The role of mission-critical resources in mitigating climate change – a causal pathway analysis of platinum's role using system dynamics

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Abstract

As the science of climate change has gathered more momentum and increased its precision in the past decade, the discussion surrounding the various entailed costs has also intensified. While the current generation of cost models can estimate across many sectors, industries, and actors, they do not take into account that there are certain components that are mission-critical in ensuring the success of climate change mitigation. This thesis employs what is called a causal pathway analysis to look at platinum's mission-critical role in current and future climate change mitigation efforts. Platinum is the primary component in a catalytic converter, which constitutes the bulk of the climate change mitigation work that is done within the ground transportation sector. What the causal pathway analysis consists of is a quantitative and qualitative analysis of the various dynamic effects and feedback mechanisms in action – something that many of the top-down and bottom-up models that constitute the bulk of the current methodology do not account for. A system dynamics model for platinum markets was used to simulate future platinum prices and the direct and indirect implications of a simulated price-rise were then discussed from an economic, political, geographic, social and ethical, as well as environmental perspective. This discussion was then extrapolated into two policy lessons, namely the inability to trust market mechanisms in the short run in pricing a strategically important resource, as well as the need to accelerate and deepen the level of research and development for substitute technologies.

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Abbreviations

AR [1-5]	Assessment Reports of the Intergovernmental Panel on Climate Change [the First to the Fifth Publication]
CMP	Meeting of the Parties (to the 1997 Kyoto Protocol)
CO_2	Carbon dioxide
COP	Conference of Parties (to the 1992 United Nations Framework Convention on Climate Change)
Garnaut Review	Garnaut Climate Change Review (by Professor Ross Garnaut)
GHG	Greenhouse Gas
GWP	Global Warming Potential
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
NO_x	Nitrous oxides
PEM	Proton Exchange Membrane
PGM	Platinum Group Metal
ppmv	parts per million volume
Stern Review	Stern Review on the Economics of Climate Change (by Sir Nicholas Stern)
U.N.	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organisation

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1 Introduction

"Climate change is a result of the greatest market failure the world has seen. The evidence on the seriousness of the risks from inaction or delayed action is now overwhelming. The problem of climate change involves a fundamental failure of markets: those who damage others by emitting greenhouse gases generally do not pay."

- Nicholas Herbert Stern, Baron Stern of Brentford,
author of the influential Stern Review

Echoing the words found in the Stern Review, climate change is arguably the most important and toughest global environmental problem facing mankind. Luckily, we have for the most part moved beyond questioning the scientific basis of climate change, and have rather started to calculate the socio-economic costs of an eventual mitigation and adaptation plan. At the heart of addressing the question of how mankind is supposed to mitigate and adapt to climate change lie a few fundamental economic concepts: the questions of externalities, discount rates, and the treatment of common and public goods[1]. These form much of the theoretical backbone when constructing economic models to simulate the socio-economic costs of climate change. While the economic concepts are important to consider when modelling on the aggregated level, alternative methods would allow for the understanding of the finer dynamics and feedback mechanisms involved when considering appropriate action for climate change mitigation.

This thesis will seek to expand on some alternative modelling concepts by highlighting the need to address certain operational issues within climate change mitigation. The approach that is taken here is to identify a specific resource – platinum – within the ground transportation sector that is mission-critical with regards to mitigating climate change. By utilising a system of analysis termed "causal pathway analysis", the role of platinum in climate change mitigation within the ground transportation sector will be analysed both quantitatively using system dynamics and qualitative by considering the associated corollaries. This is in stark contrast to much of the modelling and analytical work that has been done on the socio-economic effects of climate change, and serves as a reminder that

[1] There are obviously a plethora of other economic concepts as well as unrelated economics concepts that can be invoked when discussing climate change.

top-down models, while good at showcasing aggregated effects, might miss out on specific, crucial aspects of the physical world.

Much of the economic cost modelling that has been conducted so far with regards to climate change mitigation is what is called "top-down", which is in juxtaposition to "bottom-up" models (Metz, Davidson, Bosch, Dave, & Meyer, 2007). In the words of the IPCC: *"Top-down models evaluate the system from aggregate economic variables, whereas bottom-up models consider technological options or project-specific climate change mitigation policies."* (Hourcade, Richels, Robinson, Chandler, & Davidson, 1996). The top-down models tend to be general equilibrium models, whereas the bottom-up models can, for example, take the form of an agent-based modelling approach, or some other type of micro-level sectoral approach (Stern, 2007; Garnaut, 2011; Hourcade, Richels, Robinson, Chandler, & Davidson, 1996). As with any model, some phenomenon will be well explained, and others less so; some concepts and events will be integral, others will be ignored. This thesis seeks to address the issue of oversight in using either of these cost estimating methodologies when considering mission-critical components.

Mission-critical components in this context cover natural resources that have specific properties that are desirable in particular climate change mitigation applications. They furthermore tend to have a unique set of supply, demand, and price characteristics that cause the markets to not always behave optimally or predictably. For the study at hand, the focus will be on platinum's role in the catalytic converter, as this forms the backbone of climate change mitigation in the ground transportation sector. Beyond platinum, uranium and many of the rare earth elements would also fall into the category of being mission-critical; the former due to its role in providing carbon-free nuclear energy, and the latter in their many roles in high-tech appliances that further the low-carbon energy mix such as wind turbines (Alonso, et al., 2012). While there is no strict definition of a mission-critical resource, in this study any resource that is deemed to be a bottleneck in terms of its supply, demand, and price characteristics and is a critical input in climate change mitigation technologies and applications will be deemed mission-critical.

What is meant by the proposed causal pathway analysis is to not only analyse quantitatively some of the internal dynamics, but to go beyond and consider also qualitatively the knock-on and dynamic effects, as well as the feedback mechanisms of the system. It is the dynamic consideration of the interdependencies and interplay that is in stark contrast to most of the top-down and bottom-up models. While many top-down

models are designed to capture effects throughout the system, and as such analyse how changes in one sector can have knock-on effects in other sectors, they are usually not truly dynamic in the sense of starting from an initial point and building on the dynamics simultaneously and interdependently throughout the system.

To analyse the platinum markets quantitatively from a systems perspective entails the use of system dynamics. System dynamics is an approach to understanding how complex systems behave over time by solving a set of coupled ordinary differential equations. A system dynamics model will be used to assess the platinum price structure, as well as to simulate platinum prices. These price simulations will then be considered beyond the internal dynamics of the system dynamics model and applied to various facets of society.

The importance of using a methodology such as causal pathway analysis comes from the fact that not only would it consider in greater depth, both quantitatively and qualitatively, the role of what are deemed mission-critical resources, but also further the discussion on climate change policy and what the focus should be on. While this methodology could never achieve the breadth that the models in the current literature provide, it is intended to inspire other lines of thinking, and to stimulate discussions about the dynamics at play when planning the needed steps in climate change mitigation.

This paper is organized as follows: The following section will present the relevant environmental, economic, and technical aspects that will be referred to throughout this thesis. Section 3 will discuss the current literature on the models that are used to analyse the economics costs of climate change, as well as climate change on a policy level. Section 4 covers the methodology. Section 5 will provide the quantitative model of the causal pathway analysis, while Section 6 will cover the qualitative corollaries. Section 7 will explore policy recommendations. The penultimate Section (8) will consider the scope for future studies. Finally, the concluding remarks are offered in Section 9.

2 Background Knowledge

"As human beings, we are vulnerable to confusing the unprecedented with the improbable. In our everyday experience, if something has never happened before, we are generally safe in assuming it is not going to happen in the future, but the exceptions can kill you and climate change is one of those exceptions."

- Al Gore, former Vice-President of the United States of America, and Nobel Peace Prize winner

Given the inevitable interdisciplinary nature of this thesis, the following subsections will briefly go through many of the environmental, economic, and technical aspects related to the economic costs of climate change. This will allow the reader to gain a better grasp of the complexities in dealing with the economic costs of climate change mitigation, and with the causal pathway analysis that is performed.

2.1 A succinct briefing on climate change

Anthropogenic climate change is perhaps the most pressing environmental issue of our time. It is not a singular issue, but rather a compounded issue with many facets. What these facets have in common is that they are all contributing to increasing the amount of GHGs in the atmosphere. Furthermore, these facets share the fact that they are due to *homo faber*, as climate change concerns itself with the increased presence of anthropogenic atmospheric gases that are able to either absorb radiation, or through some chemical process able to induce a higher rate of radiation absorption (Forster, et al., 2007; UNFCCC, 1992).

