concern and that there are a number of different strategies that can be pursued, it would benefit manufacturers to better understand their upstream material supply chain and to determine whether and which actions to address their risks are possible. Firms' first step in deciding to pursue strategies that retard increasing material scarcity should be to obtain information on the risk of scarcity associated with each of the material systems that matter.

In the case of platinum we saw that, although preliminary information examined in the form of metrics to screen for risk of scarcity were helpful for comparing different materials, there were difficulties when different metrics for a given system indicated different levels of risk.

For example, in terms of the metrics presented in Section 3, the static and the dynamic depletion index for platinum based on estimated reserves are very large (332 years and 77 years, respectively). The platinum system is one in which a small number of past discoveries have been of a quality and size that far surpass any of the other discoveries. The Merensky reef, UG2 reef and Platreef, located in the Bushveld rock complex (in South Africa) provide 75% of global primary platinum and are expected to last more than 50 years at present projected growth rates (Malthusian metric). Physical constraints based on these metrics not a concern, in large part because of the existence of this platinum-rich complex. Yet inspection of other metrics on the primary supply data from this region does however indicate potential increasing scarcity. Older mines have started mining thinner platinum-rich veins (ore grade being a Ricardian metric). The higher grade Merensky reef is slowly becoming depleted. Older mines are expanding deeper into Earth's crust to reach lower-grade ore located below the Merensky reef. Newer mines are being built in parts of the Bushveld complex where the lower grade UG2 reef or Platreef are the only economically viable ore bodies. These moves towards extracting lower grade, deeper ore bodies have led and could continue to lead to higher extraction costs for South African platinum. While aggregate data on platinum exploration efforts is unavailable, it is likely that the efforts have been minimal because

of the existence of the rich source of platinum in the Bushveld region. Today's five major platinum producing regions which account for 96% of primary platinum supply were all discovered more than 50 years ago.

The dynamic depletion index based on reserves indicating 77 years of platinum remaining, the ore grade depletion and slow historical discovery rates were all taken into account in a dynamic simulation model. The results indicate that, given these primary supply conditions, increasing scarcity is possible in an exponentially growing and relatively price inelastic demand market. On average, price, cost of extraction and estimated scarcity rents increased over time. The modeling work indicates that the information obtained from the metrics is important to guide firm action. When different metrics indicate different levels of risk, the dynamics of the market should be considered. In particular, the characteristics of the platinum market that may have been the best indicators of risk of increasing scarcity are: the slow response of supply (low discovery rates, especially) and the slow response of demand (low elasticity and long delays to respond to changes in market conditions). It is worth further examining whether certain characteristics of material systems such as high market concentration in few regions or in few companies can be used to identify potentially slow supply response materials. On the demand side, it is worth further examining whether more expensive materials are associated with slower demand response since firms that are using the more expensive materials are likely either already minimizing their use of such materials and doing so only because alternatives do not exist.

In summary, the recommendations for manufacturers take the form of 3 steps: increase knowledge of materials systems, assess risk of scarcity and evaluate cost and benefits of various tools. Manufacturers should first know which materials they use, how much and at what cost. They should then consider the importance not only of increasing material costs, but also of increasing material price variability and increasing expenditure uncertainty. The effect of varying prices and expenditures may change the cost-benefit analysis for taking action in terms of increasing recycling or investing in alternative materials or processes. If manufacturers are considering changes to their processing or to their products, they should also examine their potential future material usage. Up to this stage, the analysis can be done with information solely based on the manufacturer production data.

Manufacturers can then examine the markets for the materials on which they depend, especially the upstream supply chain and the main demand industries. Materials that exhibit potentially higher

risk of increased scarcity are those that have risk of 1) physical constraint or institutional inefficiency and 2) unresponsive supply (ex: low recycling) and/or demand.

Finally, manufacturers should evaluate the costs and benefits of alternative tools in the face of increasing scarcity and prepare a strategy. The consideration of materials availability may lead to higher benefits realized for recycling, material substitution and dematerialization. In particular, they should strongly consider whether they should incentivize additional recycling to lower and stabilize prices.

9 Future Work

There are still many interesting aspects to study in the area of understanding materials scarcity from the perspective of manufacturing firms. Some general questions of interest are: (1) What strategies can be implemented by firms in the manufacturing sector? (2) What are the advantages to strategies that mitigate the impacts of scarcity? (3) When should such strategies be used?

First, the model that has been built of the platinum system can be used to further examine these questions. In particular, the model can be used to elaborate on the characteristics of material systems may be associated with risk of increased scarcity to better inform firms concerned about this risk. A few characteristics of the platinum system that may have led to the observed increase in scarcity are: exponential growth in demand of products that use platinum coupled with a price-insensitive and slow responding demand for platinum, slow discovery and steady ore quality depletion leading to increased costs of extraction, and decreased recycling rates leading to increased dependence on primary extraction. Other characteristics that deserve more examination are high market concentration of primary suppliers that may lead to even slower responsiveness of primary capacity and production and the lack of or existence of speculation and stockpiling behavior.

The model can also be used to further examine technological tools that can be used by manufacturers. Recycling deserves further exploration, especially in the area of understanding the role of direct and indirect cycles (definitions in Section 5.3.1.3). Also, while price elasticity and demand delay were examined briefly as measures of the ability of industries to substitute or dematerialize, these two tools also deserve further exploration. The use of technological tools can be compared to another common response to scarcity: stockpiling. Stockpiling occurred during the cobalt crisis in the 1970's and historical reports indicate that it wasn't particularly effective as a tool once material prices had increased as those stockpiling often purchased at very high prices and then sold at low prices.

There are many different scenarios that can be and are worth examining. The model could be further used to answer questions that specific actors within the platinum market may have. For example, the automotive demand scenario presented in section 7.2.3.1, could help market actors understand not just the impact of automotive demand on platinum price, but also the potential effect of a transition away from platinum by a large industry.

The model itself can be further improved in a number of ways. This analysis has measured the benefits of taking actions to change use patterns in the face of changing material availability. However, the costs were not measured. For certain industries, such as the jewelry industry, the cost of substitution is simply the cost of the lower priced material as there would be minimal changes required in the processing and forming of the jewelry. In the case of other industries, there may be research and capital costs. For example, for the automotive industry, dematerialization has required investment into research and development of new nanoparticle catalyst designs. Recycling also entails costs, and these costs generally increase with higher recovery rates. The benefits that are identified need to be weighed against these costs.

Another step that is worth considering is to simplify the model and to examine the simplest and most general model that can still produce similar insights. The simpler model will still need to capture the long delays in primary supply, the shorter delays in secondary supply and the slow responsiveness of demand to price. It is expected that it is possible to gain insights from a simpler model because the results presented here were also observed with earlier versions of model (see conference papers (Alonso, Field et al. 2008; Alonso, Field et al. 2009)). By first building a model that represents a complex system, here platinum, and being able to calibrate this more complete model, we were able to explore the role of the different dynamic feedbacks that could play a role in the behavior of the system. By afterwards simplifying the model to the key and basic dynamic feedbacks identified in the more complex model, a better understanding of the key dynamics may be obtained.

10 Appendices

10.1 Exploring the Utility of Metrics: the case of copper

This section is a case study of the utility of the metrics described previously. Many authors have pointed out that there are no significant examples of broad materials scarcity during the modern era and that even indirect evidence of scarcity is ambiguous (Simpson, Toman et al. 2005), (Mikesell 1995).

As such, it is not possible to characterize the diagnostic value of metrics directly. Nevertheless, decisions must be made. In light of that, this section proceeds by examining (1) a simple, imperfect screening metric, (2) the criteria for action on that metric, and (3) the use of more detailed measures for additional insight on risk. The approach that will be taken here is to evaluate indicators for resolution, computational challenge and intensity, and, where appropriate, consistency — in the context of a specific, timely case study of copper.

10.1.1 Motivation of the case

Copper has been used by mankind for over eight millennia. (Ayres, Ayres et al. 2003) Today, primary production of copper ranks third in terms of annual global metal tonnage, behind only iron and aluminum (MMSD 2002). Because of its role in construction, telecommunications and electricity (Copper Development Association 2006), a country's copper consumption is an indicator of its economic development (Simpson, Toman et al. 2005).

However, high rates of consumption also contribute to apprehension about copper's long-term availability (Ayres, Ayres et al. 2003; Gordon, Bertram et al. 2006). Copper's economic significance suggests that global supply chains are sensitive to changes (real or perceived) in copper availability. This sensitivity and copper's low depletion index (as shown in Figure 62) mean that copper supply merits closer examination.
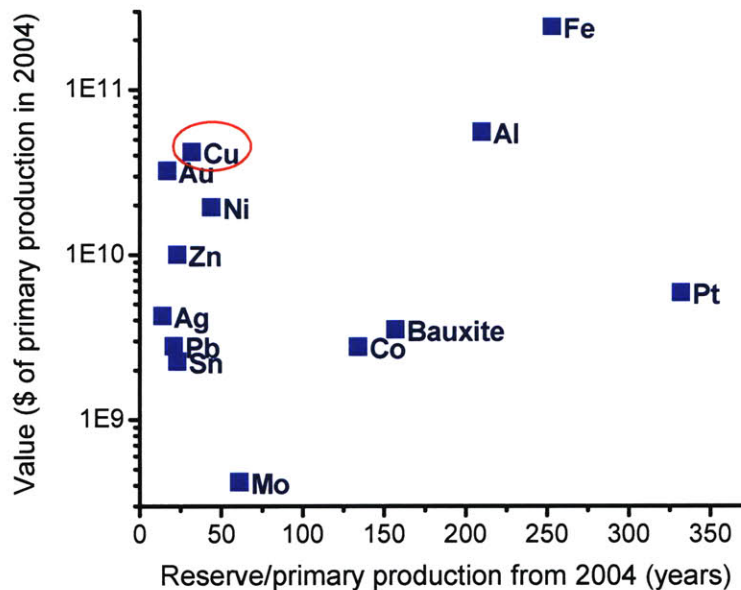
Figure 62: Positioning of metals: Malthusian static index of depletion base on reserves and global value of primary metric (U.S.G.S. 1932-2006). Metals of increasing concern have high value and low depletion index.

10.1.2 Metrics of institutional inefficiency

10.1.2.1 Simple Screening for Scarcity Vulnerability: Supply-chain Concentration

Metrics of supply-chain concentration are broadly suggested indicators of vulnerability (Chapman and Roberts 1983; McClements and Cranswick 2001). These indicators specifically point to vulnerability due to institutional inefficiency. Of these metrics, the information needed to derive global geographic supply concentration is readily available (e.g., see (U.S.G.S. 2005)), making geographic distribution a good first metric for institutional vulnerability. This metric is plotted in Figure 63 for a range of commodities for 1975 and for 2004.

The geographic concentration of cobalt was not unique in 1975 (Figure 63a). However, the combination of Zaire's control of 45% of world primary cobalt production in 1975 and local political disturbances could not be ignored by the global cobalt market. To effectively employ geographic concentration as a screening metric, decision-makers need threshold criteria to identify conditions of concern. One possible approach would be to look at the analyses of market concentration employed to measure the risks to competition in product markets. Guidelines applied by the US Department of Justice suggest that moderate levels of concern exist when individual suppliers reach market shares around 30% and high levels of concern exist when market shares

approach 40% (Hirschman 1945; Herfindahl 1950; U.S. DoJ and Federal Trade Commission. 1992, Revised 1997).
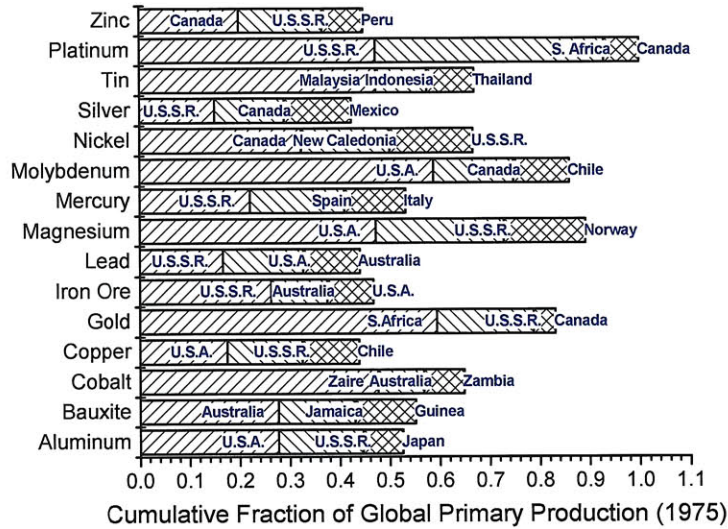
a.
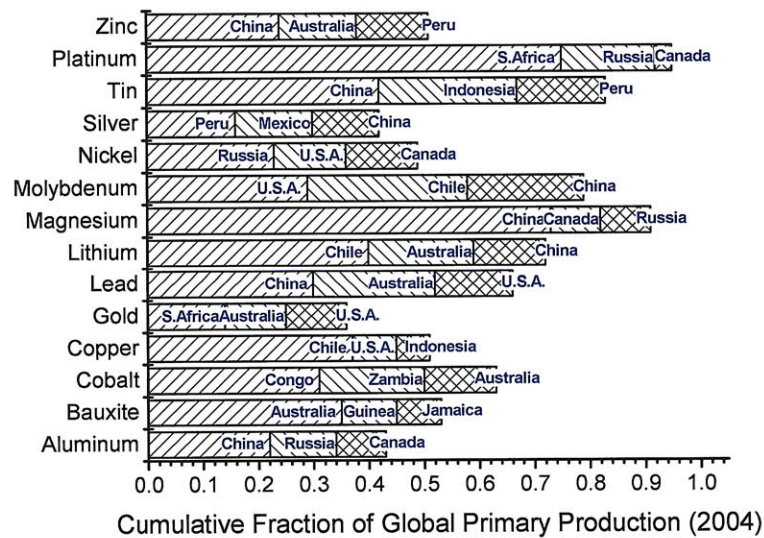
b.

Figure 63: Geographic distribution of primary production for various metals. Top three producing countries for each metal in a. 1975 and b. 2004 (U.S.G.S. 1932-2006).

Using those guidelines, platinum and magnesium appear to be particularly vulnerable to risks deriving from institutional inefficiency (Figure 63b). Copper also merits attention, as it exhibits an intermediate level of vulnerability with close to 40% of present production rates, and reserve and

reserve base concentrated in Chile (U.S.G.S. 2005). Although it is more difficult to assemble, it is possible to complement this geography-based metric with information on institutional concentration within copper supply. Presently, no single firm controls more than 15% of global copper production (U.S.G.S. 2005; Codelco Chile 2007).

10.1.2.2 Further Investigation into Supply-Chain Risk: Recycling

Into the foreseeable future, the extraction of primary stocks will dominate the dynamics of non-renewables consumption. As such, vulnerability of primary stocks represents the principal concern for most supply chains. Secondary supplies might play a role in mitigating institutional inefficiency risk for two reasons: (1) they can substitute for some primary applications and, therefore, effectively represents an additional source of supply; and (2) secondary stocks are often located and processed in different locations and by different institutions than primary.

Data from 1969-2004 show increasing overall secondary use (Jolly 2005), but the rate of growth of secondary use was modest and outpaced by the growth in total copper consumption. These observations indicate that growth of copper consumption has depended heavily on growth of mine production capacity. For example, old copper scrap accounted for only 17.5% (representing 53% recycling efficiency rate) of total world consumption in 1994, using estimates based on materials flow analyses (Graedel, Van Beers et al. 2004).

Current practices would have to be significantly improved for secondary copper to provide a significant substitute for current primary usages. Therefore, current trends do not indicate that the secondary market dramatically reduces the vulnerability of the copper supply chain. Note that secondary use and flow data for many metals is either not publicly available or not tracked.

10.1.3 Metrics of physical constraint

10.1.3.1 Simple Screening for Scarcity Vulnerability: The Static Depletion Index

The simplest way to screen for scarcity-based material vulnerability is to use static depletion times. Basing the depletion index on reserves, the amount of copper available for economic extraction is apparently only sufficient to last 32 years (U.S.G.S. 2005). This low value contrasts strikingly with those of aluminum and iron, both of whose indices suggest more than 100 years to depletion (MMSD 2002).

This is the most conservative static estimate and is indicative of the time frame within which new technologies for extraction or new sources must be found in order to continue the present yearly consumption rates under present economic conditions. With changes in economic or technological

conditions (increased prices, decreased costs), these index values could instead reflect the tapping of the reserve base, leading to a static index of **64 years,** or eventually the resource, leading to a static index of **more than 100 years.** Finally, at the far end of the spectrum, the static depletion index based on resource base is one hundred million years. This may indicate that the amount of copper in the earth's crust is so great that any concern for depletion of primary stocks lies in the distant future. However, the resource base incorporates minerals of such poor quality that complete extraction would require a prohibitively large energy, capital, environmental and land cost.

10.1.3.1.1 Limits for Concern

The question that then arises concerning the static depletion indices for copper is what index values indicate a need for action? Unfortunately, the real answer to that question derives from the complex interaction of the characteristics of known and unknown resources, the evolution of future demand and production technology, the effectiveness of secondary recovery, and changes in cost, price and the elasticity of substitutes. The development of such models is the subject of active research, but is currently only undertaken for the most strategic of global resources – typically energy resources.

Nevertheless, non-fuel supply chains must make decisions about when to allocate resources to mitigate material price risks. For this purpose, the authors would propose an inferential strategy for establishing the gravity of a particular depletion index value. In particular, the reserve-based index value should be compared against industry rules of thumb for establishing reserve capacity. Several authors have examined the issues that drive reserve management decisions, particularly exploration and technology development (Chapman and Roberts 1983; Tilton 2003). Although there is variation in their analyses, all point to a figure of about 30 years for the magnitude of the managed reserve life compared to current consumption. Accumulating stocks beyond that level does not seem to provide sufficient discounted revenues to offset exploration costs and market uncertainties. Thus, 30 years may serve as a threshold indicator for concern; greater values would represent conditions where the primary industry is unmotivated to address geophysical scarcity, while values around or below 30 years would indicate a need for further evaluation.

Based on this criterion, copper, with a static depletion index of 32 years, sits on the border of concern. Using a model of oil reserves and their use, Pindyck observed that prices increased significantly before reductions in the static depletion index were noticeable (Pindyck 1978). In light of this, current information would suggest that strategic decision-makers should pay careful attention to resources whose economic availability sits in this region.

10.1.3.2   Further Investigation into Supply-Chain Risk: Dynamic and Ricardian Measures

10.1.3.2.1   Dynamic Depletion Index

Copper consumption over the past century has increased steadily and is expected to continue increasing as countries in developing East Asia and elsewhere industrialize. In fact, between 1969-2004, global copper consumption increased exponentially (R^2=0.9643), with a total increase of 124% and an average growth rate of 2.3% (Jolly 2005). Moreover, primary consumption has also grown exponentially during this period (R^2=0.9567) with an average growth rate of 2.5%.

Extrapolating these consumption growth rates, relevant dynamic measures of copper depletion time fall to 20 to 50 years, indicating that dynamic metrics of depletion do not contraindicate vulnerability (MMSD 2002). All of the values necessary to compute dynamic depletion indices are freely and readily available for most commodities.

10.1.3.2.2   The Nature of Available Resource

Malthus' dismal statement regarding sustainability was made based on the observation that population appeared to be growing at a faster rate than the capacity to produce food. For copper, concern about consumption would be reduced if exploration and recycling rates grew in parity.

Upstream supply-chain stakeholders are well aware of the importance of the copper supply and are taking action to manage availability through exploration and technology improvements. Spending on copper exploration grew from 340M$ to 825M$ between 2003 to 2005 (U.S.G.S. 1932-2006; Metals Economics Group 2006), leading to a 460% addition to copper reserves since 1930. As a result, copper reserves have nearly kept pace with consumption, despite the exponential growth in primary consumption. In fact, for the past decade, depletion indices have remained at or above the criterion for concern at slightly above thirty years (See Figure 64.). The ability of suppliers to manage reserve size would mitigate concern over vulnerability of copper supplies. All of the values necessary to compute changes in global reserves are freely and readily available for most commodities.
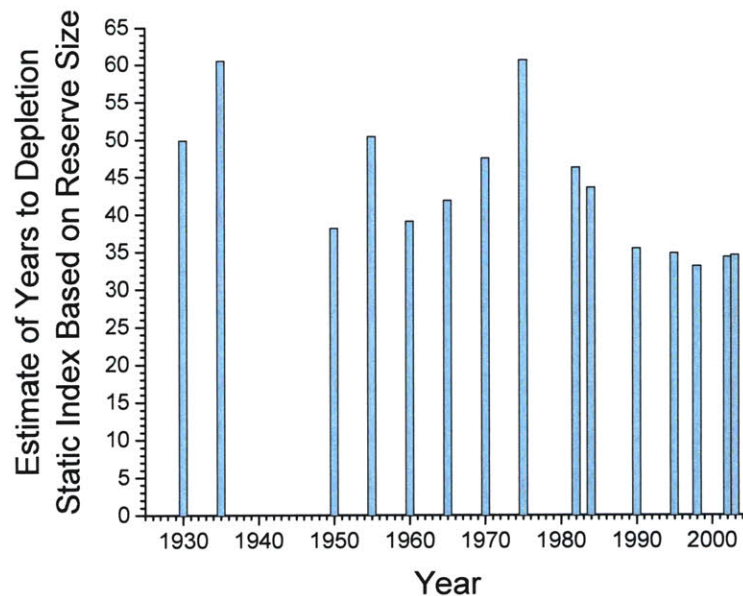
Figure 64: Change over time of estimate of future depletion year based on static index of copper reserve (U.S.G.S. 1932-2006).