The primary example of the type of aspects of manmade climate change that will be used in this thesis is that of exhaust gases emanating from the internal combustion engine. The main exhaust gas that is released from a vehicle is CO_2, which contributes to global climate change by absorbing radiation. There are, however, also other gases released that are able to absorb radiation when burning fossil fuels in an internal combustion engine, namely NO_x and CO. The catalytic converter is the main component in a vehicle that combats climate change by transforming the NO_x and CO emissions, which have much higher GWPs, into gases with lower GWPs.

The modern aim to curb the effects of GHGs in order to combat the effects of climate change was established with the advent of the UNFCCC. The UNFCCC is an international environmental treaty that was negotiated at the U.N Conference on Environment and Development in Rio de Janeiro, Brazil in 1992. The framework convention entered into force on the 21st of March, 1994, with the following mission statement (UNFCCC, 1992):

"The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

The treaty itself is not legally binding; however, it does provide a framework for creating international protocols that would set caps on GHG emissions. In 1997, the Kyoto protocol, an international treaty with binding obligations for industrialised countries to reduce their emissions of GHGs, was signed by the parties to the UNFCCC. The detailed rules for the implementation were established in Marrakesh, Morocco, in 2001, and the protocol itself has been in effect since 2005; with the Doha amendment further changing the protocol in 2012. As of 2013, there is still no globally set agenda or consensus on the atmospheric CO_2 stabilisation targets[2] (United Nations, 1998; Stern, 2007; Fisher, et al., 2007). Now we are waiting for what would be deemed to be the final agreement that will be made at the UNFCCC COP21 meeting in December 2015, in Paris, France (United Nations Climate Change Secretariat, 2013).

While the delegates of the UNFCCC COP are the ones who try to reach a consensus on any mitigation and adaptation policy plan, it is the IPCC that is the main scientific knowledge-providing organisation to the UNFCCC. The IPCC is a scientific intergovernmental body that was first established in 1988 by WMO and UNEP, and also later endorsed by the U.N. General Assembly. In their own words, the IPCC's mission is

[2] This is what one of the primary outcomes of the Kyoto protocol should be in order to limit the effects of global warming.

"to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts." (IPCC, 2013).

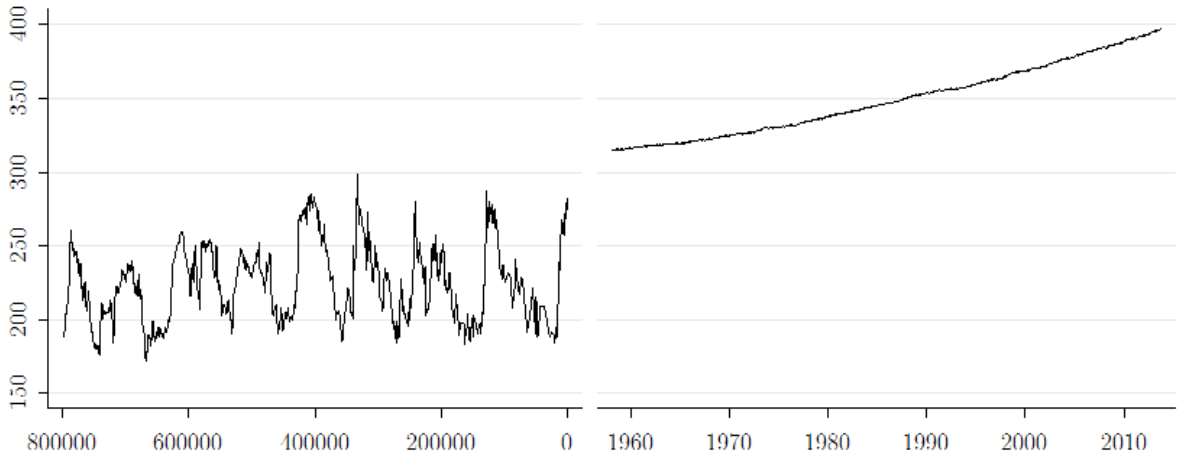
The primary activity of the IPCC is to provide what are known as Assessment Reports, which go through the current state of knowledge on climate change. These reports are intended to be used in the implementation of the UNFCCC. The current full report is the AR4 published in 2007; AR5 is set to be published in 2014, with the first working group documents already available in 2013. In order to use a more formal definition of climate change, we refer to the IPCC's definition (Solomon, et al., 2007):

"Climate change in IPCC usage refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), where climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods."

Given that the UNFCCC is more focused on anthropogenic causes, while the IPCC is interested in tracking climate change *per se*, the difference between natural compared to anthropogenic causes needs to be clarified. The following two figures illustrate the respective natural and anthropogenic contributions to atmospheric CO_2 slightly more clearly. Figure 1 on the next page shows the historic (going back to 600,000 years BP[3]) CO_2 concentration that has been estimated by analysing bubbles of air trapped inside ice at various sites; the adjacent figure shows what has become popularly known as the keeling curve[4], which show the current atmospheric CO_2 concentration. The figures have differing x-axes, although the y-axis scale is the same to allow the reader to gauge the difference in atmospheric CO_2 concentrations that we are currently witnessing.

[3] BP stands for Before Present, and is a time scale mainly used by geologist and other scientific disciplines to specify when an event occurred in the past. Standard practice is to use the 1st of January 1950 as the commencement date.
[4] The Keeling curve plots the concentration of CO_2 in the Earth's atmosphere since 1958 and it is named after Charles David Keeling. It is based on measurements taken at the Mauna Loa Observatory in Hawaii, U.S.

Figure 1. Atmospheric CO_2 concentration in ppmv, then and now



Note: The left graph shows the historic atmospheric CO_2 concentrations where the years are measured in BP. The measurements are a composite of five different studies that cover five different time ranges. The measurements are taken from either Dome C or Vostok in Antarctica. The right graph shows the current atmospheric CO_2 measurements and the years are measured in the Common Era. The measurements are taken from the Mauna Loa Observatory in Hawaii, the U.S.

Source:

2013 – 1974 CE: Tans & Keeling (2014); the Mauna Loa Observatory in Hawaii, the U.S.;
0 – 22 kyr BP: Monnin, *et al.* (2001); Dome C measured at University of Bern;
22 – 393 kyr BP: Vostok Petit, *et al.* (1999); Vostok measured at LGGE[5] in Grenoble;
393 – 416 kyr BP: Dome C Siegenthaler, *et al.* (2005) measured at LGGE[6] in Grenoble;
416 – 664 kyr BP: Dome C Siegenthaler, *et al.* (2005) measured at University of Bern;
664 – 800 kyr BP: Dome C Lüthi, *et al.* (2008) measured at University of Bern.

Biotic and abiotic activities have always contributed to CO_2 production on Earth. However, during the pre-industrial times, these rates had stabilised around a certain level (~280 ppmv), and when the discussion turns to mitigating climate change through the reduction of CO_2, we usually tend to focus on the amount of naturally occurring CO_2 and find an anchoring point there (IPCC, 2007). As depicted in the above graph (Figure 1), the long history of our planet would show that climate change in itself is inevitable and continuous; however, our current concerns lay in the fact that we as a species are causing

[5] Laboratoire de Glaciologie et Géophysique de l'Environnement.
[6] Ibid.

increased amounts of CO_2 in the atmosphere and are as a consequence exacerbating climate change for ourselves.

Each successive AR report concludes more certainly that the prime cause for the upswing in CO_2 concentration in the past centuries is due to human activity (Le Treut, et al., 2007). For policy makers, this implies that measures would need to be taken that could at least slow down the current release of GHGs in the hopes of eventually reversing the trend and paving the way for a low-carbon economy. In terms of progress, we have not gotten very far, as we are still seeing the increase of CO_2 concentration on a global scale (see Figure 1 above). One of the primary reasons why we are stuck at this stage is due to the cost-benefit component of climate change mitigation. Simply put, the current measures are too lacklustre to prevent, or even control, temperature increases (Graedel T. E., et al., 2011). Although the Durban round of the COP stated that the delegates wanted to limit global temperature increase to only 2°C, that milestone has already passed (since that was based on limiting atmospheric CO_2 concentration to between 350-400 ppmv), and an actual, realistic global target has not been set (United Nations Climate Change Secretariat, 2013; UNFCCC, 2012).

At the heart of the discussion on what amount of CO_2 ppmv in the atmosphere we should settle on, relies the science of the global ecosystem scenario predictions. These scenario predictions going through various stabilisation targets and analyse the overall effects of various ranges of CO_2 equivalent emissions being released into the atmosphere. The IPCC created the following various scenarios and stabilisation targets for the AR4:

Table 1. IPCC Working Group III Stabilisation Targets

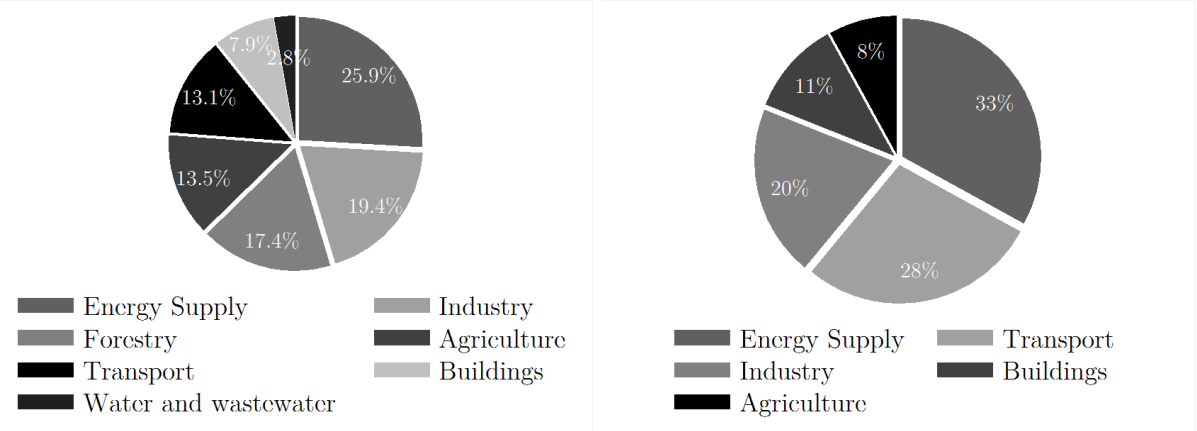
Category	Global mean temperature increase above pre-industrial at equilibrium	Change in global CO_2 emissions in 2050 (% of 2000 emissions)	Concentration (ppmv)		Peaking year for CO_2 emissions
			CO_2	CO_2-equivalent	
I	2.0-2.4	-85 to -50	350-400	445-490	2000 - 2015
II	2.4-2.8	-60 to -30	400-440	490-535	2000 - 2020
III	2.8-3.2	-30 to +5	440-485	535-590	2010 - 2030
IV	3.2-4.0	+10 to +60	485-570	590-710	2020 - 2060
V	4.0-4.9	+25 to +85	570-660	710-855	2050 - 2080
VI	4.9-6.1	+90 to +140	660-790	855-1130	2060 - 2090

Note: The CO_2-equivalent value describes, for a given mixture and amount of GHG, the amount of CO_2 that would have the same GWP, when measured over a specific time horizon.
Source: IPCC (2007)

Looking at Figure 1 we can see that at the current rate we will be toppling an average atmospheric CO_2 concentration of 400 ppmv rather soon, already crossing one scenario benchmark that has been used by the IPCC[7]. Although the climate science has become more certain, policy makers are still unsettled on what level of atmospheric CO_2 ppmv we should settle at. Arguably, from a pure policy perspective, the most pressing issue would be to get the delegates to the UNFCCC to agree on a limit, and create binding constraints, something that should occur during COP21 in Paris in 2015 (United Nations Climate Change Secretariat, 2013; Stern, 2007). One of the many reasons why the discussions are stalling is that there are significant structural and economic differences throughout the delegates' countries, which naturally implies that any specific CO_2 restrictions will hit countries and their respective sectors differently. To get a better understanding, the following graph (Figure 3) depicts both the U.S. as well as global GHG emissions by sector.

[7] This 400ppmv benchmark was already crossed at the Manu Lao Observatory in Hawaii, the U.S., in May 2013. There are, however, both seasonal and regional differences for the measurements, and hence a lag in the global average.

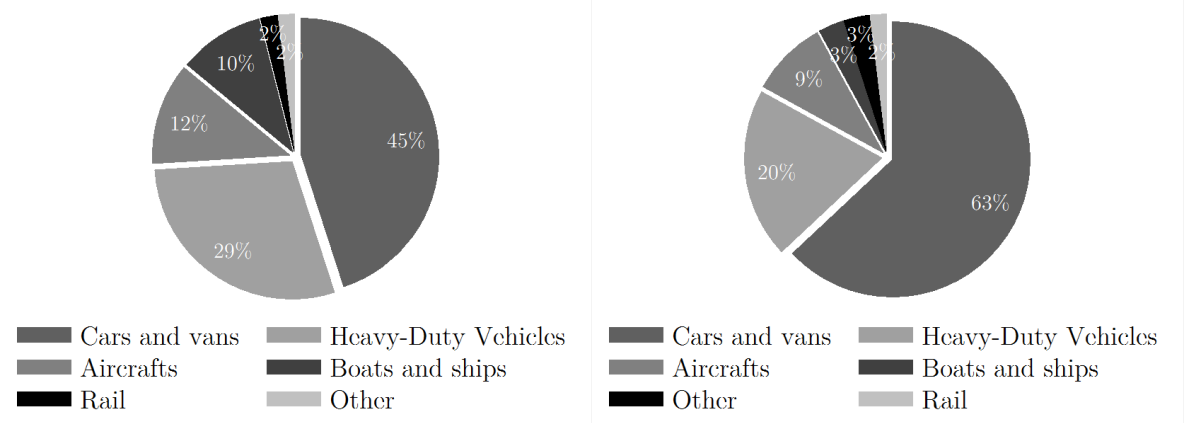
Figure 2. World and U.S. GHG emissions by sector



Note: The world figures (on the left) are from 2004, while the U.S. figures (on the right) are from 2011.
Source: The U.S. Environmental Protection Agency (2013); IPCC (2007)

These sectors can furthermore be broken down to give an even more detailed view of the various components that contribute to the GHG effect. Since the focus of this thesis will be to study the role of platinum and the catalytic converter in mitigating climate change, it would be worthwhile to also understand the transportation sector slightly better. The following graphs depict the breakdown of GHG emissions within the transportation sector.

Figure 3. World and U.S. GHG emissions within the transportation sector



Note: The world figures (on the left) are from 2000, while the U.S. figures (on the right) are from 2005.
Source: The U.S. Environmental Protection Agency (2013); Stern (2007)

Given the variety of sectors, and their respective subsectors that contribute to global warming, there are of course a myriad of other chemicals besides CO_2 that contribute to the GHG effect. Since this study is intended to analyse the use of the catalytic converter within the ground transportation sector to combat climate change, the chemicals that are of interest to us are the by-products of the internal combustion engine if it weren't for the catalytic converter[8]: CO, NO_x, as well as the by-product of using a fossil fuel: CO_2.

2.2 The abbreviated economics of climate change

This subsection will cover some of the economic concepts related to climate change – its focus will be limited to the relevant concepts and examples for the sake of brevity. The literature review in Section 3 covers the actual methodologies and up-to-date research within estimating the economic costs of climate change. For a more complete account of the economics involved with climate change, please see the Stern and Garnaut Reviews, as well as the various socio-economic sections of the IPCC's AR1-4, and the upcoming AR5.

The problem of climate change can succinctly be expressed in more formal economic terms as the problem of individuals' social discount rates not reflecting the external costs of GHGs on common goods such as the atmosphere. Thus, the main problems in terms of economic theory are those of the externalities, discount rates, time horizons, as well as the use of public and common goods.

In the words of the Stern Review, "c*limate change is a result of the externality associated with greenhouse-gas emissions – it entails costs that are not paid for by those who create the emissions."* (Stern, 2007). Thus, estimating the economic costs of climate change involves estimating this very externality, as it is the consequence of there being no global price for using the atmosphere as a dumping ground for GHGs.

At the heart of why the externality caused by current human activity is mispriced lies the societal discount rate. The societal discount rate can be defined as *"the appropriate value of the* [interest rate] *to use in computing present discount value for social investments"* (Gruber, 2010). What is problematic about using a societal discount rate is that there is no clear consensus on what this discount rate should be, as everyone will value a societal project differently. For example, some studies have analysed various discount rates to be used with

[8] Given that for the catalytic converter to function properly, it needs to be heated up to around 1000 degrees Celsius, many short trips cause there to be amounts of CO and NO_x in the air.

public infrastructure projects (and tackling climate change could be seen as one) around the 5% margin (Gollier & Rochet, 2002). Others like Stern have argued that the societal discount rate has to be zero for ethical reasons (Stern, 2007).