10.1.3.2.3 Ricardian Measures

Turning from metrics based on rates of consumption and magnitude of supply, the family of Ricardian metrics that consider resource quality, state of technology, and/or market valuations offers additional perspectives into the state of resource vulnerability. U.S. copper ore grade, which is an indicator of the ease of extraction, has been shown to decrease from above 3% in 1880's to just around 0.5% between 1970 and 1993 (Ayres, Ayres et al. 2003). This is consistent with Ricardo's theory that metals will be mined in the order of their ease of extraction (Ricardo 1821, first published 1817). The copper ore grade of 0.5% means that for every ton of ore that was dug up, only 5kg of copper could be recovered if the recovery process was 100% efficient. Another way of looking at it is that to obtain 5 tons of copper from the earth's crust, at least 995 tons of waste had to be generated.

Technological improvements have made it economically feasible to exploit lower grade ores, increasing reserve size and postponing depletion. Between 1970 and 1993, when US copper grade remained a relatively constant 0.5%, the costs of western world copper mining decreased, illustrating the effect of improving technologies (Tilton and Landsberg 1997; Ayres, Ayres et al. 2003). Copper prices somewhat decreased over the same period of time. More recently however, prices reached past half century historical highs (U.S.G.S. 1932-2006).

However, the overall trend of decreasing copper ore grade since 1880 would indicate that copper supplies are shifting into a regime of increasing vulnerability. To better understand the worst-case scenario for extraction costs for copper, an estimate was made for extracting copper from rock rather than from ore (Steen and Borg 2002). Costs would increase by two orders of magnitude.

10.1.3.2.4 The Availability of Substitutes

Not all applications have good alternatives for using primary copper, but some of the largest applications do. Secondary copper and materials such as aluminum, PVC and fiberglass are some of the possible substitutes for primary copper, depending on the application.

Secondary copper, in particular, copper recovered from consumer products at end-of-life (old scrap), is generally substituted in applications where the purity of the copper is not very important, such as in cast parts. This is because the post-consumer processing of materials often results in pick-up of contaminants that are difficult to remove. Moreover, while it is sometimes technically feasible to remove these contaminants, it is often unattractive from a financial perspective as it can cost more than the cost of extraction from ore. The case of cobalt showed that changing material availability can alter conditions such that it becomes economically interesting to use more recycled material in all applications. Using secondary copper to substitute for primary also includes another limitation: much of the secondary copper has to come either from products as they reach end-of-life and the amount of copper in products reaching end-of-life depends on past copper use and the lifetime of the product. When demand for copper is growing, as it has been over the past century, it is possible to collect 100% of all scrap copper and still need to use primary metal.

The use of other materials as substitutes is advantageous from a scarcity risk-mitigation perspective. For one, some materials, such as aluminum and fiberglass are much more abundant than copper when measured by most of the scarcity metrics listed here. Moreover, the supply-chain that delivers these materials is different from the copper supply-chain and is unlikely to experience the same limitations at the same time as the copper supply-chain.

10.1.3.2.5 Peak Production

For copper, a few such models have been prepared that project additional metrics, such as time to peak production. One estimate gives a 15 year time frame before copper primary production will no longer be able to continue increasing (Ayres, Ayres et al. 2003). For comparison, the US Department of Energy forecasts an analogous peak for oil in 31 years (Wood, Long et al. 2004).

10.1.3.2.6 Sustainability Concerns

A typical analysis of scarcity from the perspective of sustainability was done for copper, a key material for building construction and for communication (Gordon, Bertram et al. 2006). Gordon et al. estimated through materials flow analysis the amount of copper required to maintain the infrastructure and standard of living in developed nations. Based on projections of global population growth, they concluded that the estimated global resource base for copper is insufficient if developing nations demand the same amount of copper per capita. In other words, developing nations will need to find alternative materials to attain the same standards of living as the developed nations or significant new discoveries must be made.

10.1.4 Understanding supply-chain roles in addressing copper vulnerability

What businesses should take from the above analysis is that, while the complete depletion of copper is *not* imminent, most of the metrics indicate that the risk of copper disruption is significantly greater than for other major metals (e.g., iron and aluminum), and is at or near to a historical high. A proactive business that depends upon copper materials will understand that there may be actions that could mitigate these risks.

10.2 Model Stocks and Flow Diagrams

Within the framework of System Dynamics, the variables and equations that make up the model can be depicted using stocks and flow and causla link diagrams. This section shows those diagrams, simplified so that the key parameters are highlighted.
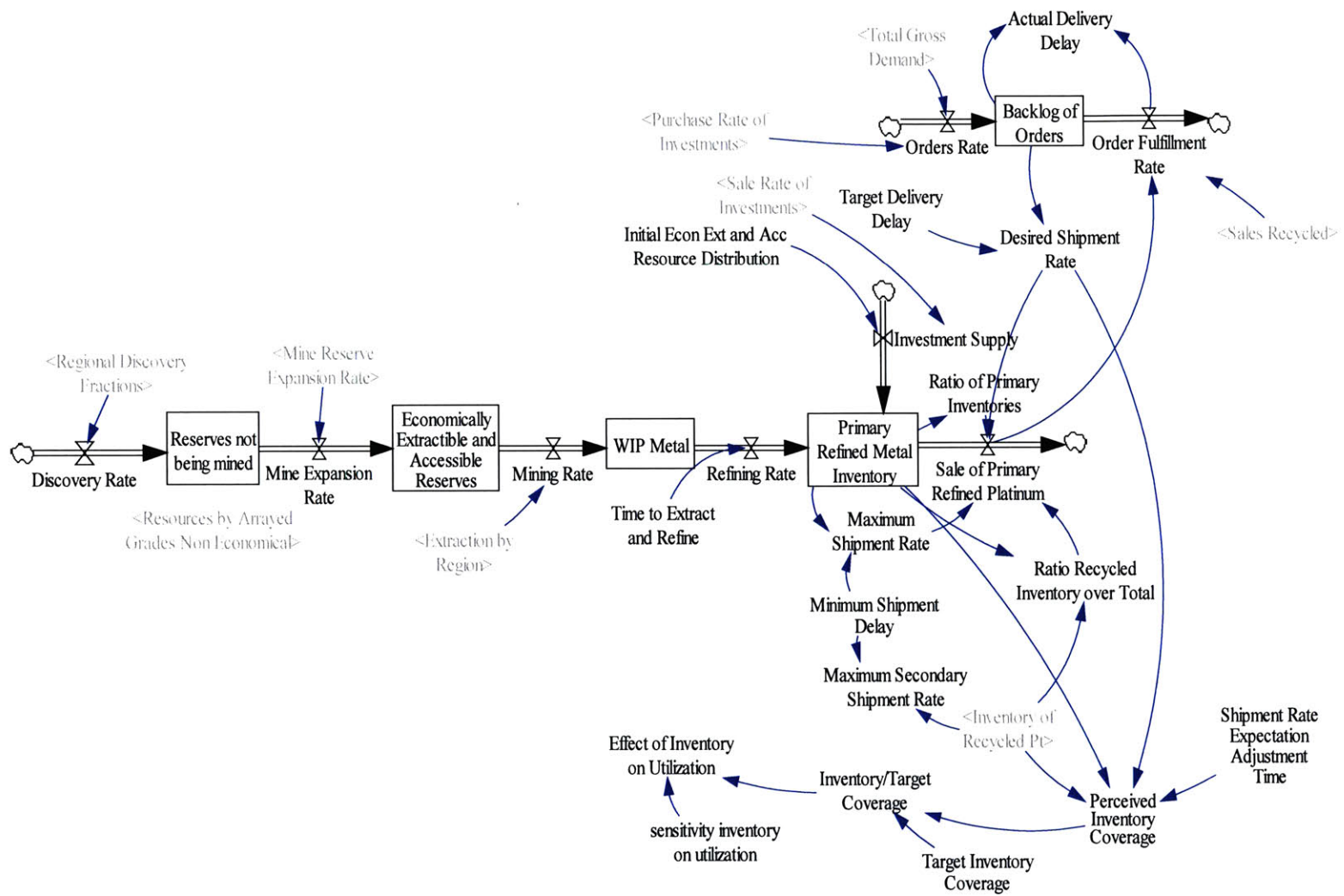
Figure 65: Overview of platinum primary production and sales stocks and flows.
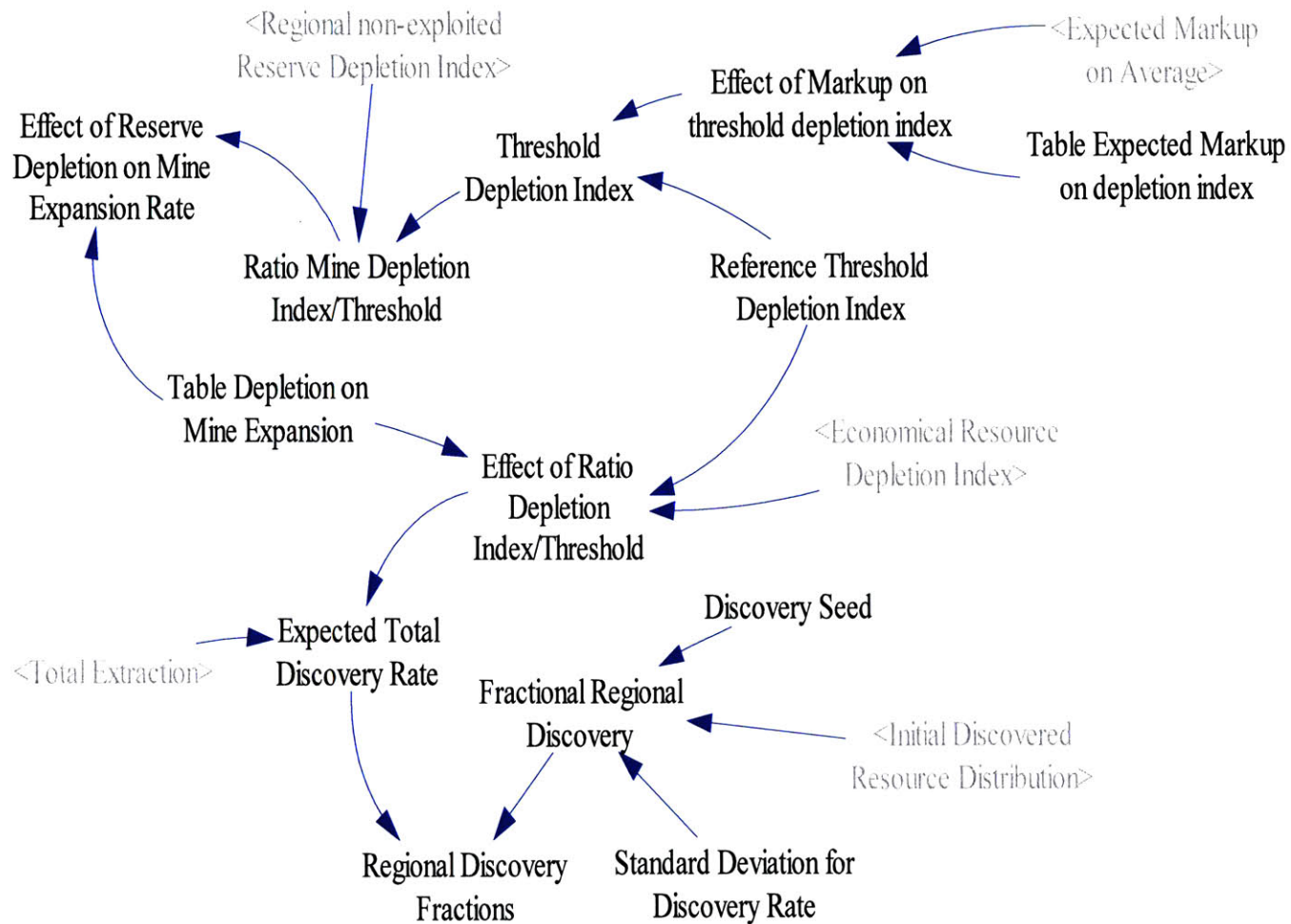
Figure 66: Variables that determine discovery rate. Threshold depletion index is an exogenous variable that tells the model how much additional effort primary suppliers will put in as reserves are depleted. Discovery occurs based on a likelihood of discovery at a given exploration effort level.
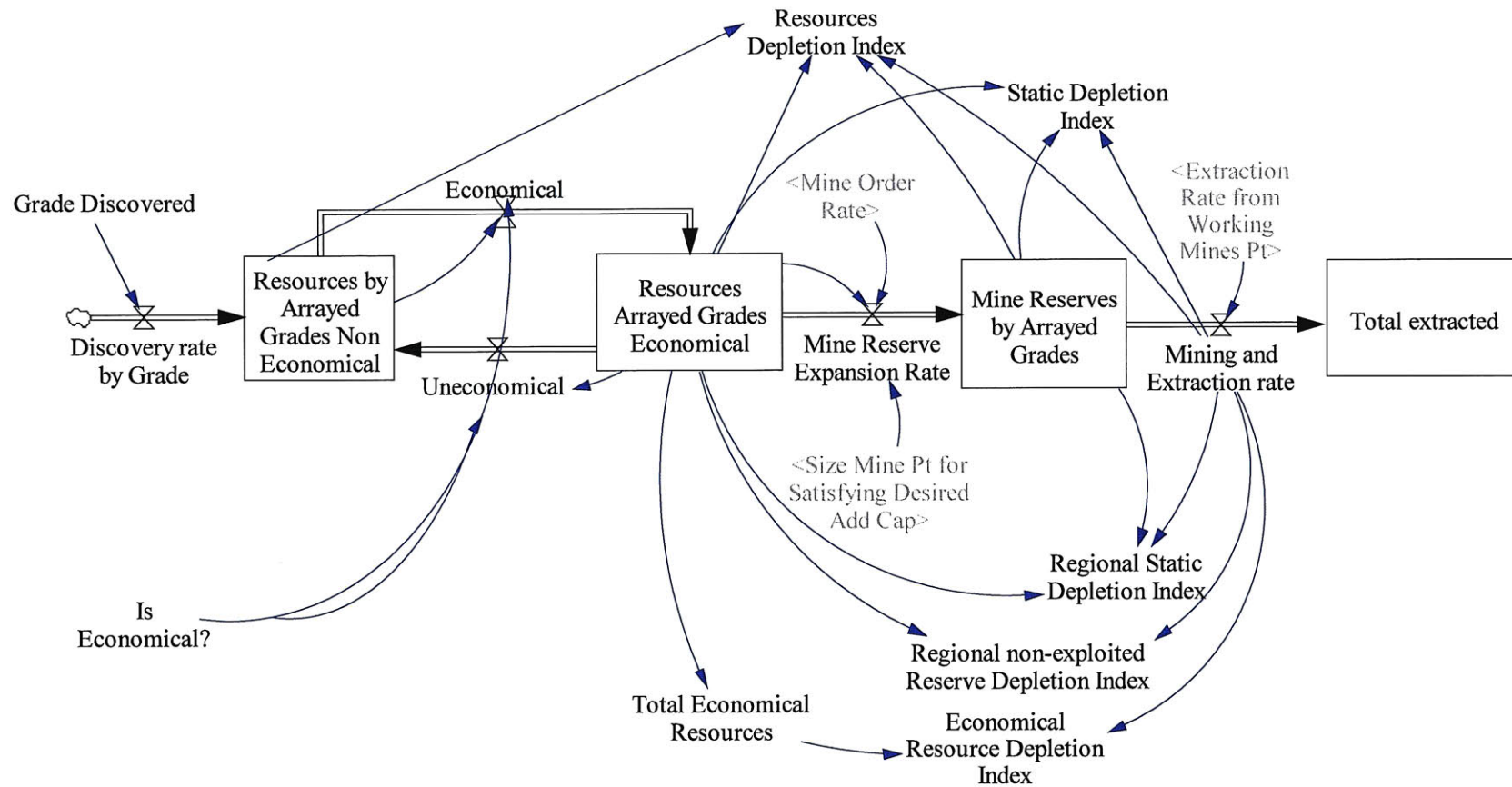
Figure 67: The different categories of resources are tracked based on whether it is economical to extract a given resource. The resource and reserve depletion indices are calculated for determining the effort for new exploration.

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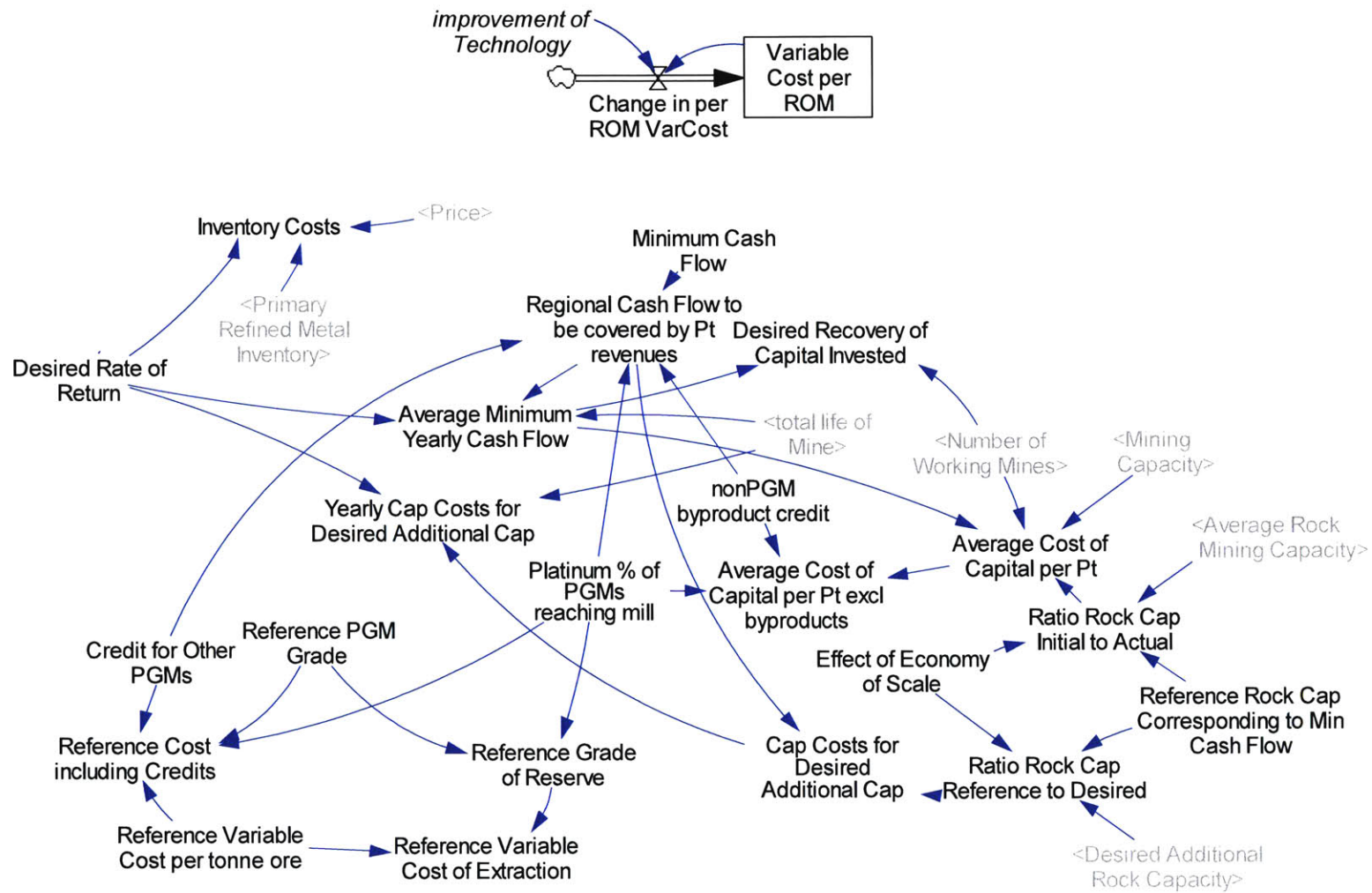
Figure 68: Cost parameters and evolution of cost with ore grade and technology. Variable costs, estimated capital costs and inventory costs are calculated for each region and ore grade level.
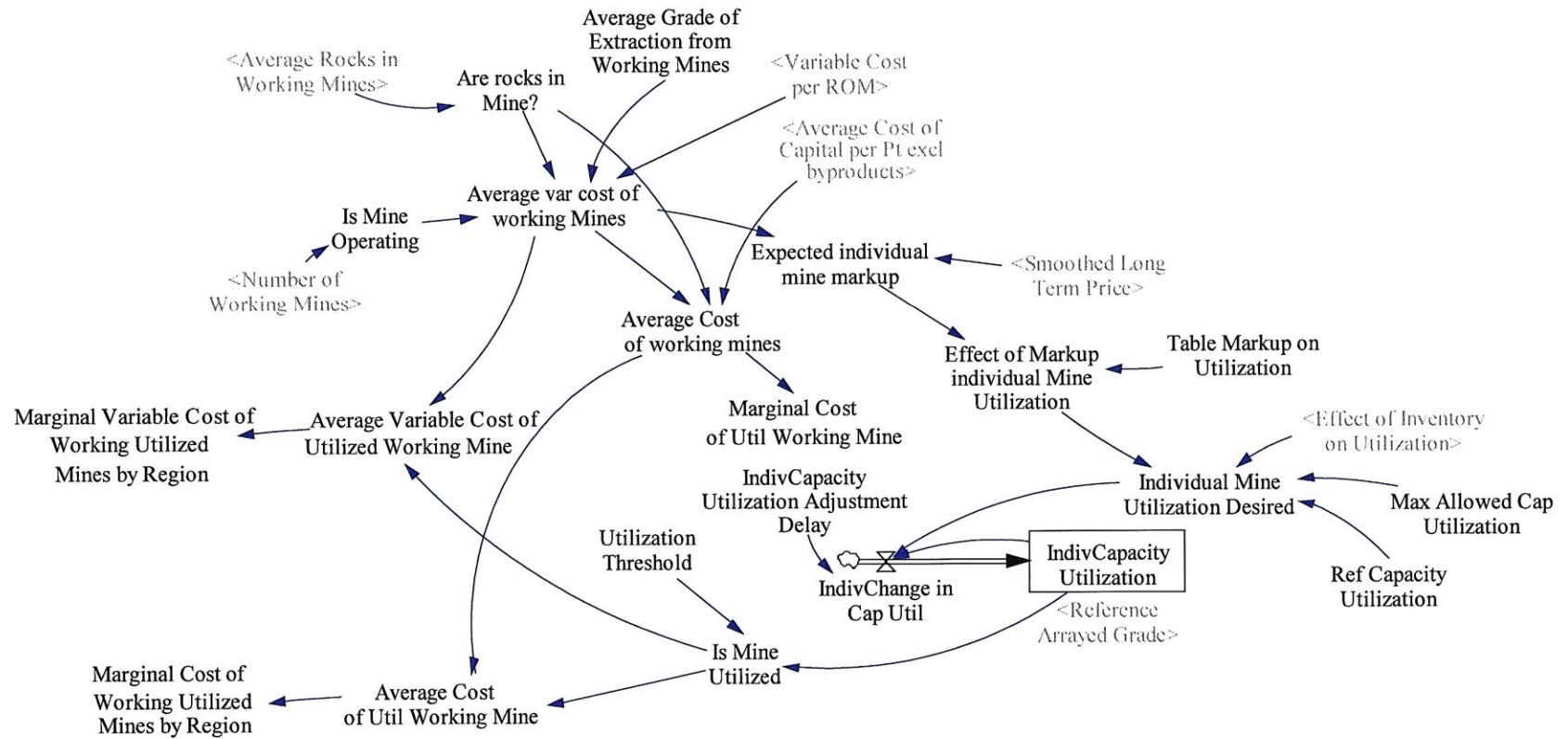
Figure 69: Utilization and marginal cost calculations.