The ethical arguments for a zero discount rate are undeniably strong. In terms of intergenerational equity, we are currently taking away economic opportunities from future generations by causing long-lasting harm to the ecosystem by releasing vast amounts of anthropogenic GHGs (Le Treut, et al., 2007; Fankhauser & Tol, 1996). One of the most common retorts is to consider the facet of intergenerational equity, whereby our children and our grandchildren will be richer than us (assuming that we can maintain our recent growth vector) (Taylor, 2006). Thus, it would seem unjust to tax the current population a larger percentage point to correct the externalities caused by GHGs, when it would cost future generations proportionally much less (Lind, 1995). However, this argument would ignore the fact that it is dependent on a sustained growth path, which we could very well destroy by removing equity from coming generations by polluting the environment.

Any discount rate is inextricably linked to the time horizon, which is the total time span that we are concerning ourselves with. Another way of framing the problem of the discount rate is that we are not currently concerning ourselves with a timeframe beyond that of our own (if we were we would have a lower discount rate and start investing more actively in climate change abatement); consequently, the longer the time horizon, the lower the discount rate (Gruber, 2010). However, a main problem concerning the time horizon is the length of human life. It would not be unreasonable to assume that the discounted future payoff from anything when one is dead is zero, which would justify a much higher social discount rate (Weitzman, 1998; Gollier & Rochet, 2002; Ramsey, 1928). However, given that there is no clear-cut answer to what the societal discount rate should be, we are still left with arguing for one or the other – effectively showing that net present value calculations lose meaning when considering intergenerational equity.

One of the approaches that has been taken to address the problem of externalities has been to attach property rights (Coase, 1960). In the case of climate change, ownership rights have been created through various carbon tax and trading schemes (more popularly known as the cap and trade schemes) (Paltsev, et al., 2007). Though the efficacy of these can be discussed, it is another concept of property rights that is more pertinent. Property rights, in North America and Europe, are for the most part based on the Latin concept of "*Cuius*

est solum, eius est usque ad coelum et ad inferos,"[9] which in layman's terms states that you have ownership of the air above and the ground beneath your property (though this is applied less literally in practise, see United States v. Causby - 328 U.S. 256, 1946). The problem of property rights represents very clearly the issue with GHGs, as once GHGs have been dispersed into the atmosphere, they are no longer constrained by the potential area that might be covered by someone's property rights or by national boundaries – it will have become a global problem.

When it comes to global problems, the literature often talks about the atmosphere as a global public good (Lele & Gerrard, 2003; Bättig & Bernauer, 2009). Now the definition of a public good is that it is a good which can still be used even if someone else is simultaneously using it (non-rivalrous) and that no one is excluded from its use (non-excludability). This is in comparison to a common good which is both rivalrous and non-excludable (Perloff, 2011). What the global public good definition is missing is that the whole global warming science is built on the argument that the atmosphere is rivalrous. Thus if we were to relax how we are defining climate change slightly, it would become apparent that we are actually concerned with a common good.

By trying to establish stabilisation targets, we are effectively saying that there is an upper limit on the amount of atmospheric CO_2 emission that we are willing to accept. While the atmosphere could still accept more than this, it should hopefully be discouraged given the potential long term effects of climate change as the consequences of going beyond the limit would be too damaging. When considering that we need to start treating the atmosphere as a common good and consider global allocation rights, it becomes apparent that climate change poses a unique problem in the amount of coordinated action that is required beyond the first-mover problem.

The platitude of invoking the tragedy of the commons sounds rather hollow, albeit it could not ring more true (Harding, 1968).

[9] Literal translation from Latin: "whoever owns [the] soil, [it] is theirs all the way [up] to Heaven and [down] to Hell."

2.3 The catalytic converter's abatement effects

Catalytic converters were originally designed to solve the problem of exhaust gases polluting the air, as the exhaust from both diesel and gasoline engines contain NO_x as well as CO. As global climate change came more into the forefront, it became apparent that the gases that the catalytic converters were transforming would have had a higher GWP. Hence, a synergistic effect arose whereby the catalytic converter not only cleaned the air up, but also helped in mitigating global climate change (Ribeiro, et al., 2007).

Catalytic converters function by using a catalyst, primarily platinum, but other PGMs such as palladium and rhodium are also used in conjunction, to react with harmful exhaust gases to produce nitrogen, water, oxygen and carbon dioxide (IPA, 2013). While catalytic converters do not serve the express purpose of mitigating climate change, they are an indispensable part of the complex equation of climate change mitigation. As long as there will be an increased global future demand for gasoline and diesel cars, then mechanisms have to be in place to minimise the cars' impact on global climate change, and for the time being, that role is primarily served by the continued and future use of catalytic converters.

In terms of environmental policy, environmental issues such as smog build-up have traditionally been addressed by using laws and regulations to curb certain behaviours, such as the U.S. Clean Air Act of 1967 (and subsequent amendments) (U.S. Environmental Protection Agency, 2007). Thus, environmental issues such as smog build-up are concerns that are relatively easily tackled since not only are they usually local in the effects, which allow individuals in the vicinity to have an immediate personal interest in dealing with it, but they can usually be reversed by either stopping the negative behaviour or using technology to abate the problem (Portney, 1990; Davidson, 1979)

When addressing the systemic problem of global climate change, and to understand how the catalytic converter plays a role in its mitigation, it is relevant to go through how a catalytic converter actually functions. There are three primary chemical reactions that take place when a catalytic converter is functioning optimally[10]:

[10] For a catalyst to function optimally, it needs to operate at a high temperature (around 1000°C). Otherwise the incomplete combustion process can produce N_2O, another harmful gas.

Equation 1. The oxidisation[11] of carbon monoxide to form carbon dioxide:

$$2CO + O_2 \rightarrow 2CO_2 \quad (1)$$

Equation 2. The reduction[12] of nitrogen oxides to nitrogen and oxygen[13]:

$$2NO_x \rightarrow xO_2 + N_2 \quad (2)$$

Equation 3. The oxidisation of unburnt hydrocarbons to carbon dioxide and water[14]:

$$C_xH_{2x+2} + \left[\frac{(3x+1)}{2}\right]O_2 \rightarrow xCO_2 + (x+1)H_2O \quad (3)$$

These three chemical reactions govern the role of the catalytic converter. It is the catalytic properties of platinum (in addition to some amount of palladium and rhodium) that enables the aforementioned transformations; and hence why we are interested in the use of platinum when considering climate change mitigation. The next subsection will discuss the role of platinum in climate change mitigation in more detail.

The table below shows why the three reactions performed by the catalytic converter are relevant when considering climate change mitigation. The table shows the GWP of the three chemicals of interest (we are not considering the case of water vapour, which is also able to absorb radiation). The GWP is measured in specific time horizons, which imply that the number represents the GHG effect that the given chemical has either 20, 100, or 500 years hence. The numbers are all normalised to CO_2 (*i.e.* they are all in relation to CO_2, *e.g.* nitrous oxide has the equivalent GHG effect of 280 times the amount of CO_2 during the following 20 years from the date of emission).

[11] A chemical reaction in which an atom or ion loses electrons.

[12] A chemical reaction in which an atom or ion gains electrons.

[13] Where the x represents the amount of oxygen atoms attached to nitrogen and hence the bonds between the molecules.

[14] Where the x represents the length of the unburnt hydrocarbon chain.

Table 2. Global Warming Potentials

		Global Warming Potential (the concerned time horizon)		
Chemical name	Chemical formula	20 years	100 years	500 years
Carbon dioxide	CO_2	1	1	1
Carbon monoxide[15]	CO	2.8 - 10	1 – 3	0.3 - 1
Nitrous oxide	N_2O	280	310	170

Source: IPCC (1995)

It is due to the effect of transforming chemicals with a higher GWP to a chemical with a much lower GWP that makes the catalytic converter part of the equation to mitigate climate change.

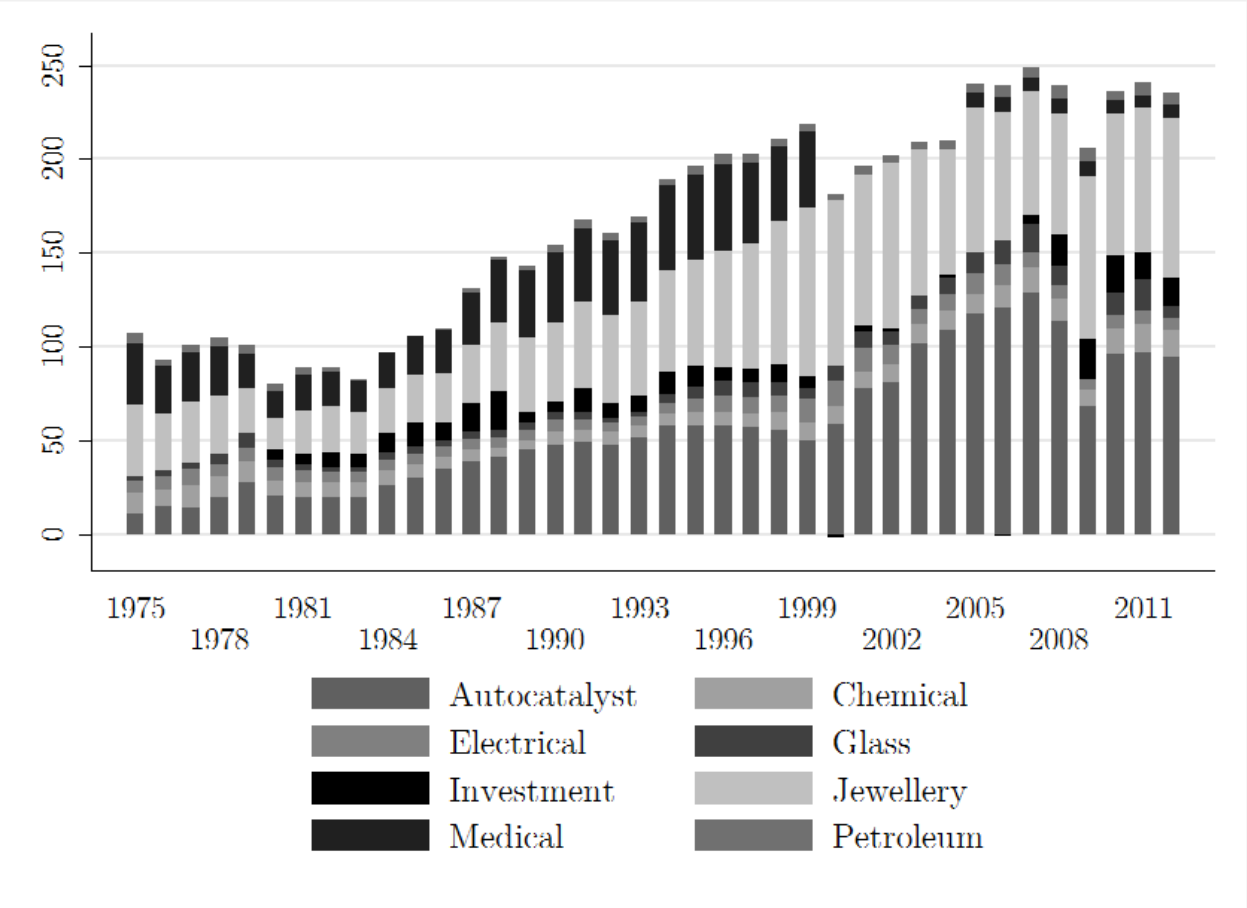
2.4 The essential role of platinum

The role of platinum in climate change is deemed mission-critical not only due to its catalytic properties, but also because of its unique supply and demand characteristics. Platinum is a precious metal that belongs unsurprisingly to the platinum group of metals. The PGMs are ruthenium, rhodium, palladium, osmium, iridium, and platinum. They are all transition metals, which imply that they have some specific properties pertaining to oxidation states, magnetism and catalytic properties.

Besides the primary use of platinum in catalytic converters, it is also used in almost equal quantities in jewellery, and to some smaller extent in other applications such as electronics and petroleum. The following graph depicts the development of demand for platinum by application:

[15] Carbon monoxide has an indirect, as opposed to a direct effect on climate change. Thus, its effects have been estimated using a variety of assumptions and conditions, and the measures represent the range taken from three separate estimates: Daniel and Solomon's (1998) box model considering CH_4 feedbacks only; the study of Fuglestvedt *et al.* (1996) considering a two-dimensional model that include CH_4 feedbacks and tropospheric O_3 production by CO itself; Johnson and Derwent (1996) considering a two-dimensional model including CH_4 feedbacks and tropospheric O_3 production by CO itself; these are all referenced in IPCC (2007).

Figure 4. Platinum demand by application in tonnes



Note: There are a few instances when there are negative values of investment, this implies that more platinum was being offloaded than invested in from a hedging perspective.
Source: Johnson Matthey (2013)

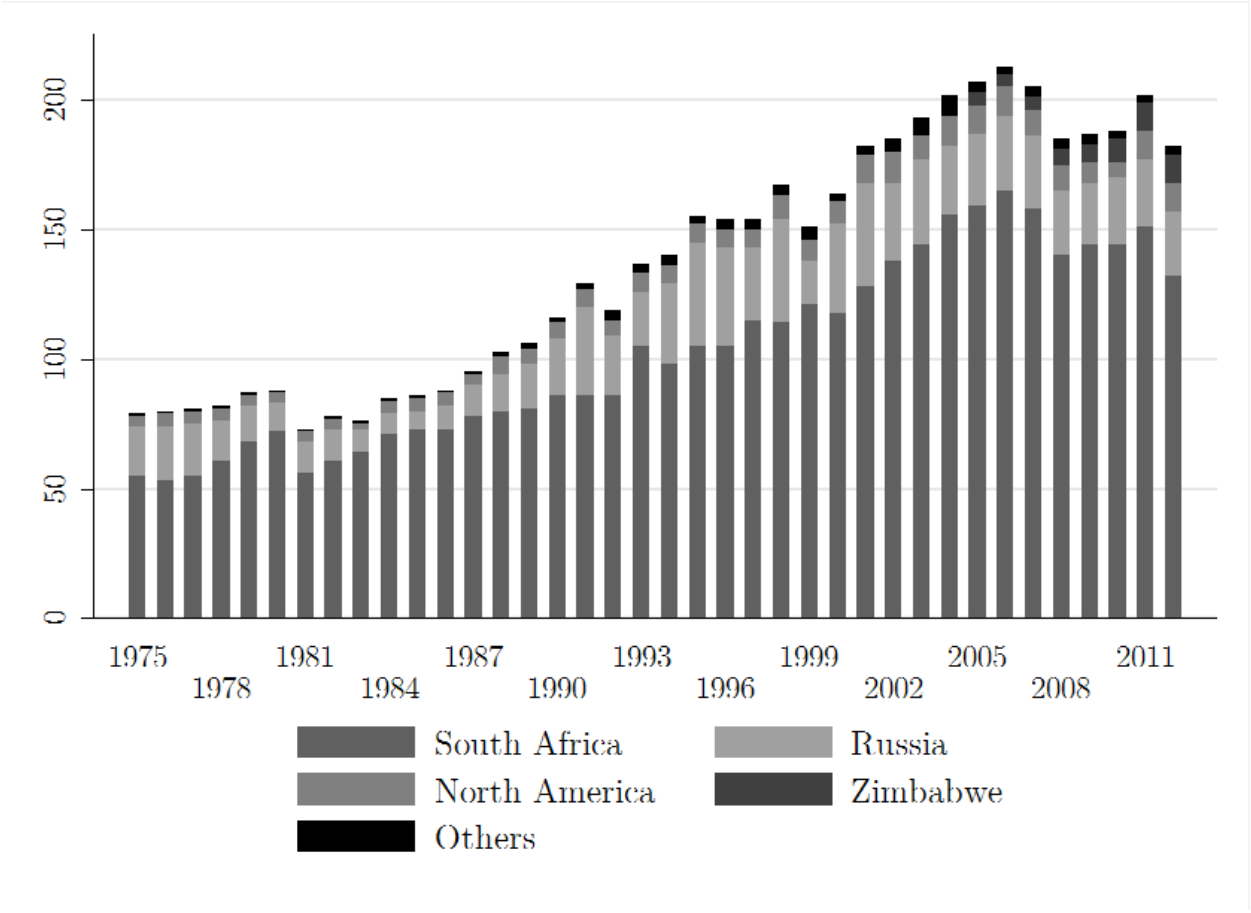
The demand for platinum is thus primarily driven by two very different purposes: one for its chemical properties, primarily as a catalyst in applications such as catalytic converters, and a second for its appeal as a luxury item.

Currently, the global supply of PGMs resembles very much an oligopolistic market as most of the supply is located in South Africa, and the market is dominated by seven publically-traded companies[16]. The following two graphs show both the global production

[16] While not an exhaustive list as there are also other companies involved in mining, the primary companies are: Anglo American – Anglo Platinum, Aquarius Platinum, Implats, Lonmin, Norilsk Nickel, Northam Platinum, Stillwater mining.