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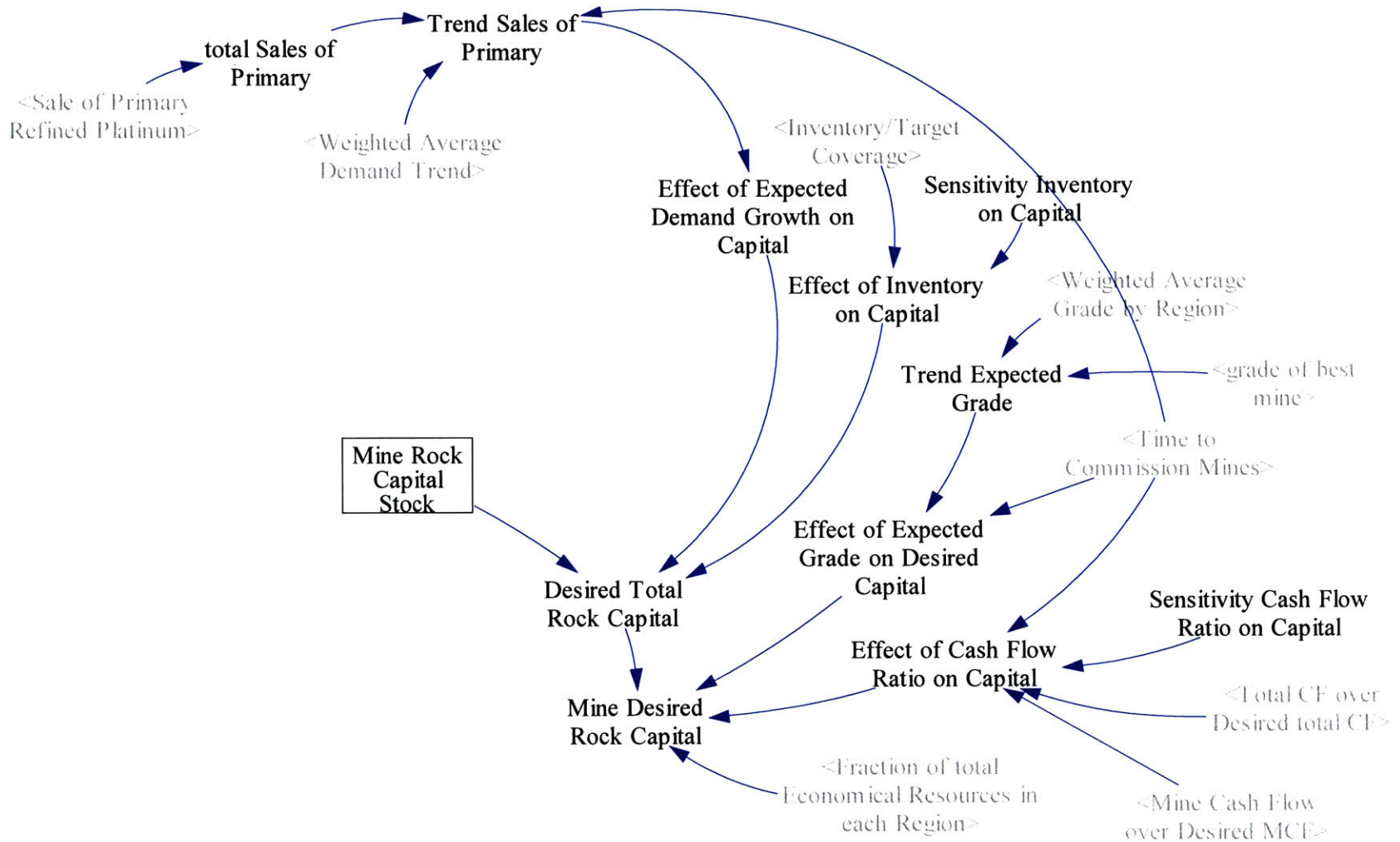
Figure 70: Determination of desired capital to invest into building capacity to mine additional ore. Higher cash flow, ore grade depletion, expected growth in demand and low inventory encourage new capital investments.
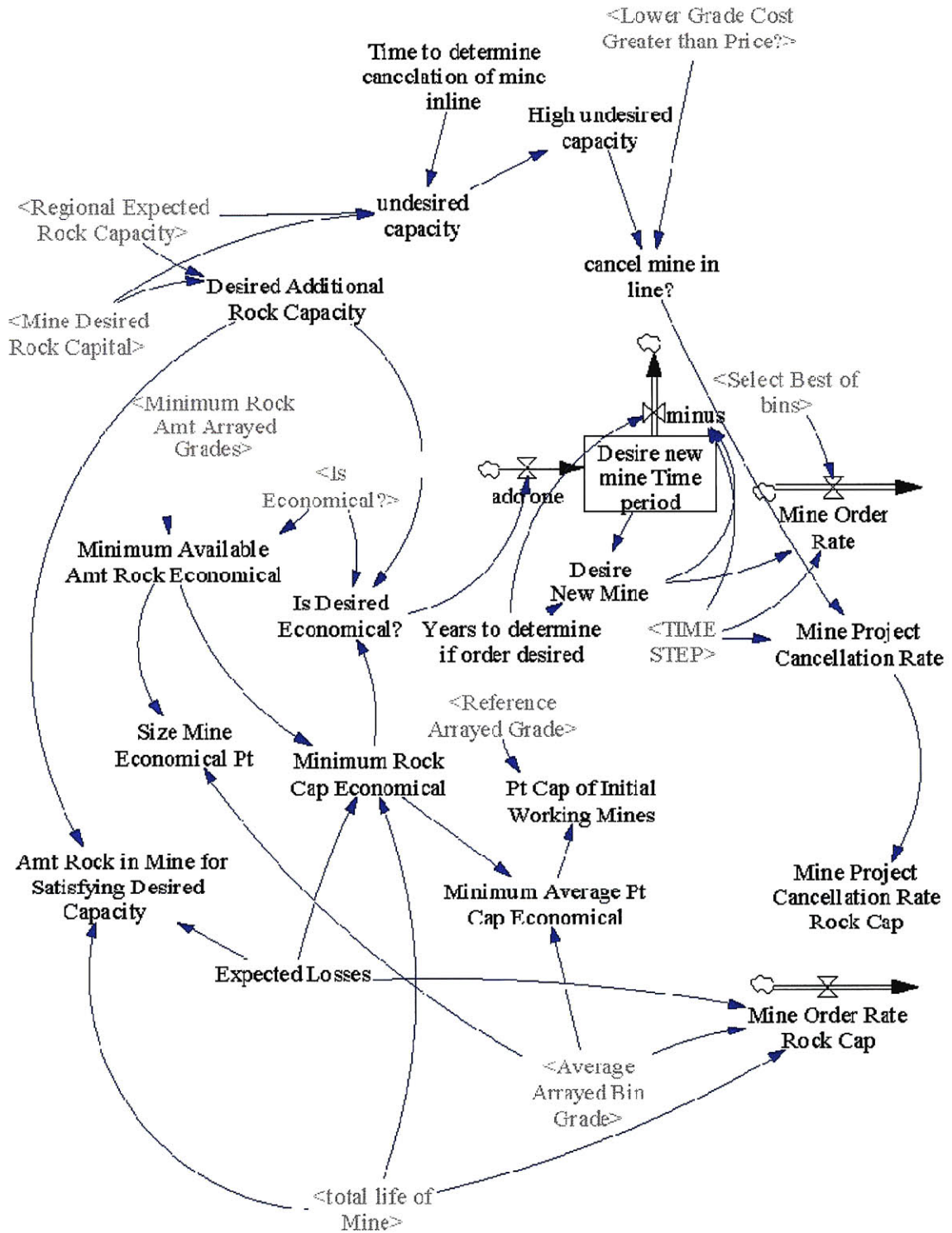
Figure 71: Based on desired new capital investment and already installed and ordered capital, new mine expansion projects are ordered. Mines can also be cancelled after being ordered and before being commissioned based on market price and market demand.
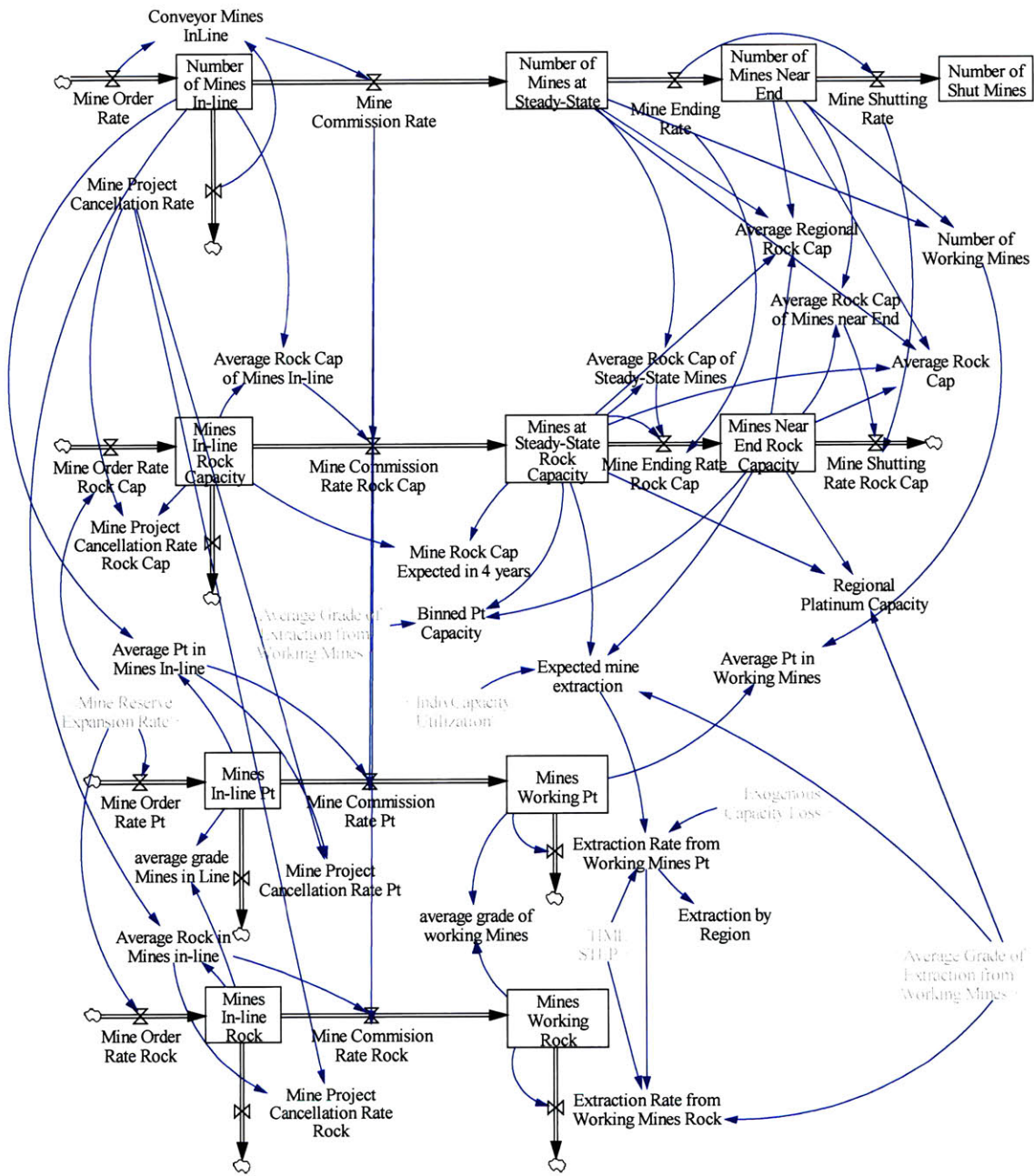
Figure 72: Once new mines are ordered, the model tracks how much ore rock and platinum metal can be and is extracted from each region.
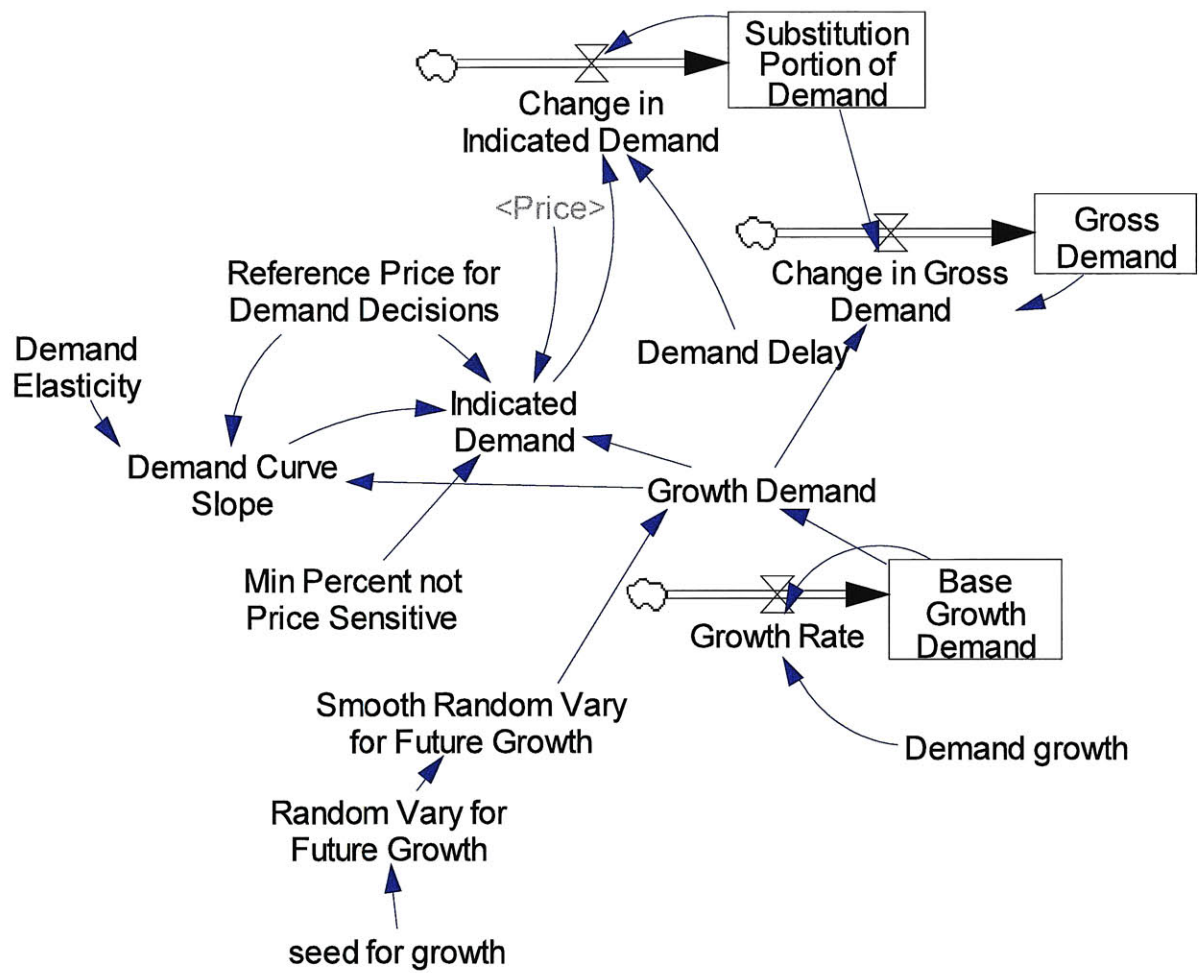
Figure 73: Demand changes based on exogenous demand growth, demand noise and price. Each demand sector (7 sectors) has a different growth, elasticity and delay. Gross demand becomes orders for platinum and satisfied orders will become platinum that enters products for consumer or industrial use.
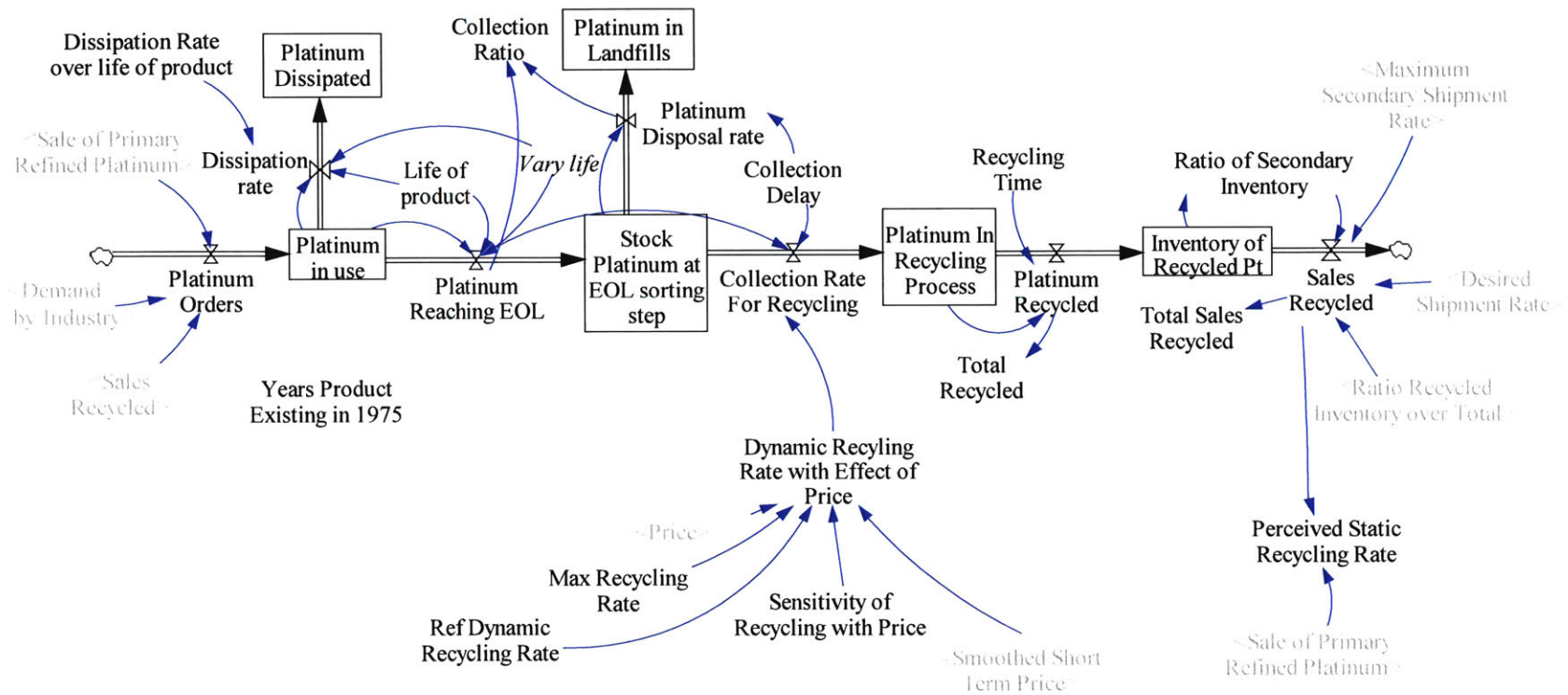
Figure 74: Platinum orders that are satisfied become products for use. Platinum is tracked through life of product, to end-of-life and recovery rate (here called collection rate) determines the amount of platinum available for sale to manufacturers. The recovery rate (dynamic recycling rate) changes with price.
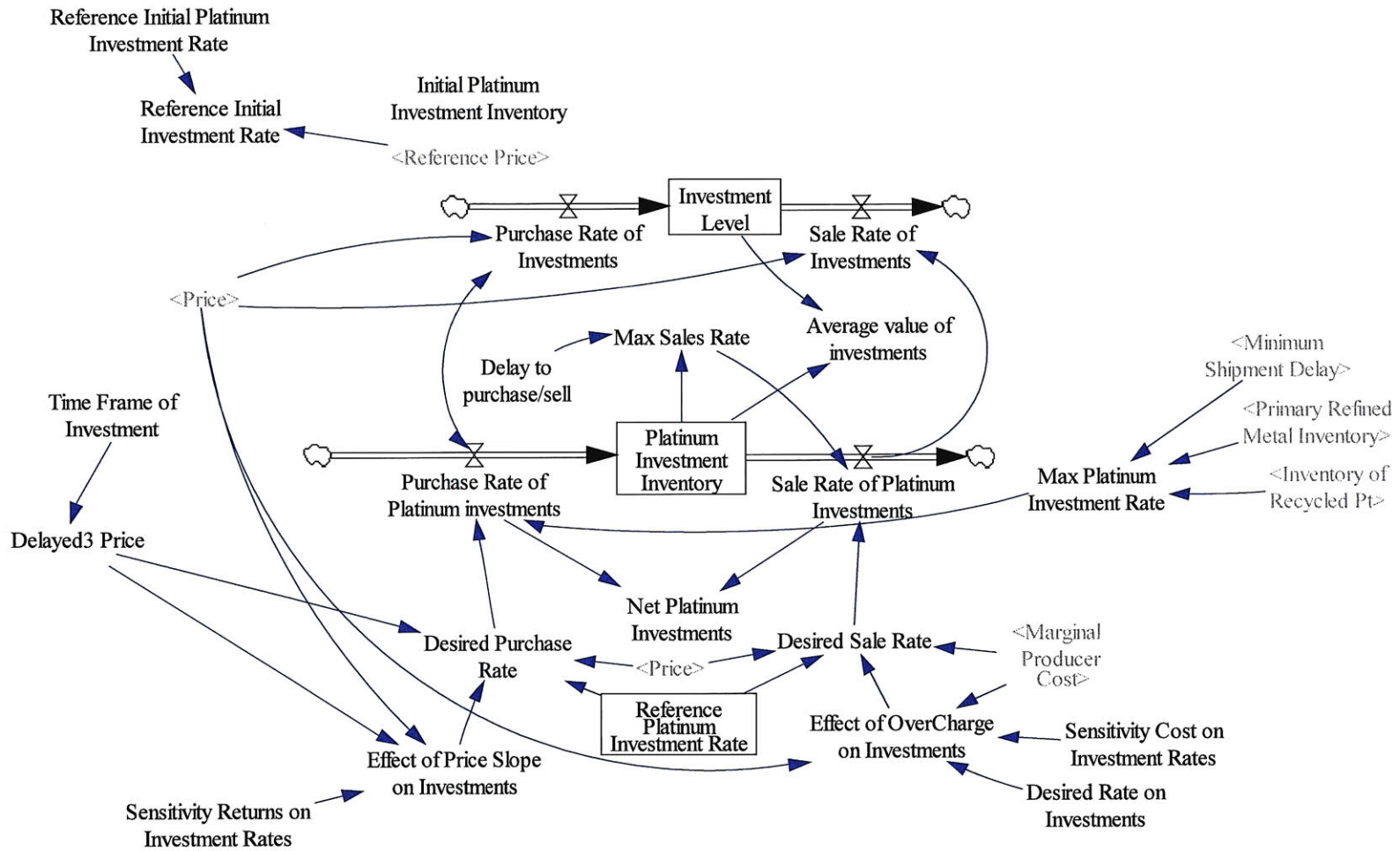
Figure 75: Investment in platinum metal is a function of price and marginal producer costs. As price increases, investors increase their purchases but when there is a large discrepancy between price and marginal producer costs, investors increase their sales. The model also tracks how much money is put into platinum investments. Investment purchase come out of market inventory and sales go back into market inventory. The magnitude of investment inventory does not impact price.
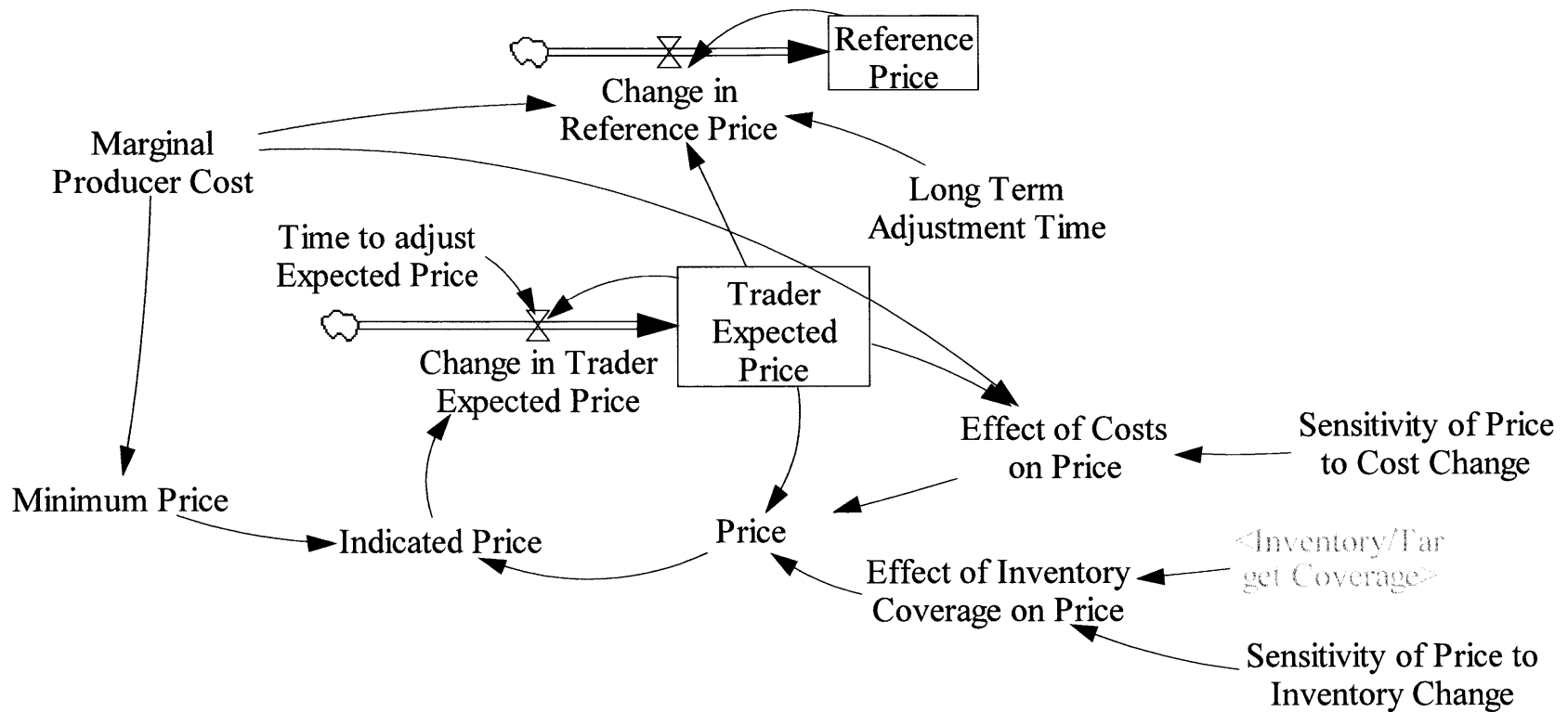
Figure 76: Price Structure. Price adjusts to changes in marginal producer costs and inventory levels. The trader expected price is a smoothed function of price. Trader expected price and marginal producer costs determine the reference price for the manufacturing industry.

10.3 Inventory Behavior

10.3.1 Historical Overview

Platinum stocks are held by primary producers, by manufacturers, by recyclers, at the metal markets that trade in platinum, by banks and by individual investors.

Platinum primary producers are mostly large multi-national companies that mine and mill the ore and then smelt and refine the metal. The mining to smelting process generally takes place at one location, while the refining may take place at a separate location, sometimes in a different country. Primary producers maintain stocks of platinum in different stages of the mining and extraction process. Partly, this is a basic buffering strategy to ensure that other stages of the production process are able to continue running if there are shutdowns at a particular part of the mine or plant, other parts would still be able to continue running. Primary producers also hold stocks and plan production in order to deal with price uncertainty (McIsaac 2008). Discussions with members of the International Precious Metals Institute indicate that it is difficult to know the size of primary producer stocks because companies are unwilling to publish such information.

There are a number of categories of manufacturers of products that use platinum. Automotive and automotive parts manufacturers and petroleum producers are generally larger multi-national companies. Jewelers are smaller companies. Larger companies (e.g.,, automotive companies) will hold stocks mainly to avoid production interruptions. Companies may deal with price uncertainty through financial hedging rather than physical metal stocks. Smaller companies may actually not hold any metal stocks, but instead may borrow platinum from banks, pay an interest rate and only buy the platinum when the product is sold to customers.

There are many firms in the recycling supply chain. Companies that collect platinum vary in size, while the companies that refine the scrap are more likely to be larger companies. In some cases, the scrap refiners are simply primary producing companies. For example, A1 is a large automotive catalyst recycler that collects scrap and sells it to South African primary producers who refine the scrap together with their primary ore. Recyclers will hold stocks of platinum in scrap form.

The best (and, in fact, only) data available on platinum inventory is the stock levels held at metal markets. Platinum is traded on the NYMEX, LME and Tokyo Stock Exchange. Data on platinum prices at the LME and inventory at the NYMEX were available (see below) (Thomson Reuters 2009). When these data were analyzed, a statistically significant correlation between platinum

inventory levels and price could not be found, unlike what has been found in the palladium market (own modeling work). It is not likely that prices on the LME were significantly different from prices at the NYMEX to account for the lack of correlation.

Because some manufacturers prefer to borrow platinum from financial institutions rather than tie up their cash in platinum stocks, banks and other financial institutions will hold platinum metal stocks.

Finally, platinum, as with other precious metals, is purchased by individuals or individual firms (e.g., Berkshire Hathaway) for investment purposes. Platinum metal can be purchased in the form of bars or coins. Data on coin purchases is available (CPM Group 2007). Stocks of platinum purchased by individual investors is suspected to be kept mainly in bank vaults in Zurich (Christian 2006). Data published by Johnson-Matthey, a large platinum-producing company, is available for global investments in platinum (Johnson Matthey Precious Metals Marketing 2008).
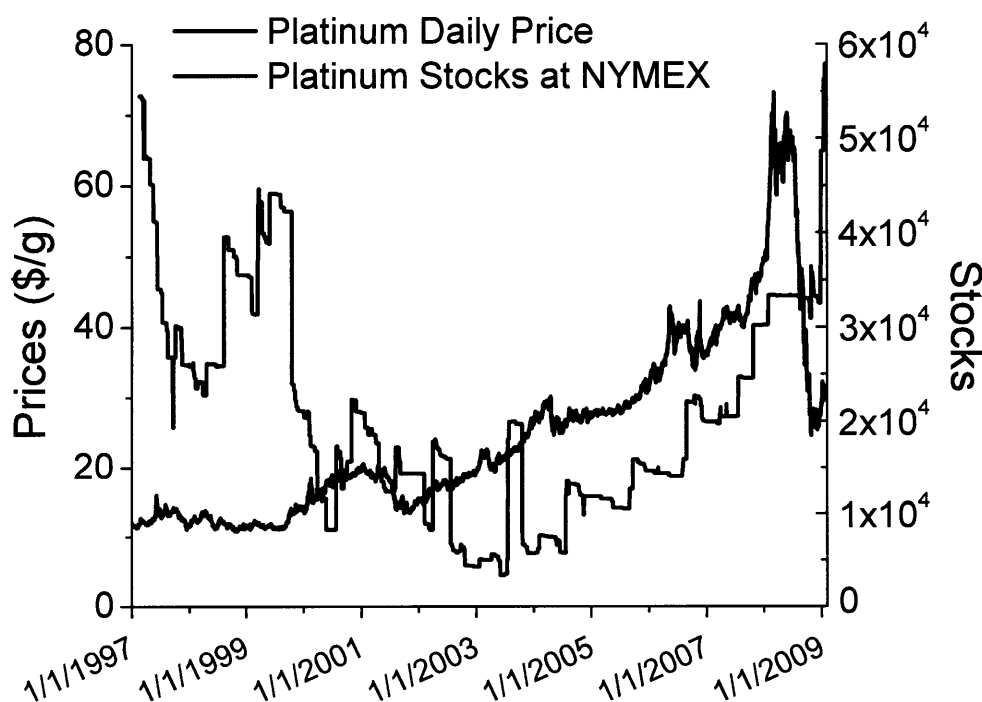

Figure 77: Daily LME platinum nominal prices and daily platinum stocks at the NYMEX (Thomson Reuters 2009).

As there is limited information about inventories of platinum, one way to estimate aggregate inventory changes globally is to compare data on production of platinum with data on purchases of

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platinum by manufacturers. The difference between published data on supply and demand can be used to approximate the change in global platinum inventory.

Estimated Change in Global Inventory = Estimated Supply$_t$ – Estimated Fabrication Demand$_t$

The cumulative excess supply can be calculated if the first year is set at 0 inventory level.

$$\text{Cumulative Excess Supply}_T = \sum_{1975}^{T}(\text{Estimated Supply}_t - \text{Estimated Fabrication Demand}_t)$$

Two sets of published data will be compared here: one produced by Johnson-Matthey (Johnson Matthey Precious Metals Marketing 2008), a multinational platinum producer, and the second produced by CPM Group (CPM Group 2007), a commodities trading consulting company based in New York. The data covers supply from primary producers of platinum and purchases at the industry-level. The data also covers recycling of automotive catalytic converters. For both sets of data, estimated supply therefore does not include non-automotive recycling. Moreover, I was unable to gather complete information from the individual companies, and so could not independently verify the accuracy of the data from these two sources.

The two sets of data differ quite significantly in terms of whether a surplus (supply greater than demand) or deficit (demand greater than supply) of platinum occurred in any given year (see Figure 78, Figure 79 and Figure 80). The surplus or deficit in any given year could be as large as 28% of fabrication demand in that same year.

The cumulative excess supply is plotted as a function of time for each set of data (see Figure 82 for Johnson-Matthey data and Figure 83 for CPM Group data).

For comparison, in Figure 82, the cumulative excess supply is plotted along with the cumulative investment data published by Johnson-Matthey and the yearly fabrication demand estimates. Between 1975 and 2008, Johnson-Matthey estimates that there was 130 tonnes of cumulative excess supply. Total cumulative investments from 1980 (first year where data was available) to 2008 was 198 tonnes.

In Figure 83, the cumulative excess supply is plotted along with cumulative platinum coin purchases and the yearly CPM group fabrication demand estimates. Between 1977 and 2008, the cumulative excess supply is calculated at 12 tonnes. The cumulative investment in platinum in the form of coins is estimated at 76.5 tonnes.
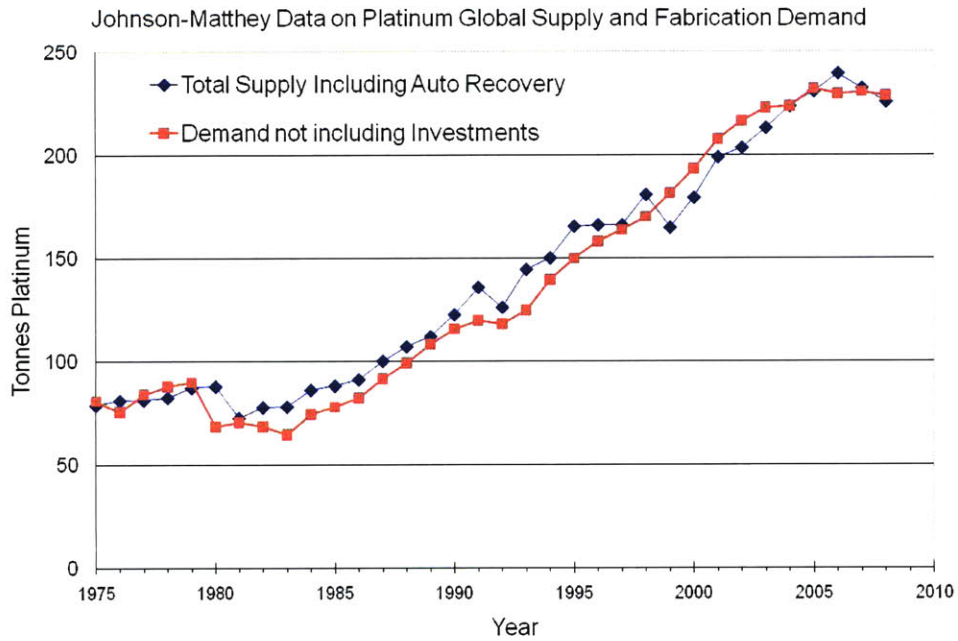
Figure 78: Johnson-Matthey published data. Supply data includes primary production and automotive recovery production. Demand data is approximated with use data. Demand includes fabrication use of primary platinum and fabrication use of automotive secondary platinum.
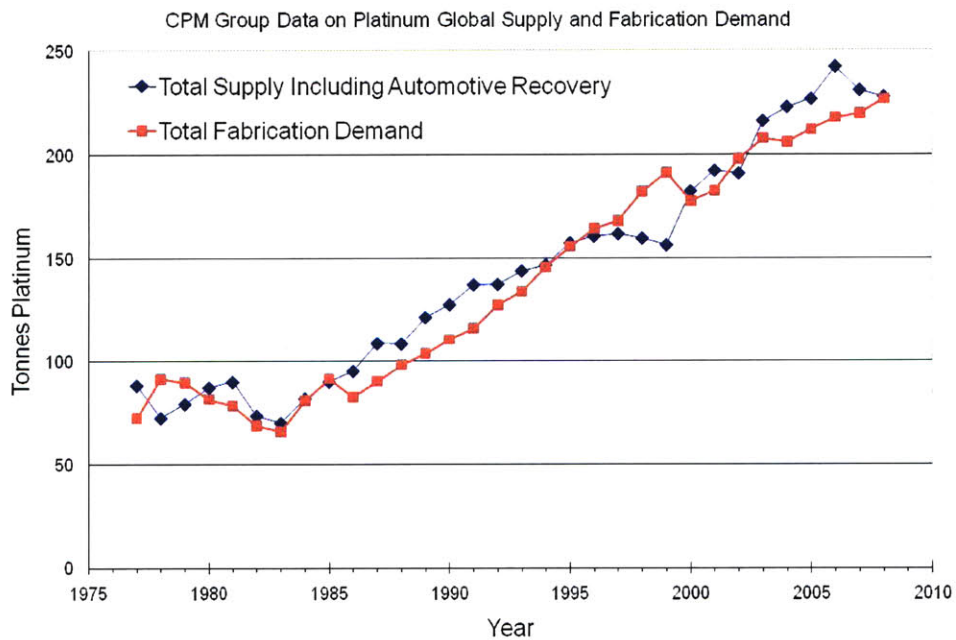
Figure 79: CPM Group data from annual published precious metals report. Supply data includes primary production and automotive recovery production. Demand data is approximated with use data. Demand includes fabrication use of primary platinum and fabrication use of automotive secondary platinum.
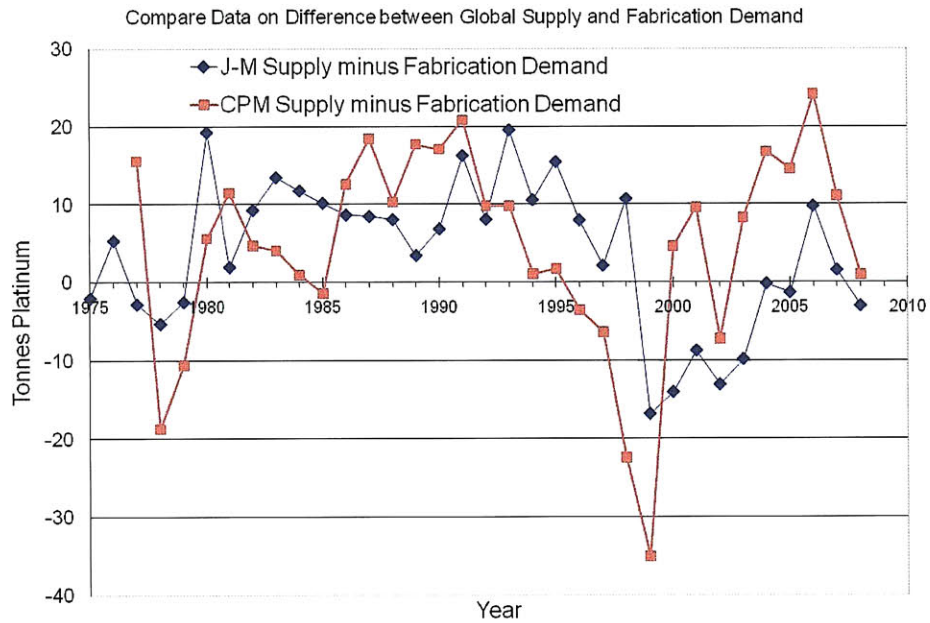
Figure 80: Comparison of two sets of data: Johnson-Matthey and CPM Group. Yearly supply minus demand data are plotted vs. time. Supply data includes primary production and automotive recovery production. Demand data is approximated with use data. Demand includes fabrication use of primary platinum and fabrication use of automotive secondary platinum.
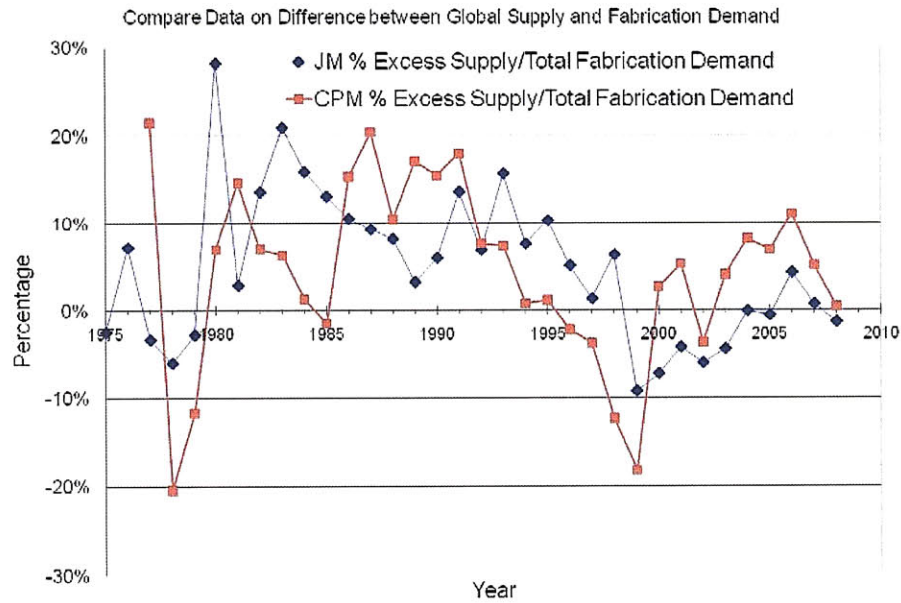
Figure 81: Comparison of two sets of data: Johnson-Matthey and CPM Group. Yearly supply minus demand data divided by demand are plotted vs. time. Supply data includes primary production and automotive recovery production. Demand data is approximated with use data. Demand includes fabrication use of primary platinum and fabrication use of automotive secondary platinum.