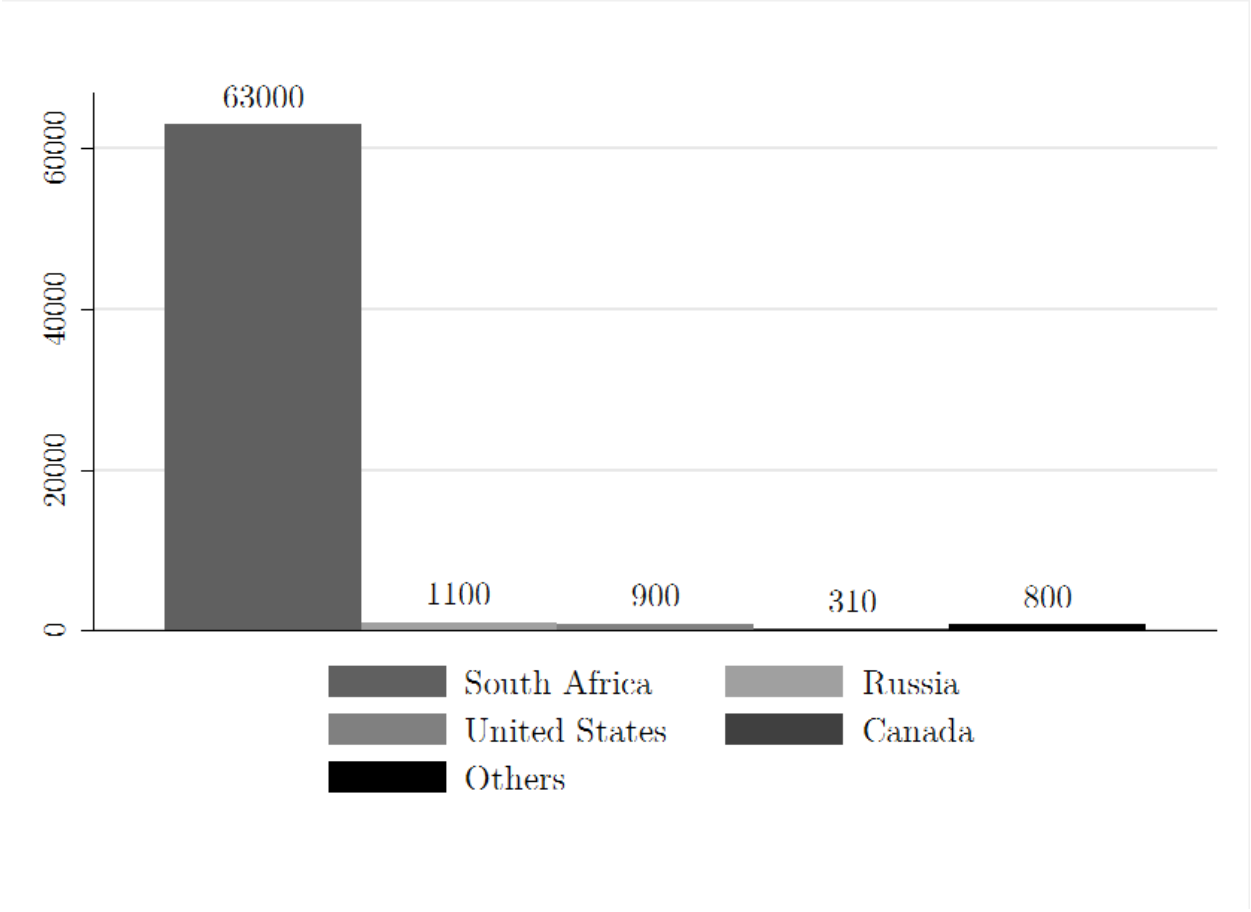
and estimated reserves of platinum. South Africa's dominant position within both respects is rather salient.

Figure 5. Global production by country or region in tonnes



Note: The 'others' group consists of countries with relatively small production such as Finland.
Source: Johnson Matthey (2013)

Figure 6. Estimates global reserves by country in tonnes



Note: These estimates are for 2012.
Source: Kelly & Matos (2012)

On top of the high concentration in one country, most of the platinum harvesting in South Africa takes place in the Bushveld Igneous Complex. When platinum is harvested, other PGMs are also found in the ore, hence most of the companies engaged in platinum mining are also able to extract other PGMs (Loferski, 2013).

There are natural barriers to entry in mining as well, given its high entry cost. The effects down the road imply that mining operations take a while to set up and get running, which imply that the supply conditions are not necessarily fluid and respond rather sluggishly to demand changes. Whilst it is easy to wind-down an existing mine, setting up a new mine can require a lot of work (Hagelüken, 2006).

While PGMs do not face the problem of starting to run out (current global predicted reserves are at 66,000 tonnes and current global supply is at roughly 180 tonnes per year),

they do face varying costs of procurement (Loferski, 2013). The cost would vary depending both on the quality of the ore as well as the depth at which the ore is being mined (Alonso, 2010; Glaister & Mudd, 2010; Johnson Matthey, 2012; Hotelling, 1931; Loferski, 2013). The ore quality of PGMs is particularly low, which implies a very high energy cost in its processing (Alonso, 2010). South Africa has also had some issues with delivering sustained amounts of electricity to the mining sites, which has severe implications in the mining process (Alonso, 2010). Thus, the marginal cost of extraction tends to increase as the ore quality gets worse and as mining has to be down at lower depths (Alonso, Field, & Kirchain, 2008; Johnson Matthey, 2013). Furthermore, sustainability studies have shown that the PGM sector in South Africa has been unable to reap necessary economies of scale, which might imply that larger production won't necessary see any cost-benefits (Glaister & Mudd, 2010). Taken together, these facts might indicate potential supply-side bottlenecks.

Although there are theories on optimal rates of extraction of non-renewable natural resources such as PGMs, these should be considered in their proper context (Pindyck, 1978; Hanson, 1980; Slade, 1982). One of the consequences of extracting too large of a portion at too low of a marginal cost too early on is that the incentives to invest in newer and alternatives technologies disappear. A prime example of this is the continued use of coal and oil. When the price of oil started climbing to unsustainable highs, the world saw an upsurge in the use of renewables; however, this momentum has since been lost (Renewable Energy Policy Network for the 21st Century, 2013; Makeower, Pernick, & Wilder, 2009). This incentive would obviously be reintroduced once prices would be exorbitantly high, but this whole process would nevertheless add another dimension of volatility to the pricing mechanism.

3 Literature Review

"The damage that climate change is causing and that will get worse if we fail to act goes beyond the hundreds of thousands of lives, homes and businesses lost, ecosystems destroyed, species driven to extinction, infrastructure smashed and people inconvenienced."

- David Suzuki, Global Climate Change Advocate

As the previous section sought to elucidate, climate change is a real and present danger. Moreover, the use of platinum in a catalytic converter in the ground transportation sector is an effective way to combat climate change. Although a danger, there are technologies currently available that can mitigate the effects of climate change, and we will be focusing on the role of the catalytic converter within the ground transportation sector, and as a consequence on the platinum that is used as the actual catalyst. What this thesis seeks to carry out is a multi-faceted approach in analysing platinum's role in climate change mitigation. This is done in order to highlight the need for literature that would consider certain bottlenecking resources when modelling climate change. Thus, the proposed methodology of a causal pathway analysis is not directly comparable to the standard socio-economic models estimating the costs and effects of climate change, such as the large IAMs. The proposed methodology is rather an alternative analysis methodology that seeks to highlight some of the limitations that are inherent in the current generation of models by looking specifically into a component that is mission-critical in mitigating climate change. As is the case for platinum within the ground transportation sector.

The main limitation that this thesis seeks to shed light on is the fact that by their very nature, large macroeconomic models are unable to account for specific market characteristics or elaborate dynamics and interdependencies. In this essay, the associated dynamics in the platinum markets are investigated both quantitatively and qualitatively. In the process, a framework that bridges the gap between the management of natural resources and understanding the bottleneck properties of living in a physical world, with what the current generation of models do and their associated policy recommendations is created. The current generation of IAMs are very encompassing and will always be broader than what the proposed analysis could possibly be. One of the main goals of this thesis is to analyse the socio-economic costs of climate change from a physical constraints perspective, rather than

using standard economic methods. This is done due to the fact that standard economic models tend to rely on a few basic assumptions such as establishing various equilibria rather than considering physical constraints.