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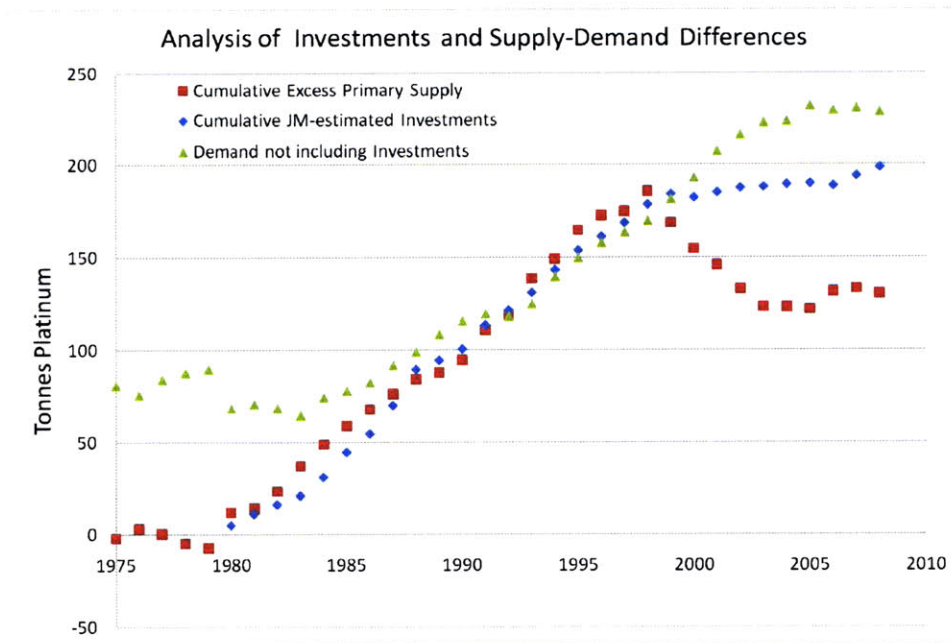
Figure 82: Johnson-Matthey Data: cumulative excess supply (red squares), cumulative investment in platinum bars and coins (blue diamonds) and the yearly fabrication demand estimates (green triangles) are plotted as a function of time.
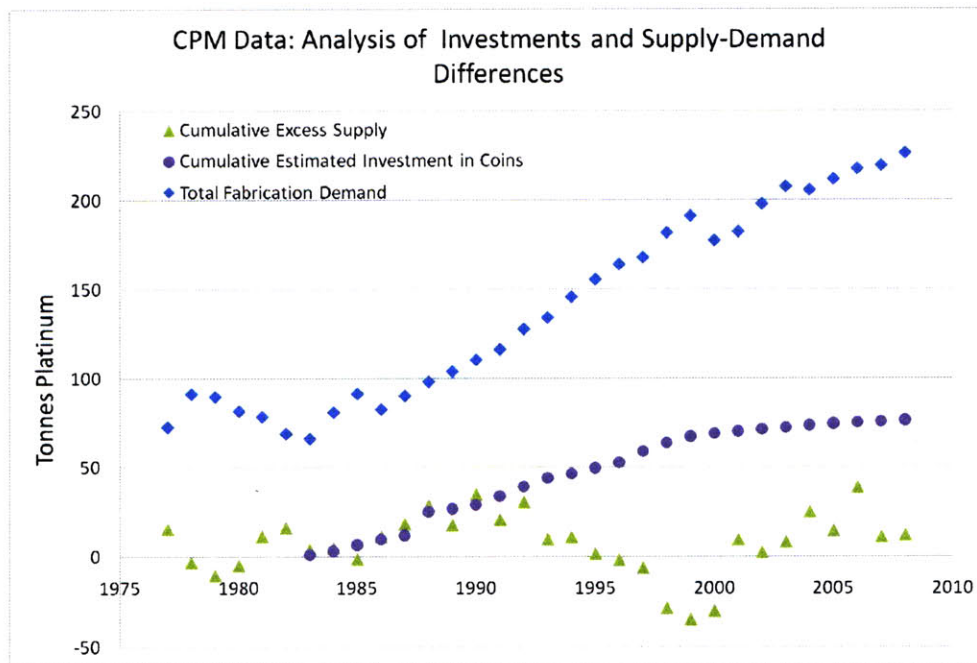
Figure 83: CPM Group Data: cumulative excess supply (green triangles), cumulative investment in platinum coins (purple dots) and the yearly fabrication demand estimates (blue diamonds) are plotted as a function of time.

With the Johnson-Matthey data, the cumulative investment amount between 1995 and 1999 are almost equal to fabrication demand for platinum in those years, which is a significant amount. The cumulative excess supply in 2008 is more than half one year's fabrication demand.

The CPM data shows a much tighter supply and fabrication demand balance than the Johnson-Matthey data. Cumulative excess supply varies around zero and is never greater than 25% of total demand of the same year (year 1990). The cumulative investment amount in 2008 is equal to 1/3 of fabrication demand of 2008.

The cumulative investments in both sets of data exceed the cumulative excess supply, indicating there is either more platinum being produced that is not being accounted for and/or there is less demand than estimated. From discussions with members of the International Precious Metals Institute, they suggest that recycling from non-automotive sources is one source of uncertainty and possible error. Also, investment purchases of platinum, except for coin purchases, are especially difficult to measure accurately and therefore Johnson-Matthey's investment purchase data are another source of error. There were also comments about inaccurate data collection, especially on the Johnson-Matthey data. Johnson-Matthey is a large producer of platinum and could theoretically benefit by manipulating market information.

10.3.2 Model Structure for Inventory

In the market model, inventory is represented by stocks, in the jargon of systems dynamics. There are mainly two stocks that track inventory, one which represents primary and secondary platinum inventory from primary and secondary platinum producers and a second which represents platinum inventory held by investors. For the inventory of platinum from production, the stock is equal to the integral of platinum produced (primary plus secondary) minus platinum purchased. Platinum purchased is equal to platinum demanded at the price determined in the previous time step, unless there is insufficient inventory. This structure is a modified version of the inventory structure presented in chapter 20 of Business Dynamics (Sterman 2000). The inventory of platinum investments is equal to the integral of platinum purchased for investment minus the platinum sold from the investments. When platinum is sold from investments, the model assumes that the platinum goes to satisfy fabrication demand. Platinum that is sold from one investor and purchased by another is not tracked in the model. Platinum inventory and production rates and purchase rates are represented using a system dynamics stocks and flows diagram.
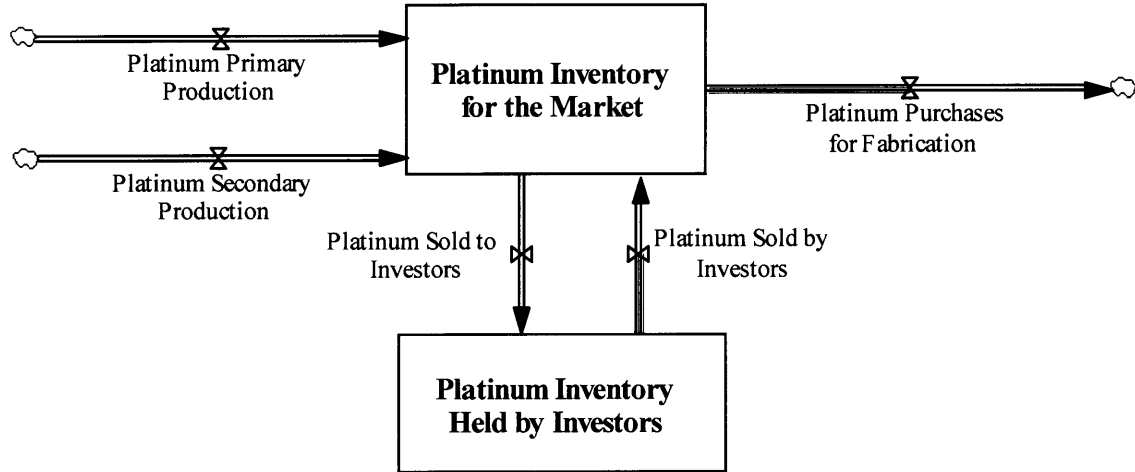
Figure 84: System Dynamics schematic of platinum stocks and flows.

In the model, there is a variable defined as target inventory coverage, measured in years (fraction of years), where:

$$\frac{\text{Platinum Inventory for the Market}}{\text{Platinum Fabrication Demand}} = \text{Inventory Coverage}$$

Target inventory coverage is the desired ratio of platinum inventory over fabrication demand. Price increases when inventory coverage is below the target coverage and decreases when inventory coverage is above the target coverage, given a constant cost of marginal producer. The platinum target coverage and the change in price when inventory increases above or below the target were determined through model calibration with historical price and supply-demand data.

In summary, for the present model set-up, inventory is endogenously determined from production and sales. Production and sales are endogenously determined from past prices. Prices depend in part on inventory coverage.

The behavior of the structures within the model that directly control inventory (instead of controlling production and demand decisions) can be changed by changing certain exogenous variables:

1. Changing the magnitude of investment purchases and sales by changing the initial platinum inventory held by investors and the way investment decisions are made. It is even possible to shut down the whole investment sector by eliminating the platinum inventory held by investors.

2. Change the target inventory coverage time. This will change the amount of platinum that is desired in the inventory for the market.

3. Change how price is affected by the inventory coverage. This will affect production and purchase rates.

Each of these ways to control inventory can affect inventory levels, variability of inventory levels and price.

For the base case scenario in the model, historical supply-demand behavior and price were used to set or calibrate variables that controlled inventory: the initial amount held by investors in 1975 (to calculate the cumulative excess supply, the 1975 investment inventory had been set at 0), the activity level of investors in the face of increasing or decreasing prices, the target inventory coverage time, and the response of price to changes in market inventory.

In the model, and in real markets, maintaining inventory is a way to ensure demand is met despite fluctuations in production and in demand. The variables of *target inventory coverage* and *price sensitivity to inventory coverage* (changes how price is affected by the inventory coverage) are model parameters that try to capture a market's desire to ensure supply meets demand at every point in time: the larger the target inventory coverage, the larger the stock of inventory that is desired, and the larger the sensitivity of price to inventory coverage, the larger the increase in price when coverage is low.

Price is affected by these model parameters in the following way:

$$
\text{Price}_t = f \left\{ \text{Price}_{t-1} * \left(\frac{\text{Inventory Coverage}}{\text{Target Inventory Coverage}} \right)^{\text{Sensitivity of Price to Inventory}} \right\}
$$

The value of the parameters Target Inventory Coverage and Sensitivity of Price to Inventory were determined through model calibration to historical data and the base case values for these parameters are presented in Table 21 as Case A.

Given that yearly surplus or deficit between supply and demand have been as large as 28% of yearly fabrication demand and there have been successive years of either surplus or deficit, it seems that the platinum market is comfortable with having a large inventory, or at least the perception of a large inventory.

The sensitivity value of price to market inventory change was expected to be small. This is consistent with the view by people who work in the platinum industry that the data on inventory is not very reliable because of the difficulties involved in determining inventory.

10.3.3 Exploration of Behavior through Simulation

In this section, I explore the model changes that occur when I change the target inventory coverage time and the sensitivity value that determines how price is affected by the inventory coverage. Price, inventory coverage divided by target inventory coverage, cost of the marginal producer and estimated scarcity rent (price minus cost of the marginal producer) will be compared for the different scenarios.

In all scenarios, demand for products that use platinum follows an exponential growth path with historically-calibrated growth rates and exogenously-imposed noise in the demand. The base case is the same as in the body of the thesis. The changes for each run are described in the table below.

Table 21: Inventory Parameter Exploration: description of scenarios examined.

Case	Scenario Description	Target Inventory Coverage (years)	Price Sensitivity to Inventory Coverage (unitless)
A	Base Case	0.5	-0.32
B	Sensitivity of Price Low	0.5	-0.01
C	Sensitivity of Price High	0.5	-2
D	Target Coverage Low	0.125	-0.32
E	Target Coverage High	2	-0.32

The demand and supply for platinum for the base case are shown in Figure 85. Primary and secondary productions are stacked so that their sum can be compared to the total demand value. Excess supply and excess supply divided by total fabrication demand have also been calculated and are plotted in Figure 86. These graphs show how supply and demand fluctuate as well as grow over time and how they do not necessarily match up.

The inventory coverage will fluctuate in order to match the two. If the inventory coverage is insufficient, there will be an increase in the backlog of orders (see Figure 87). The backlog of orders is generally of the same order of magnitude as the demand, i.e. grows with demand. It is a

stock that tracks platinum demand and is reduced when orders are fulfilled. In this way, orders from past periods that are not met are not discarded, but must be fulfilled in addition to the new orders.
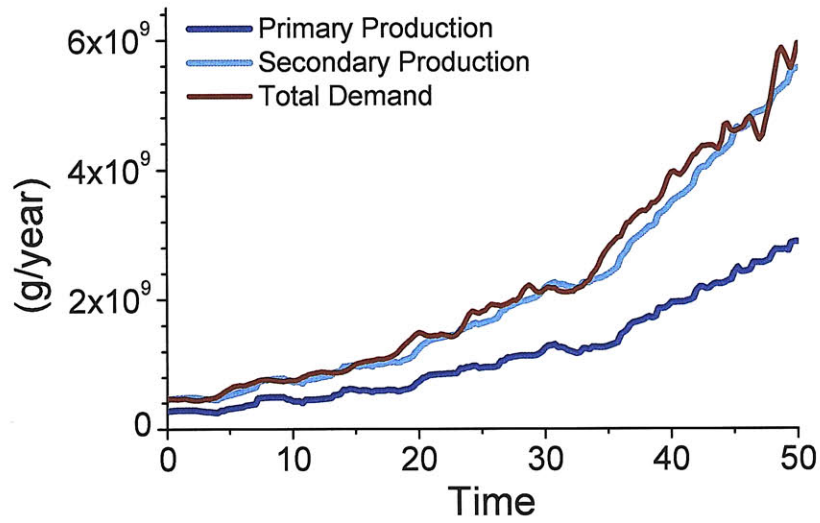
Figure 85: Model results for base case (Case A). Primary production and secondary production are stacked and plotted with total demand for platinum as a function of time.
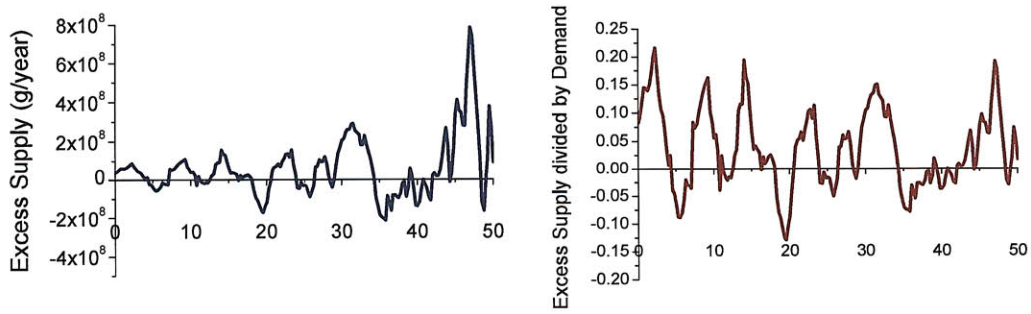
Figure 86: Excess supply and excess supply divided by total fabrication demand vs. time for modeled base case (Case A).
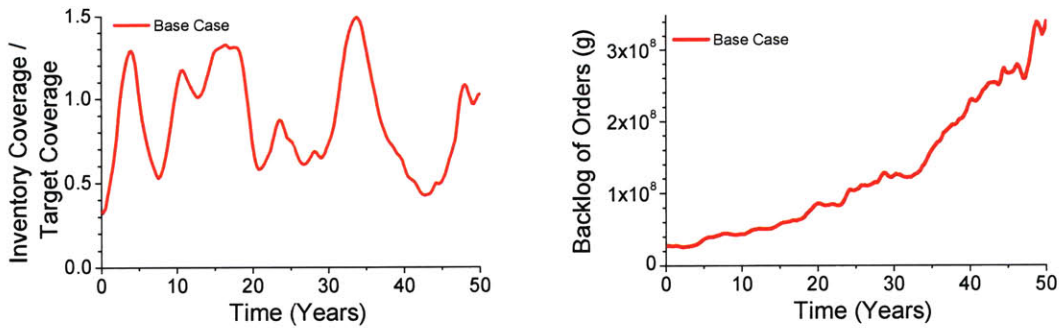
Figure 87: Base Case Inventory Coverage divided by Target Inventory Coverage (left) and Backlog of Orders (right).

I begin by exploring the effect of the sensitivity of price to inventory coverage (see Figure 88). When the sensitivity of price to changes in inventory increases, the average price over time and the standard deviation of price over time increase. The higher fluctuation in price occurs because price responds very highly to fluctuations in inventory that occur as a result of fluctuations in production and demand. The fluctuations in the inventory coverage actually decrease: inventory coverage divided by target inventory coverage stays closer to the value of 1. When the sensitivity of price to changes in inventory is low (Case B), the inventory coverage is allowed to decrease to almost zero with little effect on price. In this scenario, the backlog of orders for platinum increases significantly (not shown). The sensitivity parameter determines whether or not the market cares about the inventory coverage and the ability of the market to satisfy demand.

In a market that cares very much about the inventory coverage (Case C), the model shows that there are higher average estimated scarcity rents that result from the higher sensitivity to inventory coverage. Despite the higher fluctuations in price, the higher rents encourage higher cost producers to enter the market and to keep produce in anticipation of the increase in demand for platinum, driven by exogenous economic growth conditions (ex. demand for cars).
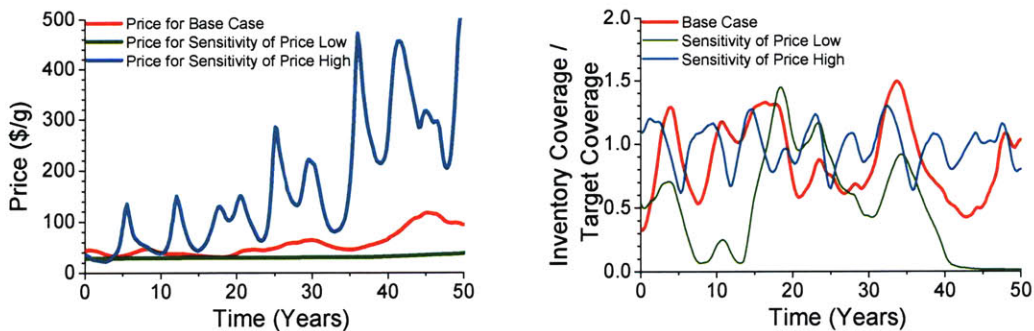
Figure 88: Modeling Results comparing effect of sensitivity of price to inventory coverage. For Cases A, B and C, price (upper left), inventory coverage divided by target inventory coverage (upper right), cost of marginal producer (lower left) and estimated scarcity rent or net price (lower right) are plotted as a function of time.

Figure 89: Price, Average Inventory Coverage divided by Target Inventory Coverage and Average Standard Deviation of Inventory Coverage divided by Target Inventory Coverage as a function of Sensitivity of Price to Inventory Levels. Each point represents the results from a separate simulation run. 200 simulations were run.

I will continue by exploring the effect of the target inventory coverage (see Figure 90). The target inventory coverage determines the relative size of the market inventory to fabrication demand that

is desired. The model shows that in a system with a small inventory relative to demand (Case D), the fluctuations in production and demand will lead to greater backlog of orders – in other words, there will be more occasions during which the demand for platinum may not be satisfied. The smaller inventory coverage also leads to larger fluctuations in price because it is more difficult to keep inventory at the desired level (larger fluctuations of inventory coverage divided by target inventory coverage).

For the large target inventory coverage case (Case E), average price is higher than in the base case. While the inventory coverage is more stable, it becomes increasingly difficult to maintain 2 years worth of inventory in a growing demand system. The inventory coverage divided by target inventory coverage drops below 1 for the last 10 years of the modeling period in this scenario. As with the high sensitivity of price case (Case C), the desire to ensure demand is always met results in higher estimated scarcity rents (although fluctuations are less).
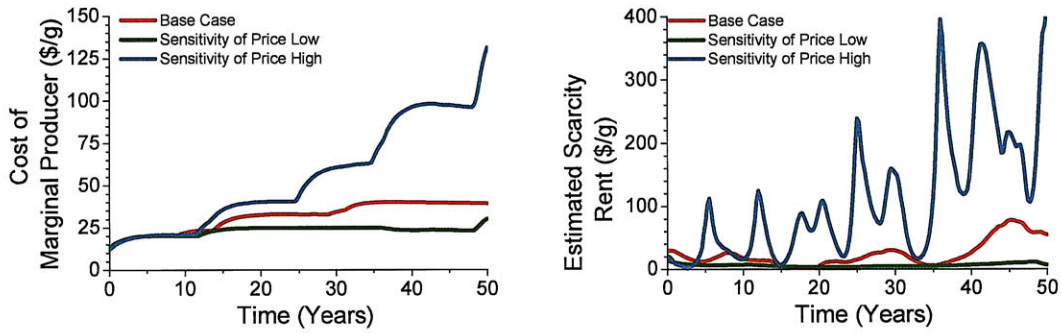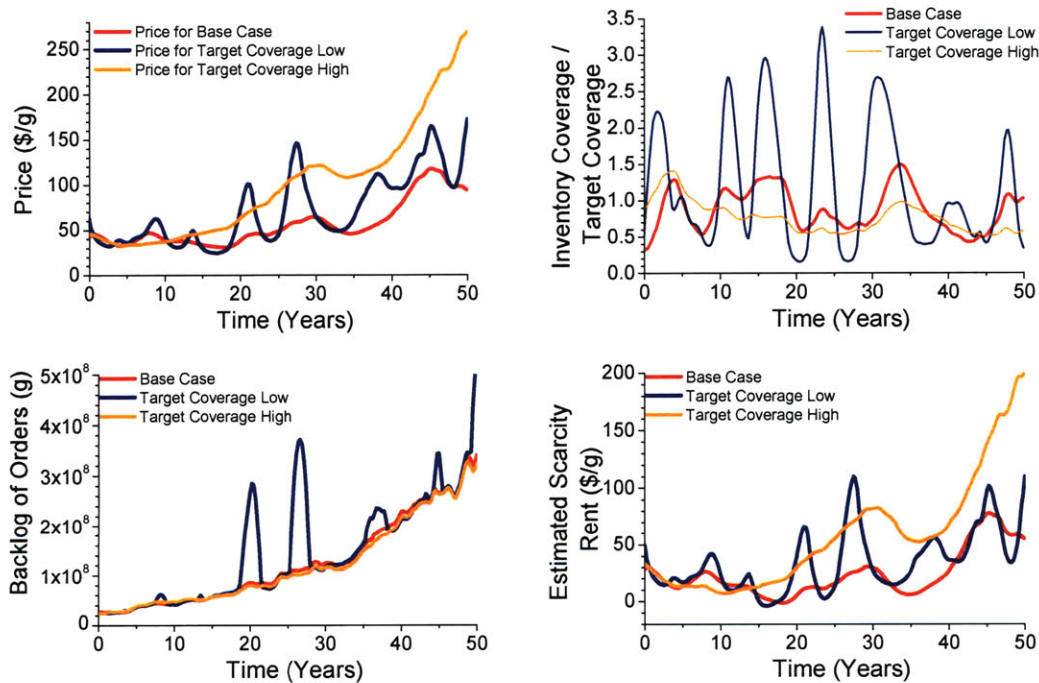

Figure 90: Modeling Results comparing effect of target inventory coverage. For Cases A, D and E, price (upper left), inventory coverage divided by target inventory coverage (upper right), backlog of orders (lower left) and estimated scarcity rent or net price (lower right) are plotted above.
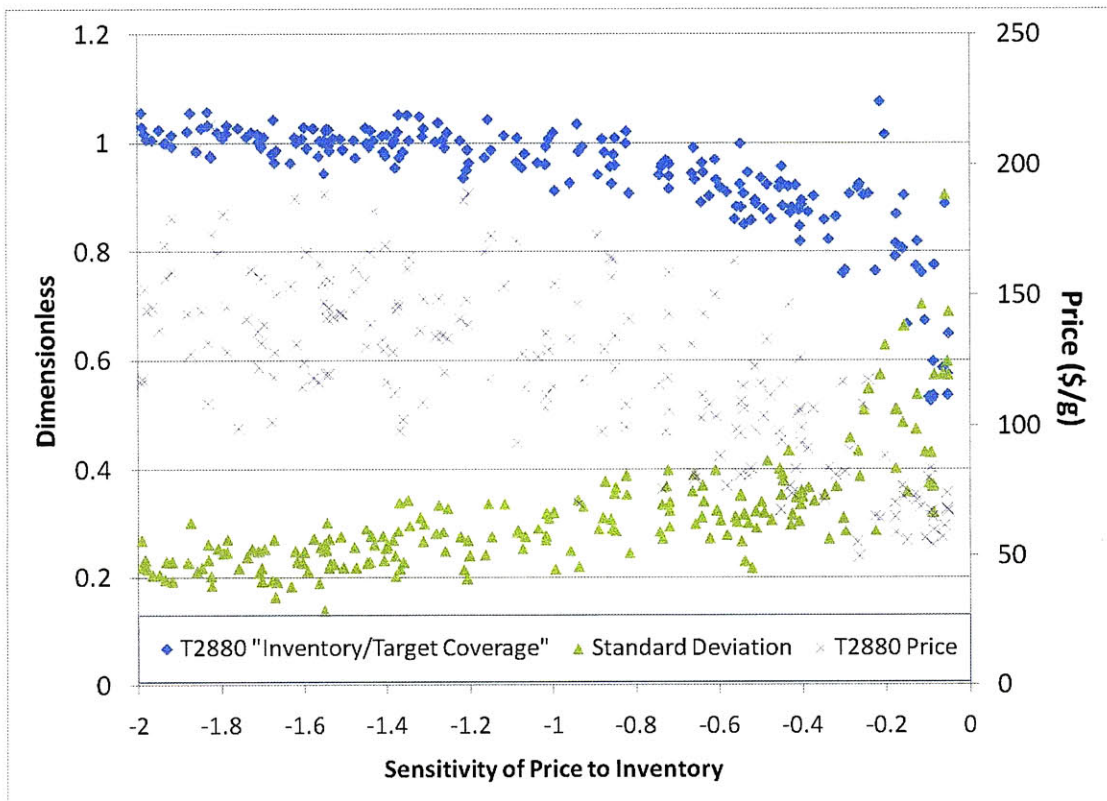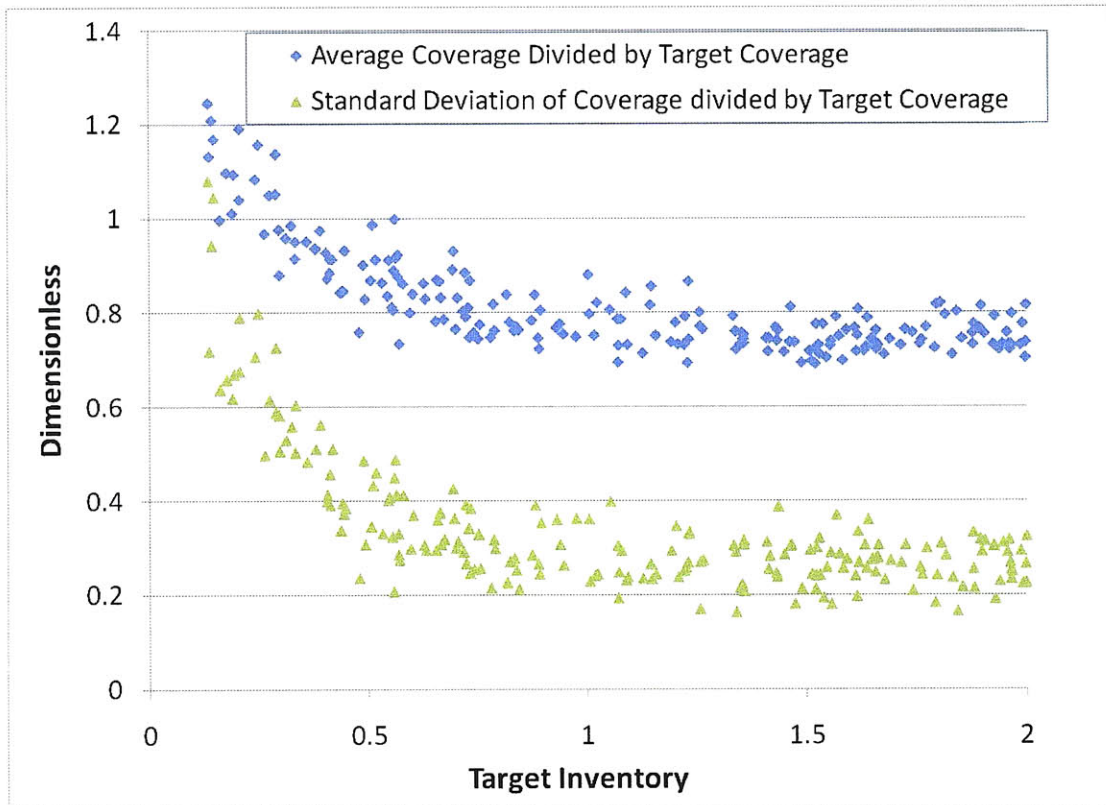
Figure 91: Average Inventory Coverage divided by Target Inventory Coverage and Average Standard Deviation of Inventory Coverage divided by Target Inventory Coverage as a function of Target Inventory Coverage (years). Each point represents the results from a separate simulation run. 200 simulations were run.

The behavior of inventory coverage was compared over various recycling rates. The recovery rate multiplier was varied as described in Section 7.2 for 200 simulation runs. All other exogenous variables were set as in the base case, including the target inventory coverage and the sensitivity of price to inventory coverage. As shown in Figure 92, the inventory behavior remains consistent across recycling rates.
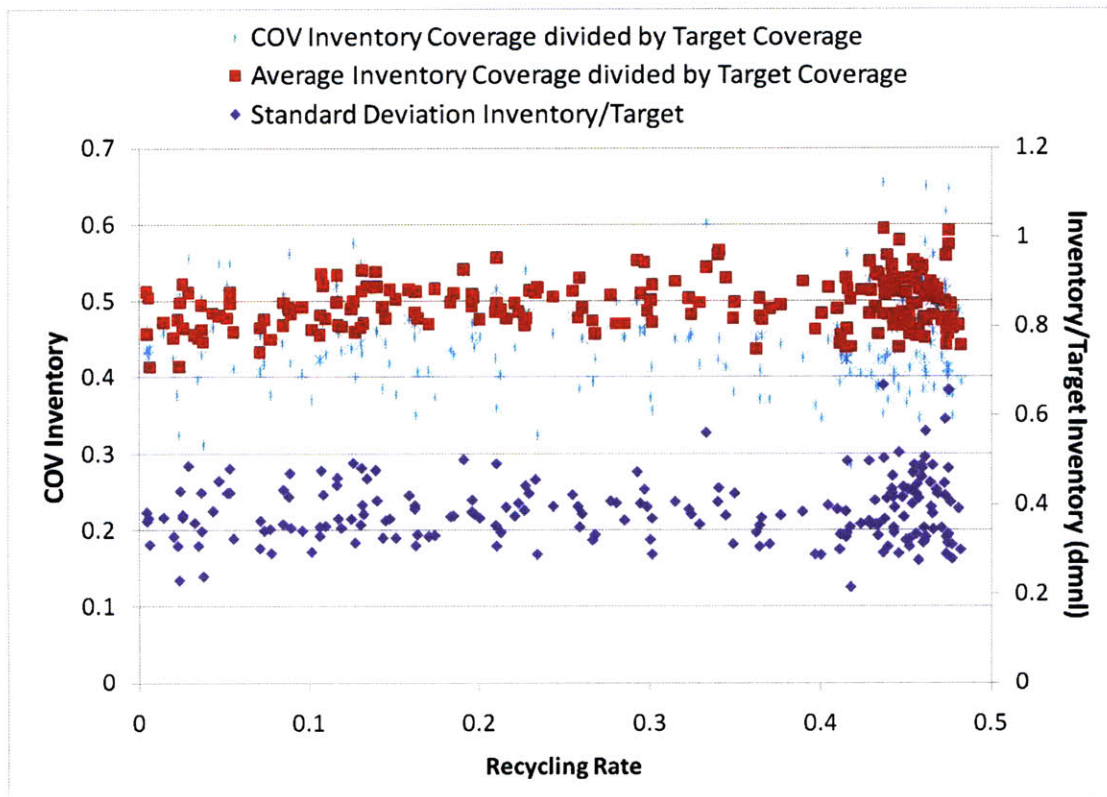
Figure 92: Inventory behavior as a function of average recycling rate for 200 simulation runs with different noise seeds and recovery rate multipliers. Average coefficient of variation (COV), average and standard deviation of Inventory coverage divided by target inventory coverage are plotted showing no trend with recycling rate.

10.4 Exploration of Effect of Delays in the Model

There are a number of types of delays in the model. There are delays that describe a physical process or aging process. Variables that describe about processing delays include Time to Process Recycling, the amount of time following collection of products that have reached end of life before they are recycled, and Time to Extract and Refine, the amount of time required from mining to extraction. Variables that describe aging include product average life, the average amount of time a consumer uses a product after purchasing before it reaches end-of-life, and life of mine, the average amount of time after commissioning a new mine before the mine is shut down or new capital needs to be invested to expand the mine.

There are also delays that describe the amount of time it takes information to be processed and for trends to be established. In System Dynamics, these are called information delays, although they are not usually thought of as delays in other contexts. For example, markets form expectations

about future price based on a smoothed average of past prices, but only for a specific period of time (i.e. they do not generally look at prices from 50-years ago when trying to determine price trends). Another example of an information delay is the time frame that primary suppliers consider for estimating future growth in demand. Primary suppliers build new mines based on expectations of future growth in demand. The expected growth rate depends on past growth rates and it takes time for primary suppliers to adjust their expectations when growth rates change, such as when a new market for platinum emerges.

Each of the delays in the model is an exogenous variable. Since model delays describe real system delays, literature information was obtained to provide an estimate of realistic values for each delay. For example, the life of an automotive catalytic converter was estimated based on the average life of a US car. Based on literature values for any given delay, a value within an estimated realistic range of values was selected for the base case model based on calibration to historical data.

The effect of the changing the model delays varies depending on the type of delay. The main types of changes to price from a change in a delay are:

- a vertical shift of the price curve,

- a change in the oscillation pattern of the price curve.

An example of each of these effects will be shown here.

Many delay variables lead to a vertical shift of the price curve. Longer delays in the production sectors (primary and secondary) lead to slower response to growing demand and therefore insufficient inventory levels as demand grows exponentially. For example, longer recovery delays in secondary production result in lower recovery rates (described in more detail in Section 7.2.2.2.2).

The prices for 5 different values of delay to commission new mining projects are compared in Figure 93. The same product demand growth settings are used in all five scenarios. The base case scenario is 5 years following mine ordering before a new mining project begins to produce platinum. As demand grows, the longer it takes between ordering a new mine and getting platinum out of the new mine, the tighter the supply and changes in demand lead to lower average inventory coverage (see Figure 94).

The vertical shift in the price curve is also observed for the scenarios with idealized demand paths (see Figure 95).
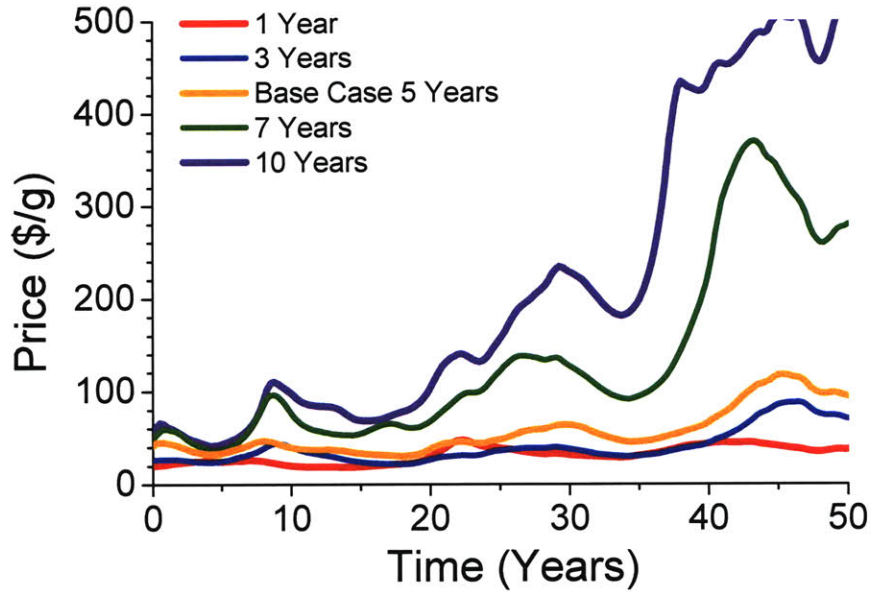
Figure 93: Comparing Price for different values of Delay to Commission New Mining Projects.
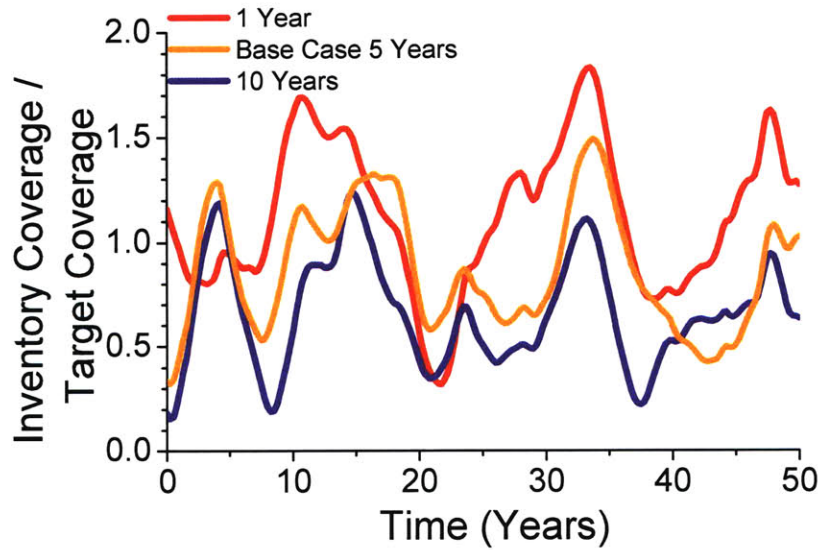
Figure 94: Comparing Inventory Coverage divided by Target Inventory Coverage for different values of Delay to Commission New Mining Projects.
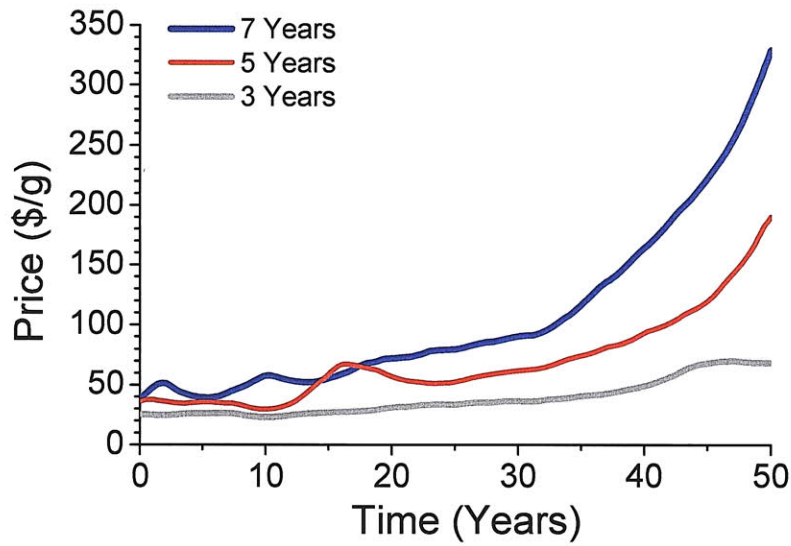
Figure 95: With idealized (smooth) demand: comparing Price for different values of Delay to Commission New Mining Projects.

In some cases, changing the delays can lead to instability in the system. In the model, shortening the information delays can lead to large fluctuations as market actors try unsuccessfully to respond to each short-term change. The variable that will be examined here represents the period of historical prices considered by markets when making their expectations for future prices. This parameter will be called the Time to Adjust Trader Expected Price. Price is plotted as a function of time for 4 different levels of time to adjust trader expected price in Figure 96.
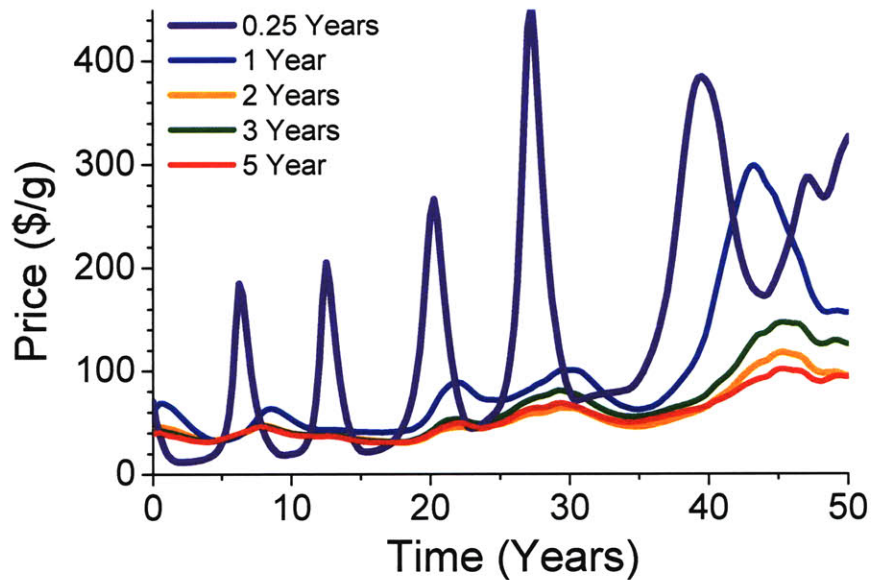
Figure 96: Comparing Price for different values of Time to Adjust Trader Expected Price.