To the author's best knowledge, there is no specific literature on analysing climate change with physical constraints, or more specifically as is done in this thesis, analysing a particular mission-critical resource within the domain of climate change mitigation. Due to this, we will cover the three constituent components of interest instead. Initially, some literature on natural resource management will be considered. Then the review will focus on the many models that are used to measure socio-economic costs of climate change, as well as some of the potential policy implications. In essence, this section seeks to bridge the gap between natural resource management, the current socio-economic modelling efforts within climate change, and the relevant policy implications. These are tied together by the fact that there are certain resources that we need to have a steady access to in order to carry out various environmentally friendly policies, and the current generation of socio-economic models do not generally consider this resource management aspect.

3.1 Natural resource management

In this thesis we are interested in analysing what has been deemed as mission-critical resources within climate change. By mission-critical we mean resources that contribute to material dependencies and bottlenecks. Consequently, we need to consider the scarcity of the material. Alonso (2010) approached this by considering classic economic theories. To extend these classic theories to more modern model building, we should also look at how the current IAMs work and whether the idea of scarcity is incorporated into the models or not.

The question of scarcity is something that came up often in the discussions of the late great economists Thomas Malthus, David Ricardo, and William Stanley Jevons. Although the notion of scarcity has underpinned economics throughout its existence, scarcity has arguably fallen out of vogue as general equilibrium theory came to the vanguard. This happened arguably with the invention of a Walrasian equilibrium would always ensure that a resource would not run out as prices would adjust accordingly. While allocative efficiency might be ensured this way, there are no guarantees that any questions of distributive justice or equity would be considered. Furthermore, the allocation is built on the assumption that

markets function well enough based on the available information. Markets are, however, rather agnostic to *e.g.* societal or global concerns, as these cannot by their very nature be priced as easily as a natural resource. Malthus already brought up the issue of scarcity several hundred years ago in a very practical fashion (Malthus, 1798). He was concerned that the amount of human beings would outnumber the available resources, as planetary resources are rather finite and humans have an excellent ability of reproducing. In his times, technological development was not as consistent as it is today, which ensured that the human population was kept in check by diseases etc. This has, however, changed dramatically with the advent of the industrial age.

While Malthus's ideas of scarcity laid the seeds for having to consider the physical constraints of the world, it was not until Ricardo that the idea of scarcity was put into a more formal economic context. More specifically, Ricardo looked at availability of productive resources as he considered the various classes in society. In one of this many observations about the rentier class (*i.e.* the class that gains its wealth through rent as opposed to labour), he noted that less productive land, that was usually farther away from an estate, would have to be worked harder on to achieve the same amount of output. Thus came the notion of increasing extraction costs, or the law of diminishing returns. It is this same problem that the extraction of several minerals and metals face, as mines have to be built deeper and the process becomes more energy intensive. Technological development can obviously counteract the law of diminishing returns, as has been shown with, for example, the expansion of arable land during the past two centuries. This does not, however, mean that there would not be an upward price pressure associated with diminishing returns, which, if not counteracted by technological development, would lead to higher prices.

Much like many of his peers, Jevons also believed that we would end up using resources without necessarily considering the physical limitations of the planet (Jevons, 1866). He noticed this in the coal industry in Great Britain, as the amount of coal use increased at the same time as coal production was being ramped up and extracted more cheaply This later became known as Jevons paradox, which more formalised proposes that as technology progresses, the increased efficiency that a resource is used in tends to increase the use of said resource, as opposed to decrease its use. This result does not obviously hold for everything, but it is still an important reminder of the ways that we do use non-renewable natural resources. While we have not run out of coal, we are running out of an atmosphere that is able to absorb it, as the increase in atmospheric CO_2 concentration shows.

What the classic economists nevertheless understood was that we live in a finite world with finite resources, and that this should be taken into account in the larger scope of the political economy. Fast-forwarding a few centuries and we are where we are now, in a zeitgeist when the use of non-renewable finite resources cannot really be seen as becoming too scarce as a price equilibria would always ensure a counterbalance. This is one of the fundamental drawbacks of using general equilibrium based models, and a real danger when addressing issues such as climate change.

3.2 Current models of the socio-economic costs of climate change

When considering the current socio-economic models that are used to calculate costs in climate change, it is firstly important to understand a bit more about the nature of the models. Most of the models that are used when estimating costs are what are known as Integrated Assessment Models. What is particular about these is that they try to bridge some of the scientific facts established by the IPCC with economic theory, so as to incorporate both the climatic science as well as the economic modelling aspects. Some models abide by using notions of general equilibria, such Nordhaus's DICE model, and consequently abide by the same rules that govern many macroeconomic models (Nordhaus & Boyer, 1999). There are also other models and approaches, such as the famous PAGE2002 model that was used in the Stern Review. At its heart it is a micro simulation model that utilises Monte Carlo methods[17] to explore the impacts and social costs under a user-specified climate change scenario (Hope, 2006). This implies that the model iterates several runs using random variables to estimate the outcomes of interest.

In either general equilibrium or micro simulation models involving Monte Carlo methods, the dynamic feedback effects would be missing as the models are generally not designed to take into account that there might be variables that affect each other within and between periods, requiring different simulation techniques to estimate an effect. Hence why systems thinking is required and consequently proposed with the causal pathway analysis. In order to understand better what might be gained from taking a systems

[17] In essence, Monte Carlo methods entail using random variables as inputs to assess an output. For example, when no analytical solutions exist to integrating a function, random draws can be used to determine the properties of said function. In much the same way, a function or system can be optimised by drawing random numbers over a range and using the most optimal value. Also, in statistics, when dealing with various distributions, one might also need to use Markov Chain Monte Carlo methods to determine the probabilistic distribution.

approach whereby the various dynamic effects, kickback mechanisms, and the associated interdependencies could be better understood, the current generation of models need to be explored in more detail.

The most current, major economic cost calculations of climate change come from several compounded reviews. The seminal works include the impact and socio-economic cost sections of the IPCC's AR4, the Stern Review, as well as the Garnaut Review (Garnaut, 2011; Stern, 2007; IPCC, 2007). AR4 is the most up-to-date and complete[18] assessment of the scientific, technical, and socio-economic information concerning climate change – the information that drives much of the factual basis of the COP/CPM meetings of the UNFCCC. The Stern Review, released in 2006 and commissioned by the British Government, analyses the effects of global warming on the world economy; and the Garnaut Review, a similar climate change review, was commissioned by the Australian government and released in 2010[19].

Since this thesis will focus on alternative methodologies to analysing problems with a resource dependency such as climate change, the literature for modelling the economic costs of climate change will be a natural extension to considering the management of natural resources. As was mentioned in the introduction, a distinction between various types of models has been made. The second AR released by the IPCC had a long discussion on the differences between top-down and bottom-up approaches to modelling when it comes to analysing the economic costs of climate change – one of the reasons why this discussion has not appeared in the newer ones is that most models today employ facets of both. In the words of the IPCC (IPCC, 2001):

"Top-down models account for various industrial sectors and household types, and many construct demand functions for household expenditures by summing "individual demand functions". Such functions can facilitate a reasonably detailed assessment of economic instruments and distributional impacts of climate change mitigation policies."

Many of the modern models account for many of the behaviours that could have been witnessed by analysing economic agents in detail. One of the more famous models is William

[18] Currently, AR5 is being completed, with the first section on the scientific basis having been completed and the full report scheduled for a 2014 publication.

[19] The final report was released in 2010, whilst an earlier draft version was released earlier in 2007.

Nordhaus's DICE model (shortened from the Dynamic Integrated Climate Economy model) (Nordhaus, 1993). The DICE model functions by maximising a social welfare function subject to a few constraints that determine behaviours and preferences for the agents involved. A fractional reduction in GHG emissions is then calculated as a fraction of the total cost of the reduction in world output. Macroeconomic models like these tend be able to give good overall results on the overarching level, however, they are unable account for any real finer dynamics. Hence the need for more elaborate models based on systems thinking – the proposed causal pathway analysis could serve as a rudimentary first step in understanding the dynamics between climate change and the economy better.

Going back and considering Nordhaus's model, his conclusions back in 1993 were that a modest carbon tax would be an efficient approach, while a rigid emission-stabilisation scheme would impose significant net economic costs. The model, however, only accounts the loss of world GDP due to the fact that resources had to be invested elsewhere – namely in climate change abatement. Any potential knock-on effects on GDP of not abating are nowhere to be found. Furthermore, any real sectoral consideration was omitted, most likely due to the lack of computing power at the time.