Changes in the parameter between 2 and 5 years lead to vertical shifts in price. The pattern of the shift is not monotonic since the price for the 2 year time is lower than the price for the 3 year time but higher than the price for the 5 year time. These simulations have very similar cost and inventory change profiles.

At time 1 year, the onset of instability may be occurring, although the price for the 1 year delay can still be described as a vertical shift of price. When the time is shortened to 0.25 years, the price behaves very differently and fluctuates wildly. In a real market, if the market tries to respond to each small change in price without examining the larger context of historical prices, there can be increased fluctuations.

The behavior observed with noisy demand is reproduced with smoothed idealized demand as shown in Figure 97. Here the order of the vertical shift between 1 and 5 years is different from with noisy demand but is also not monotonic.
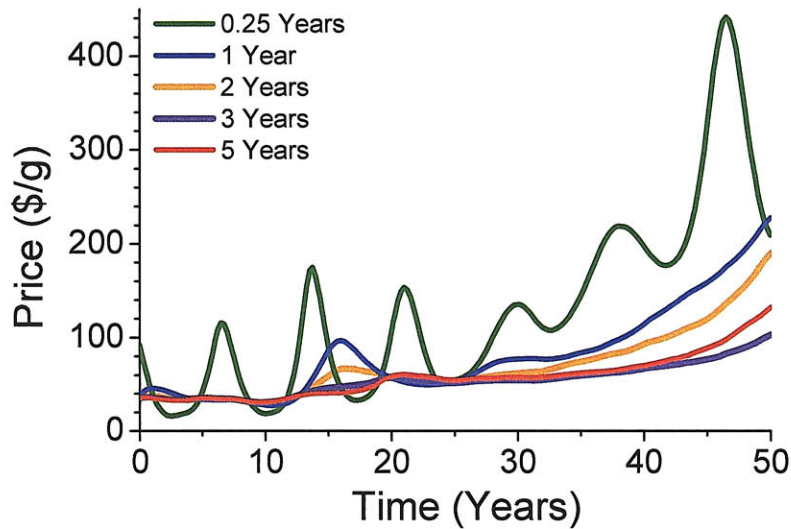
Figure 97: With idealized (smooth) demand: comparing Price for different values of Time to Adjust Trader Expected Price.

For the model analysis, the vertical shifts in price behavior are not of significant concern because they do not significantly change the overall results, except possibly in magnitude. However, onset of instability is of concern because this represents a very different dynamic behavior. For the delay variables in the model, onset of instability was not observed except when the value of the variable was changed significantly, such as with the time to adjust trader expected price. The base case was set at 2 years and instability occurs at 0.125 years, a value which is one order of magnitude smaller. As such, the model behavior is considered not very sensitive to the changes in this parameter.

10.5 Econometric Modeling Key Results

The time series data that was used for econometric modeling was:

For platinum demand data, global and North America data: Total primary demand, Automotive gross purchase, Automotive net purchases, Automotive recycling purchase, Investments, Jewellery purchase, Chemical industry purchase, Electrical industry purchase, Glass industry purchase, Petroleum industry purchase, Coin investments, total Fabrication industry purchases, Yearly change in each of the industry purchases.

Total primary supply, total secondary supply

Economic indicator data: , Excess Supply, Relative Inventory Change, Real Price, US PPI for commodities, real gdp for OECD, real gdp for US, Yearly Change in GDP for US and OECD

Data to better understand platinum demand: global and US oil distillation capacity, global and US oil supply, US Domestic Auto Sales, US imported auto sales, US total auto sales, US light truck domestic and imported sales,

Substitute material data: Real price of Gold, Yearly change in price of gold, Real price of palladium, yearly change in price of palladium, Palladium Primary Supply, Palladium Automotive purchases, Palladium total purchases, Palladium excess supply

First, multiple linear regression was run for the data. Also, multiple regression on the logarithm of the data was run. Then the data was checked for autocorrelation of the first order using Durbin-Watson method and first-order Arima models were corrected with Prais-Winsten and Cochrane-Orcutt methods.

Results were tabulated and examined. For example in the table below, total primary demand was set as the y-variable and real price of platinum and the real gdp for the OECD were set as the x-variables in the regression. The coefficients were determined using Prais-Winsten method (prais), Cochrane-Orchutt method (corc) and without any correction for autocorrelation (regular). The Durbin-Watson (DW stat) for the regular non-corrected regression is 0.47, indicating the existence of autocorrelation of first order. The t-statistic for the Prais-Winsten and Cochrane-Orchutt regressions are greater than 2 and indicate that the null hypothesis cannot be rejected at the 95% confidence interval.

Regress Y X1 X2...			prais	corc	regular
	X-variable	**Y-variable**	ttldemand	ttldemand	ttldemand
Coefficient	Price		-0.54548	-0.51249	-0.43223
	gdpOECD		8.27E-06	9.21E-06	8.73E-06
	Constant		-30.8987	-55.8232	-44.2694
T-Stat	Price		-2.12	-2.1	-1.57
	gdpOECD		11.52	13.26	25.03
	Constant		-2.04	-3.51	-5.69
	R2 adjusted		0.7733	0.8497	0.9554
	DW stat (transformed)		1.7363	1.711	0.47333
	rho		0.76154	0.7023	

Platinum individual demand sector data were regressed with price and gdp of the OECD. Results with t-stat greater than 2 following Prais-Winsten or Cochrane-Orcutt corrections are shown below.

	X-variable	corc autogross	prais autogross	corc jewellery	corc investment	corc investment
Coefficient	Price			-0.53157	0.12168	
	gdpOECD	6.91E-06	6.00E-06		-5.18E-07	-4.22E-07
	Constant	-96.91	-70.8222	83.591	13.9161	14.2943
T-Stat	Price			-2.77	1.1	
	gdpOECD	5.37	6.85		-2.94	-2.66
	Constant	-2.87	-3.53	2.71	3.79	3.75
	R2 adjusted	0.4732	0.4337	0.1767	0.2218	0.2018
	DW stat	1.7212	1.6673	1.1474	2.0938	2.015
	rho	0.87451	0.88457	0.96842	0.30076	0.32642

corc electrical	prais electrical	corc chemical	corc petroleum	corc ttlsupply
3.81E-07	2.75E-07	4.38E-07	2.70E-07	8.33E-06
-0.79198	2.0046	2.26	-2.55077	-48.723
2.65	2.45	2.26	2.45	14.67
-0.23	0.8	-0.42	-0.98	-3.75
0.1622	0.231	0.1166	0.1389	0.8736
1.59699	1.5354	2.25296	1.42448	2.2018
0.75198	0.74444	0.83649	0.72931	0.57179

10.6 Simulation Model Calibration Results

First, each individual demand sector and recycling sector was calibrated separately. For these calibrations, price was set to historical real price and primary production was set to historical primary supply. Parameters were allowed to vary within a range that was determined from literature or econometric analysis and the calibration was run using Vensim's (system dynamics software used for the model) optimization tool. Each demand sector was given a different range for each parameter. For example, the price elasticity of the automotive industry was expected to be low but it was expected to be high for the jewelry industry. The parameters that were determined through calibration of the demand sector are: price elasticity of demand, delay for demand to respond to price and product demand growth rate. The recycling parameters that were determined through calibration were sensitivity of recycling to price and product average lifetime before recycling. In the figures below, the simulated demand curves from calibration are plotted with the historical demand for auto and jewelry.
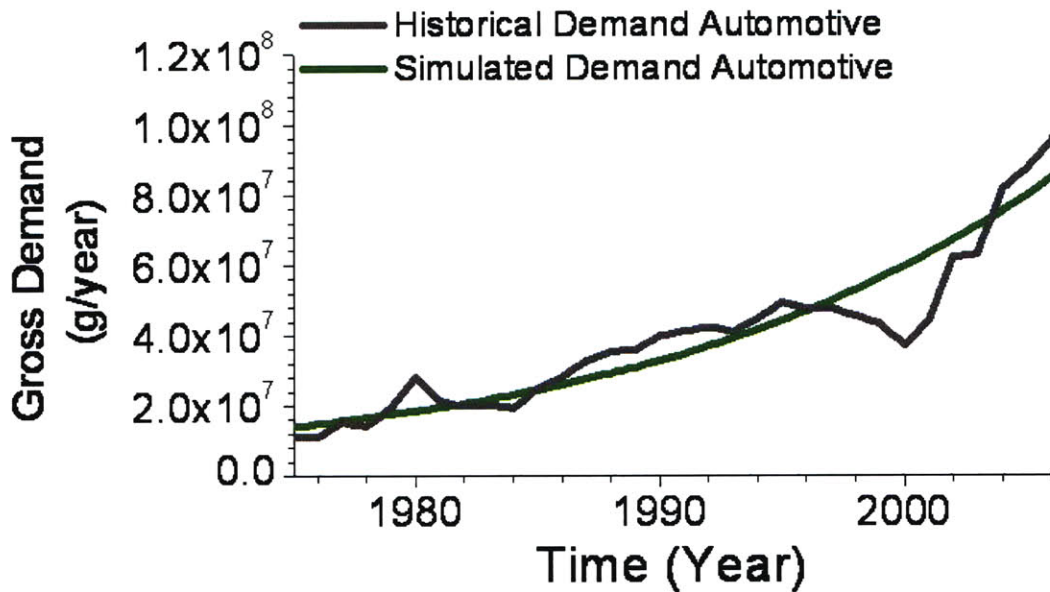
Figure 98: Comparison of simulated model automotive primary demand and historical automotive primary demand following calibration.
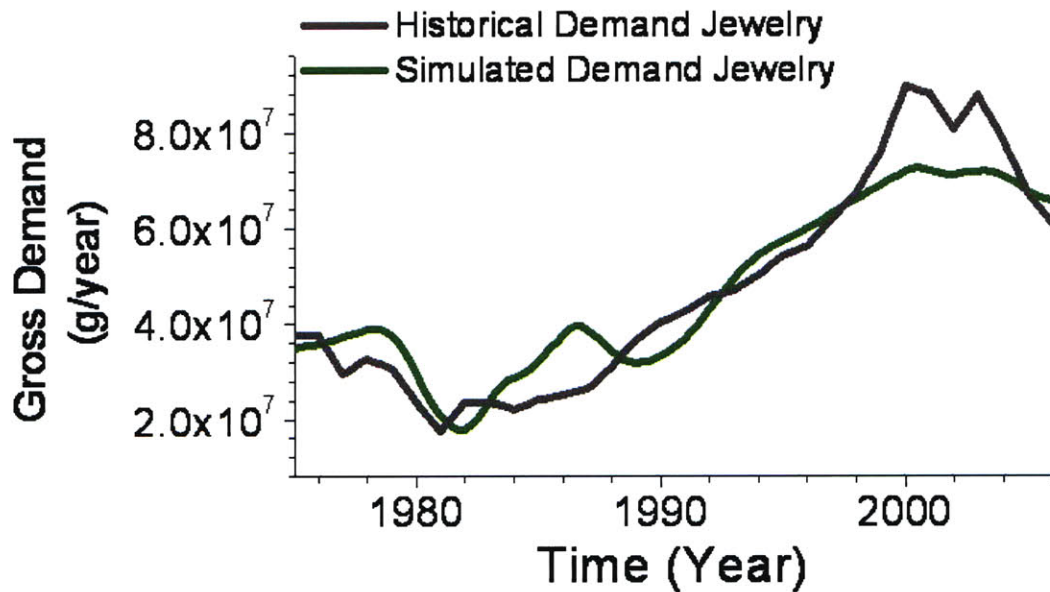
Figure 99: Comparison of simulated model jewelry primary demand and historical jewelry primary demand following calibration.

The total primary supply was calibrated to total global historical primary demand. The data was not available for each primary supply group. The price and demand were set to historical values. The parameters that were varied were the lifetime of mines, the capital cost per additional mining project, delay to commission a new mine, the effect of present cash flows on future mining project

additions, and the discount rate of capital. The simulated primary production is compared to historical primary supply below.

Graph for Total Extraction
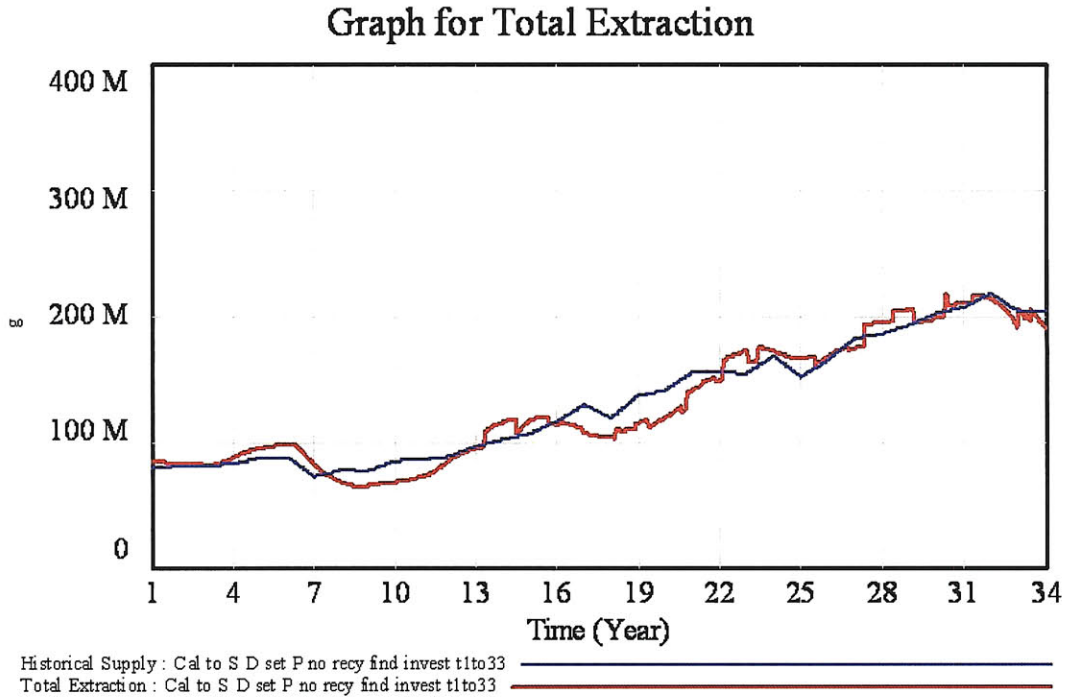
Figure 100: Comparison of simulated model primary production and historical supply following calibration.

Finally, the simulated price was calibrated to historical real price. The parameters selected from calibration of the demand and supply sectors were set in the model and based on simulated primary production and demand, the price parameters were determined. Key price parameters determined through calibration were the sensitivity of price to marginal producer costs, the sensitivity of price to available market inventory, and the time to consider changes in the market conditions and react to those changes. The simulated price from the calibration is plotted with historical real price below.

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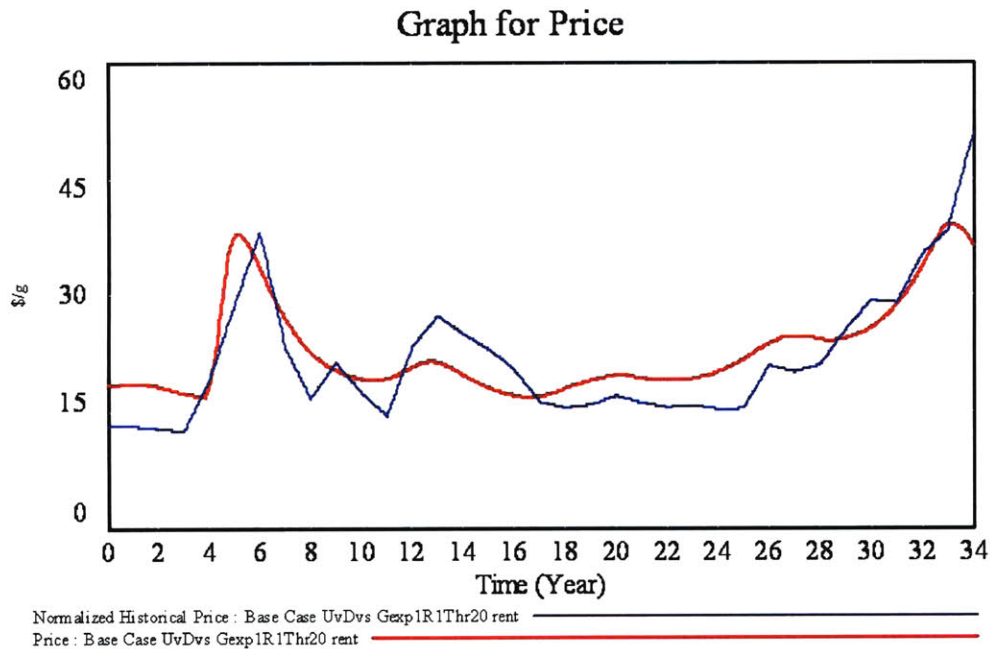
Figure 101: Comparison of simulated model price and historical price following calibration.

10.7 Additional Definitions and Terminology

10.7.1 Geological Definitions for Primary Supply

This section will quickly review some of the geological terms used when discussing non-renewable materials. The allocation of non-renewable materials in Earth's crust is determined by geological processes over tens and hundreds of thousands of years and exploration is the means of obtaining information on the resource distribution and concentration in Earth's crust and on the ocean floor. Given the time frame of geological processes, the timing of exploration will not impact the allocation of these resources. It can be assumed that materials will neither degrade nor form in a time frame of interest.

Geologists subdivide primary sources of metals by how well they have been identified and measured and by how economic and technically viable it is to extract them today (Figure 102). Exploration work can be preliminary or detailed and the level of detail involved will determine the level of certainty in the accuracy of the results of the exploration.
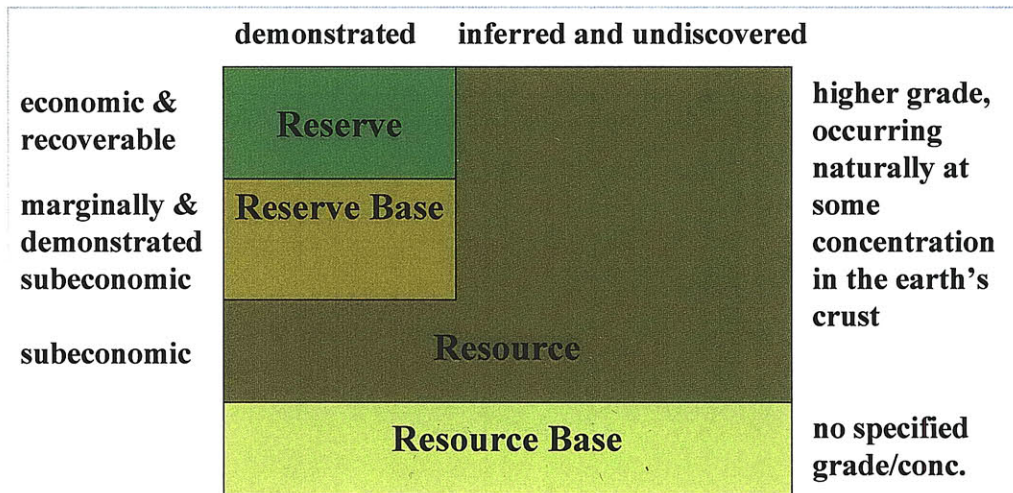
Figure 102: Definition of reserves and resources (U.S.G.S. 2009).

The materials that are mined today form part of the global *reserves*. The reserves incorporate all ore bodies at a given *ore grade* and location that make it economically and technically viable to extract. The ore grade is the concentration of the desired material in the ore body that is being extracted and is generally given as a percent by weight. The size of global reserves changes as prices change, as new ore bodies are discovered and as minerals are extracted. The size of global reserves is relatively well identified, although there is some statistical uncertainty in its measurement.

The *reserve base* incorporates reserves, but also includes ore for which extraction is marginally economic and demonstrated sub-economic with present prices and technologies. Sub-economic deposits may become marginally economic with improved technologies.

In geologic terms, the word "*resource*" has a very specific meaning. The *resources* include the reserve base and the rest of the sub-economic deposits as well as estimates of the quantity of material that have not yet been properly measured. There is much more uncertainty in the size of the resources than with the size of the reserves.

The largest number that defines primary material sources is the estimated size of the *resource base*, which includes all material content in the earth's crust (to a certain depth) and oceans, at all concentrations. The size of the resource base can be several orders of magnitude greater than the size of the resource for a given metal, but is generally not a number that is used in analyses of depletion.

As stated above, the materials that are mined today form part of the global *reserves*. Through extraction, reserves are depleted. In generally, depletion of reserves results in both a decrease in the amount of mineral of interest present in the ore body and a decrease in the average ore grade of the material found in the ore body. Extraction is followed by transformation of the resource (material processing) to a form that can be used by consumers and transportation of the resource to the location where it can be used by consumers.

10.7.2 Secondary Supply: Recycling

When products reach end-of-life, they may be disposed of or collected for recycling. End-of-life products effectively become a resource. *Secondary resources*, a term used for all recycled materials including industrial scrap (*new scrap*) and post-consumer scrap (*old scrap*), can be categorized so that economical ones can be identified and exploited through recycling. The concentration and distribution of the material that form the secondary resources depends on where the products are disposed, how many products reach end-of-life and the amount of material contained in the product. In general, much of the world's secondary resources are found in industrialized countries, which account for most of the world consumption. However, waste is also exported to developing countries so secondary resources are not always located where they are produced (Basel Action Network 2006).

The *recycling rate* will here be defined as the amount of secondary material used as a fraction of the total amount of material used. The term recyclers will be used interchangeably with the term secondary producer. The *recovery rate* will be defined as the amount of secondary material collected and recycled as a fraction of the amount of total material in being disposed of and recycled, landfilled or otherwise dispersed without recovering. A high recovery rate means that very little end-of-life products are reaching landfills. The recovery rate has also been called a *recycling efficiency rate* (Ruhrberg 2006) or a *dynamic recycling rate (Hagelüken, Buchert et al. 2006)* in literature. An efficient recycling system is one in which the recovery rate is high which means that most of the material in products reaching end-of-life are being reused. *Maximum recycling efficiency* is the expected recovery rate if collection of end-of-life products is 100% and losses in usage (due to erosion for example) and losses in the recycling process (smelting of secondary platinum results in losses, for example) are taken into account. High recovery rate could still result in low recycling rate if the product lifetime is long and demand is growing rapidly.

10.7.3 Risk

The decisions that are made by manufacturers that make daily decisions with limited funds in the context of uncertainty involve risk. Risk is a term used in many contexts, including business risk, investment risk and economic risk.

One way to define risk is as combination of uncertainty and damage that may be mitigated by taking appropriate safeguards (Kaplan and Garrick 1981). More specifically, risk can be defined as a curve satisfying the following equation:

$$\text{Risk} = \left\{ \left\langle s_i, p_i, x_i \right\rangle \right\}$$

where, s_i is a scenario or an outcome, p_i is the probability of that scenario of occurring and x_i is the measure of the damage or the consequence of that scenario should it occur. Risk, would therefore be represented as a curve of the cumulative probability of damage occurring plotted as a function of the measure of damage.

An excursion of the price of a given material for a period of time is generally considered an exogenous occurrence from the perspective of a manufacturer. However, risk of scarcity is not, since the firm can control the risk scenarios and the magnitude of scarcity consequences.

Risk will not be quantified or evaluated separately in this work. Instead, the consequences or outcomes of increasing scarcity will be examined. In the context of this work, if there is a possible undesired outcome, then there is a possible risk for manufacturers.

References

Adelman, K. L. (1978). "Zaire's year of crisis." African Affairs 77(306): 36-44.

Adelman, M. A., G. C. Watkins, et al. (2003). Oil and natural gas reserve prices, 1982-2002 : implications for depletion and investment cost. [Cambridge, Mass.], Massachusetts Institute of Technology, Center for Energy and Environmental Policy Research.

Alonso, E., F. Field, et al. (2007) "Materials Availability and the Supply Chain: Risks, Effects, and Responses."

Alonso, E., F. R. Field, et al. (2008). A Case Study of the Availability of Platinum Group Metals for Electronics Manufacturers. International Symposium on Electronics and the Environment San Francisco, IEEE.

Alonso, E., F. R. Field, et al. (2008). A dynamic simulation model for examining the implications of limited materials availability: The case of platinum. International Precious Metals Institute 32nd Annual Conference. Phoenix, AZ, IPMI.

Alonso, E., F. R. Field, et al. (2009). Impact of recycling on materials availability: a case study of platinum. TMS 2009 Annual Meeting and Exhibition. San Francisco, CA.

Alonso, E., J. Gregory, et al. (2007). "Material Availability and the Supply Chain: Risks, Effects, and Responses." Environmental Science & Technology 41(19): 6649-6656.

Angerhofer, B. J. and M. C. Angelides (2000). System dynamics modelling in supply chain management: research review. Proceedings of the 32nd conference on Winter simulation, Orlando, FL USA, Society for Computer Simulation International.

Anglo Platinum. (2007). "Company Website." Retrieved April 2007, from http://www.angloplatinum.com/.

Ayres, R. U. (1997). "Metals recycling: economic and environmental implications." Resources, Conservation and Recycling 21(3): 145-173.

Ayres, R. U., L. Ayres, et al. (2003). The life cycle of copper, its co-products and byproducts. Dordrecht ; Boston, Kluwer Academic.

Ayres, R. U. and A. V. Kneese (1969). "Production, Consumption, and Externalities." American Economic Review 59(3): 282.

Barnett, H. J. and C. Morse (1963). Scarcity and growth; the economics of natural resource availability. Washington, Resources for the Future, Johns Hopkins Press.

Basel Action Network. (2006). "Official Website." Retrieved July 2006, 2006, from www.ban.org.

Blechman, B. M. and D. Sloss (1985). National security and strategic minerals : an analysis of U.S. dependence on foreign sources of cobalt. Boulder, Westview Press.

Blomberg, J. and P. Söderholm (2009). "The economics of secondary aluminium supply: An econometric analysis based on European data." Resources, Conservation and Recycling 53(8): 455-463.

Brunetti, C. and C. L. Gilbert (1995). "Metals price volatility, 1972-1995." Resources Policy 21(4): 237-254.

Bureau of Labor Statistics. (2008). "Producer Price Indexes." Retrieved May 30, 2008, from http://data.bls.gov/cgi-bin/surveymost?wp.

Campbell, G. A. (1989). "The response of US copper companies to changing market conditions." Resources Policy 15(4): 321-337.

Cawthorn, R. G. (1999). "The platinum and palladium resources of the Bushveld Complex." SOUTH AFRICAN JOURNAL OF SCIENCE 95(11/12): 481-489.

Chapman, P. F. and F. Roberts (1983). Metal resources and energy. UK, Butterworths.

Chertow, M. R. (2007). ""Uncovering" Industrial Symbiosis." Journal of Industrial Ecology 11(1): 11-30.

Christian, J. M. (2006). Commodities rising : the reality behind the hype and how to really profit in the commodities market. Hoboken, N.J., Wiley.

Cleveland, C. J. (1993). "An Exploration of alternative measures of natural-resource scarcity - the case of petroleum resources in the United-States." Ecological Economics 7(2): 123-157.

Cleveland, C. J. and R. K. Kaufmann (1997). "Natural gas in the U.S.: How far can technology stretch the resource base?" Energy Journal 18(2): 89-108.

Cleveland, C. J. and M. Ruth (1997). "When, where, and by how much do biophysical limits constrain the economic process? A survey of Nicholas Georgescu-Roegen's contribution to ecological economics." Ecological Economics 22(3): 203-223.

Codelco Chile. (2007). "World presence." Retrieved March 2007, from http://www.codelco.com/english/la_corporacion/fr_presencia.html.

Copper Development Association. (2006). Official Website Retrieved February 2006, 2006, from www.copper.org.

CPM Group (2007). Platinum Group Metals Yearbook. Hoboken, NJ, John Wiley & Sons.

Dasgupta, P. and G. Heal (1974). "Optimal Depletion of Exhaustible Resources." Review of Economic Studies: 3-28.

Davis, S. C. and S. W. Diegel (2006). Transportation Energy Data Book. Oak Ridge, Tennessee, Oak Ridge National Laboratory.

Department of Energy. (2007). "EIA.DOE Annual Energy Outlook." Retrieved April 2007, from http://www.eia.doe.gov/oiaf/aeo/supplement/index.html.

Ehrenfeld, J. and N. Gertler (1997). "Industrial Ecology in Practice." J. Industrial Ecology 1(1): 67-79.

Ernst, W. G. (2000). Earth systems: processes and issues. Cambridge; New York, Cambridge University Press.

Esty, D. C. and M. E. Porter (1998). "Industrial Ecology and Competitiveness: Strategic Implications for the Firm." Journal of Industrial Ecology 2(1): 35-43.

Frosch, R. A. and N. E. Gallopoulos (1989). "Strategies for Manufacturing." Scientific American 261(3): 144.

Gaustad, G., P. Li, et al. (2007). "Modeling methods for managing raw material compositional uncertainty in alloy production." Resources, Conservation and Recycling 52(2): 180-207.

Gerard, D. and L. B. Lave (2005). "Implementing technology-forcing policies: The 1970 Clean Air Act Amendments and the introduction of advanced automotive emissions controls in the United States." Technological Forecasting and Social Change 72(7): 761-778.

Gertler, N. (1995). Industrial Ecosystems: Developing Sustainable Industrial Structures. Technology and Policy Program and the Department of Civil and Environmental Engineering. Cambridge, MA, Massachusetts Institute of Technology. **M.S. Technology and Policy and M.S. Civil and Environmental Engineering:** 142.

Gibson-Jarvie, R. (1976). The London Metal Exchange: a commodity market. Cambridge, Woodhead-Faulkner [for] Metallgesellschaft AG.

Gordon, R. B. (1987). Toward a new Iron Age? : quantitative modeling of resource exhaustion. Cambridge, Mass., Harvard University Press.

Gordon, R. B., M. Bertram, et al. (2006). "Metal stocks and sustainability." Proceedings of the National Academy of Sciences of the United States of America 103(5): 1209-1214.

Graedel, T. E., D. Van Beers, et al. (2004). "Multilevel cycle of anthropogenic copper." Environmental Science & Technology 38(4): 1242-1252.

Hagelüken, C. (2005). Materials Flow of Platinum Group Metals, Umicore, Oko Institut, GFMS: 264.

Hagelüken, C., M. Buchert, et al. (2006). Materials Flow of Platinum Group Metals in Germany. 13th CIRP International Conference on Life Cycle Engineering.

Hayenga, M. L. (1979). "Risk Management in Imperfect Markets: Commodity Procurement Strategy in the Food Manufacturing Sector." American Journal of Agricultural Economics **61**(2): 351-357.

Herfindahl, O. C. (1950). Concentration in the steel industry. Economics, Columbia University. **Ph.D. dissertation**.

Hirschman, A. O. (1945). National power and the structure of foreign trade. Berkeley, University of California Press.

Hotelling, H. (1931). "The Economics of Exhaustible Resources." The Journal of Political Economy **39**(2): 137-175.

Hubbert, M. K. (1962). Energy resources. Washington, National Academy of Sciences-NRC.

Impala Platinum. (2007). "Company Website." Retrieved April 2007, from http://www.implats.co.za/business/impala.asp.

Jevons, W. S. (1866). The Coal question: an inquiry concerning the progress of the nation, and the probable exhaustion of our coal mines, Macmillan and Co. **London**.

Johnson Matthey Precious Metals Marketing. (2008). "Platinum Today." Retrieved March 2008, from http://www.platinum.matthey.com/.

Jolly, J. L. (2005) "The U.S. copper-base scrap industry and its by-products - 2004: an overview." 78.

Kaplan, S. and B. J. Garrick (1981). "On the quantitative definition of risk." Risk Analysis **1**(1): 11.

Kitco Inc. (2009). "Charts and Data." Retrieved September 2009, from http://www.kitco.com/charts/.

Kleindorfer, P. R. and G. H. Saad (2005). "Managing Disruption Risks in Supply Chains." Production and Operations Management **14**(1): 53-68.

Krautkraemer, J. A. (1998). "Nonrenewable Resource Scarcity." Journal of Economic Literature **36**(4): 2065-2107.

Labys, W. C., J. B. Lesourd, et al. (1998). "The existence of metal price cycles." Resources Policy **24**(3): 147-155.

Lee, H. L., V. Padmanabhan, et al. (1997). "The Bullwhip effect in supply chains." Sloan Management Review **38**(3): 93.

Lensing, R. P. and Massachusetts Institute of Technology. Engineering Systems Division. (2003). Historical events and supply chain disruption : chemical, biological, radiological and cyber events: 113.

Lifset, R. J., R. B. Gordon, et al. (2002). "Where has all the copper gone: The stocks and flows project, part 1." Jom-Journal of the Minerals Metals & Materials Society **54**(10): 21-26.

Lonmin. (2007). "Company Website." Retrieved April 2007, from http://www.lonmin.com/main.aspx?pageId=62.

Malthus, T. R. (1798). An Essay on the principle of population, as it affects the future improvement of society with remarks on the speculations of Mr. Godwin, M. Condorcet and other writers. London, J. Johnson.

Matos, G. and L. Wagner (1998). "Consumption of materials in the US, 1900-1995." Annual Review of Energy and the Environment **23**(1): 107-122.

Mazda Press Release (October 1, 2007). Mazda Develops a World-First Catalyst Material Structure for Autos Using Single Nanotechnology.

McClements, J. and R. Cranswick (2001). "World mining overview." Engineering & Mining Journal **202**(11): 28-37.

McIsaac, G. (2008). Strategic Design of an Underground Mine under Conditions of Metal Price Uncertainty. Department of Mining Engineering. Kingston, Ontario, Canada, Queen's University. **PhD**: 262.

Meadows, D. H., D. L. Meadows, et al. (1972). Limits to growth; a report for the Club of Rome's project on the predicament of mankind. New York, Universe Books.

Metals Economics Group (2006). World Exploration Trends. PDAC 2006 International Convention, Prospectors & Developers Association of Canada.

Mikesell, R. F. (1995). "Limits to growth: a reappraisal." Resources Policy 21(2): 127-131.

Mikesell, R. F. and J. W. Whitney (1987). The world mining industry: investment strategy and public policy. Boston, Allen & Unwin.

MMSD (2002) "Breaking new ground: the report of the Mining, Minerals and Sustainable Development project." Mining, Minerals and Sustainable Development.

Nelles, J. and C. Ruegemer (2009). "Managing Commodity Volatility." Inside Supply Management 20(10): 26.

Norilsk Nickel. (2007). "Company Website." Retrieved April 2007, from http://www.nornik.ru/en/.

Northam Platinum Limited. (2007, 2007). "Company Website." Retrieved January 2008, from http://www.northam.co.za/.

NRCan. (1886-2004). "Minerals and metals sector." Retrieved March 2006, from Data gathered from Canadian Minerals Yearbook and other publications found online at http://www.nrcan.gc.ca/mms/topi-suje/met_e.htm.

Odorn, L. C. T. P. (1993). "Shaba II: The French and Belgian intervention in Zaire in 1978." Retrieved May 17, 2006, from http://www-cgsc.army.mil/carl/resources/csi/odom2/odom2.asp.

Oxford University Press. (2006). "The Oxford English Dictionary (OED)." 2nd., 2007, from http://dictionary.oed.com/entrance.dtl, http://libraries.mit.edu/get/oed

Paquette, J. R. (2006). The Supply Chain Response to Environmental Pressures. Department of Civil and Environmental Engineering, Technology and Policy. Cambridge, MA, Massachusetts Institute of Technology. **Master of Science:** 135.

Pickett, C. B. (2003). Strategies for maximizing supply chain resilience : learning from the past to prepare for the future. Engineering Systems Division. Cambridge, MA, MIT. **Master of Engineering in Logistics:** 126 p.

Pindyck, R. S. (1978). "The Optimal exploration and production of nonrenewable resources." Journal of Political Economy 86(5): 841-861.

Pindyck, R. S. (1994). "Inventories and the Short-Run Dynamics of Commodity Prices." The Rand Journal of Economics 25(1): 141-159.

Ricardo, D. (1821, first published 1817). On the principles of political economy and taxation. London, John Murray.

Rice, J. B., Jr. and F. Caniato (2003). "Building a secure and resilient supply network." Supply Chain Management Review **September/October:** 22-30.

Ruhrberg, M. (2006). "Assessing the recycling efficiency of copper from end-of-life products in Western Europe." Resources, Conservation and Recycling 48(2): 141-165.

Schwartz, E. S. (1997). "The stochastic behavior of commodity prices: Implications for valuation and hedging." Journal of Finance 52(3): 923-973.

Secretariat of the Basel Convention. (2006). "About Basel Convention." Retrieved Aug. 11, 2006, from www.basel.int/about.html.

Sheffi, Y. (2001). "Supply chain management under the threat of international terrorism." International Journal of Logistics Management 12(2): 1.

Simchi-Levi, D., L. Snyder, et al. (2002). "Strategies for uncertain times." Supply Chain Management Review **January/February:** 11-12.

Simpson, R. D., M. A. Toman, et al. (2005). Scarcity and growth revisited : natural resources and the environment in the new millennium. Washington, DC, Resources for the Future.

Slade, M. E. (1980). "An econometric model of the U.S. secondary copper industry: Recycling versus disposal." Journal of Environmental Economics and Management 7(2): 123-141.

Slade, M. E. (1982). "Trends in natural-resource commodity prices: An analysis of the time domain." Journal of Environmental Economics and Management 9(2): 122-137.

Slade, M. E. (1985). "Noninformative trends in natural resource commodity prices: U-shaped price paths exonerated." Journal of Environmental Economics and Management 12(2): 181-192.

Slade, M. E. (1992). Do markets underprice natural - resource commodities? Washington, DC, USA, The World Bank.

Solow, R. M. (1974). "Intergenerational Equity and Exhaustible Resources." Review of Economic Studies: 29-45.

Stata Corporation. (2003). Getting started with Stata for Windows. College Station, Tex., Stata Press.

Steen, B. and G. Borg (2002). "An estimation of the cost of sustainable production of metal concentrates from the earth's crust." Ecological Economics 42(3): 401-413.

Sterman, J. (2000). Business dynamics : systems thinking and modeling for a complex world. Boston, Irwin/McGraw-Hill.

Sterman, J. D. and G. P. Richardson (1985). "An Experiment to Evaluate Methods for Estimating Fossil Fuel Resources." Journal of Forcasting 4(2): 197-226.

Stiglitz, J. (1974). "Growth with Exhaustible Natural Resources - Efficient and Optimal Growth Paths." Review of Economic Studies: 123-137.

Stillwater Mining Company. (2007, 2007). "Company Website." Retrieved February 2008, from http://www.stillwatermining.com/index.html.

Thomson Reuters (2009). Datastream database. [Online], Datastream International Ltd.

TIAX and E. J. Carlson. (2003). "Platinum Availability and Economics for PEMFC Commercialization " Retrieved December 2003, from http://www.cleanfuelcellenergy.com/tiax_platinum.pdf.

Tilton, J. and R. Gordon (2008). "Mineral economics: Overview of a discipline." Resources Policy.

Tilton, J. E. (1977). The future of nonfuel minerals. Washington, Brookings Institution.

Tilton, J. E. (2003). On borrowed time? : assessing the threat of mineral depletion. Washington, Resources for the Future.

Tilton, J. E., R. G. Eggert, et al. (1988). World mineral exploration: trends and economic issues. Washington, D.C. [Baltimore, Md.], Resources for the Future; Distributed worldwide by Johns Hopkins University Press.

Tilton, J. E. and H. H. Landsberg (1997) "Innovation, productivity growth, and the survival of the U.S. copper industry." Understanding Productivity Change in Natural Resource Industries, 32.

U.N.S.D. (2006). "National accounts main aggregates database." Retrieved June 5, 2006, from http://unstats.un.org/unsd/snaama/Introduction.asp.

U.S. Bureau of Mines, U. S. G. S. (1980). Principles of a Resource/Reserve Classification for Minerals. **Circular 831:** iii, 5 p. ; 26 cm.

U.S. DoJ and Federal Trade Commission. (1992, Revised 1997). Horizontal merger guidelines.

U.S. Geological Survey (1932-2006). Minerals Information, U.S. Department of the Interior.

U.S.G.S. (1932-2006). Minerals information, U.S. Department of the Interior.

U.S.G.S. (1998). Metal Prices in the United States through 1998. ed. Janet Sachs and U. S. D. o. t. Interior.

U.S.G.S. (2005). "Minerals commodity summaries." Retrieved December 2006, from Data gathered from http://minerals.usgs.gov/minerals/pubs/commodity/.

U.S.G.S. (2007). "Minerals commodity summaries." Retrieved January 2008, from Data gathered from http://minerals.usgs.gov/minerals/pubs/commodity/.

U.S.G.S. (2009). "Minerals information." Retrieved April 2009, from Data gathered from Mineral Yearbook and Mineral Commodity Summary found online at http://minerals.usgs.gov/minerals/.

United States. Federal Highway Administration. Office of Highway Policy Information. (2000). "A guide to reporting highway statistics procedures for the compilation, analysis, and reporting of state motor-fuel, motor-vehicle, driver-license and motor-carrier data [and]

highway finance data of state and local governments." from
http://purl.access.gpo.gov/GPO/LPS4686 Adobe Acrobat Reader required.

University of Pennsylvania. (2004). "Penn world table." Retrieved June 5, 2006, from
http://pwt.econ.upenn.edu/php_site/pwt61_form.php.

Urbance, R. J. (2001). The Impact of Increased Automotive Interest on the World Magnesium
Market: Dynamic Market Simulation. Department of Materials Science and Engineering.
Cambridge, MA, Massachusetts Institute of Technology. **Master of Science:** 143.

Urbance, R. J., F. Field, et al. (2002). "Economics: Market Model Simulation: The Impact of
Increased Automotive Interest in Magnesium." JOM-Journal of the Minerals Metals &
Materials Society 54(8): 25-33.

Ward's Communications Inc. (2007). Ward's world motor vehicle data. Southfield, MI, Ward's
Communications: v.

Wood, J. H., G. R. Long, et al. (2004). "Long-term world oil supply scenarios." Retrieved August
4, 2006, from
http://www.eia.doe.gov/pub/oil_gas/petroleum/feature_articles/2004/worldoilsupply/oilsup
ply04.html.

World Commission on Environment and Development. (1987). Our common future. Oxford ; New
York, Oxford University Press.