Nordhaus updated his model in 1999 and came up with a new set of results (Nordhaus & Boyer, 1999). The updated model, now going by the name of RICE-98 (which stands for Regional Dynamic Integrated model of Climate and the Economy) builds on the previous DICE model as well as an earlier incarnation of RICE (found in Nordhaus & Yang (1996)). The methodology has also been updated, as the models do not rely on a parameterised emissions-cost relationship any longer. This has been replaced in the new model with a three factor production function in capital, labour, and carbon-energy. Furthermore, the updated RICE models also consider regions or countries, which allows for further detail to be added[20].

While it is apparent that what is being reviewed in this section is somewhat different from what is being subsequently analysed, it is important to highlight where the current models ends and where the proposed methodology of analysis would begin. By showing the thinking behind the current generation of models and to what extent they cover various facets of interest, it is easier to show where a fuller dynamic model that would employ systems thinking would start. Thus, the models that are being reviewed are intended to be used to analyse economies and climate change together as a whole, compared to the thesis

[20] The latest incarnation, RICE13, is available to the public as a GAMS programme.

at hand which is analysing the causal effects of one resource within one sector more specifically. Hopefully this process would highlight what is needed in the current generation of models. Ideally, a full system dynamics model could be built that would consider the dynamic effects, feedback mechanisms, and interdependencies between an economy and climate change together – this is, however, far beyond the scope of this thesis.

While the proposed causal pathway analysis in this thesis is focused entirely on one sector, and on the use of one natural resource within that sector, the general line of thinking about the different causes that various climate change pathways would have on the economy and vice versa shows the potential for this line of thinking. The model that will be presented in section 5 is very limited in its scope, as its intended use is to look at the pricing structure quantitatively and then assess qualitatively how a price change could bottleneck climate change mitigation efforts in the ground transportation sector. Ideally, the model should be expanded to take into account various economic scenarios in much the same way that the aforementioned climate change models do. The qualitative corollaries that are explored in section 6 should also be analysed in a larger systems dynamics model to get a better understanding of the scope of individual policy decisions, however, these were not implemented in the current model and are instead considered separately.

Beyond that of the aforementioned models which either use a production function to establish a general equilibrium (as RICE does) or solve a complex set of equations using Monte Carlo methods to derive the results of interest (as PAGE2002 would), there are also other applicable approaches to estimating the economic costs of climate change. Martin L. Weitzman constructed probability density functions to estimate the costs of catastrophic events using Bayesian methodologies (Weitzman, 2009). While this type of modelling is novel in itself, it is his conclusion by using prior information that fat-tailed structural uncertainty can readily outweigh the effects of discounting in climate-change policy analysis that is extremely interesting. This is significant as it allows the discussion to move beyond that of the discount rate which it seems to be stuck in with most of the big IAMs. Thus, taking the discussion to the question of whether we value current consumption more than preparing for catastrophic damage tomorrow. This should perhaps even be reframed in terms of buying catastrophic insurance as suggested by Ackerman *et al.* (2009). This line of thinking is interesting as discounting is after all one of the main criticisms that was directed against Nicholas Stern in the aftermath of releasing the Stern Review.

The proposed causal pathway analysis does not consider discounting due to the fact that we are not analysing economies at large, but rather just looking at the pricing structure of a natural resource – a resource that is essential in climate change mitigation in the ground transportation sector. Moreover, the approach taken in the causal pathway analysis is rather of an operational and transitory nature, *i.e.* to identify and evaluate mission-critical resources involved in climate change that would hamper any efforts to conduct reasonable climate change mitigation policy. Moreover to also consider transition plans that would allow a more stable path of economic development that addresses the concerns of climate change. Thus, it is a long step from what the current models do, but the idea is to highlight the need of considering mission-critical resources in the current modelling efforts, and the proposed analysis provides a framework for the context that needs to be considered.

At the vanguard of the current line of thinking is perhaps the Stern Review's results. While there is no specific model that is built in the Stern Review, the uses and extrapolations of the results is what has come under much scrutiny. The Stern Review uses the PAGE2002 model which is explained in more detail in Hope (2006). In essence, the model is able to account for risks to unique and threatened ecosystems, risks from extreme climate events, distribution of impacts, aggregate impacts, and risks from future large-scale discontinuities according to Hope (2006) . In comparison to DICE or RICE, PAGE2002 is built around a myriad of equations that all feed into one another, which consequently implies that it is not as rigorously bounded in economic theory as some other general equilibrium models. The PAGE2002 model has seen rather active use, and the set up *per se* is not problematic, however, how it is used has received some critique as showcased by the comments on the results derived in Stern (2007).

Most of the critique that has been used against Stern's work stem from his imposition of a very low discount rate in the use of the PAGE2002 model (what he would argue for is the ethical zero percent discount rate (Stern, 2007)). Martin Weitzman, whilst skeptical of Stern's choice with regards to discount rates due to the formality of economics (*i.e.* it is difficult to justify a zero or near zero discount rate economically), acknowledges nevertheless that we know much less about what the discount rate should be than what we are willing to admit (Weitzman, 2007). As Stern posited, it is difficult for economists to break out of their comfortable shell and having to consider intangibles such as intergenerational equity and the question of ethics (Stern, 2007).

Richard Tol and Gary Yohe, while agreeing that the choice of discount rate is debatable, nevertheless criticised the Stern Review's approach more thoroughly by accusing it of double-counting risk as well as assuming that vulnerabilities exist for too long. Furthermore, they suggest that the low costs of mitigation at 1% of GDP found in the Stern Review (which Stern later himself doubled to 2% upon reviewing the material), is primarily due to omitting the economic repercussions of more expensive energy and ignoring capital investments that need to be made (Tol & Yohe, 2006; Jowit & Wintour, 2008). Given what is at stake, it is inevitable that the Stern Review would face a plethora of criticism, and as among others Tol and Yohe show, much of the critique is sound since there are many methodological issues at stake. This should not, however, detract from the main point of the Stern Review, which is to make us understand the gravity of the situation and for us to prepare to do something about it.

What is missing is the fact that the Stern Review has to be considered beyond being a mere economic cost calculation as it is a formalisation of the need to address a future danger – a danger which modern economics does not know how to quantify appropriately, and hence deal with. Weitzman noted with regards to the Stern Review that perhaps Stern was getting the arguments right, but for the wrong reasons, as the Stern Review should perhaps be seen more as a political document than anything else (Weitzman, 2007). When it comes to climate change mitigation, the approach of trying to curb emissions through taxes, trading, or even regulation is the right thing to do. To reason this by using a pure-rate of time preference of effectively zero and other parameters which are at the low end of what is theoretically feasible, but not witnessed in the real world, then the arguments themselves become somewhat flawed.

There are, however, some elements of cherry picking that do exist in the Stern Review. Stern argued that if we do not act now, we risk losing at least 5% of GDP each year now and forever; if the wider systemic effects are also accounted for, the estimates would go up to 20% of GDP. However, Tol & Yohe (2006) point out that this 5% of GDP is in fact the mean for one particular scenario. The 5%ile may be as low as 0.3% and the 95%ile as high as 33%. This of course raises the question of whether it is acceptable to present situations in a more dire light if it is ethically warranted. Obviously, this would be intolerable from a technocratic standpoint, but given that the normal cost-benefit analysis breaks down when considering intergenerational equality, it might be warranted.

It is important to remember that discount rates can be discussed *ad infinitum*, without necessarily reaching a consensus. It is easy to conclude that there are a myriad of discount rates given the heterogeneity shown by mankind. This does not however change the fact that discount rates are a part of our everyday calculations. Human being constantly make inter- and intra-temporal choices subject to the various constraints that we face. In more real terms, it is difficult to worry about climate change when one is living from paycheque to paycheque, clearly reflecting a very high discounting rate. While this might be one reality, another one is that the vast consequences of global warming stretch beyond merely one lifetime (IPCC, 2001). Thus, while there are ethical reasons for having a low discount rate, there are equally valid reasons to having a normal discount rate given the needs of the current generation.

In addition, it is the Ramsey equation which describes the social discount rates using the pure rate of time preference, a measure of relative risk aversion, and the rate of growth in per capita consumption (Ramsey, 1928). Anthoff, Tol, & Yohe (2009) argue that too much role has played by the pure rate of time preference, while the two other elements are numerically just as important when considering anthropogenic climate change. They find the interesting fact that impacts of climate change grow slower than income (assuming that we can keep the same rates of growth of course, which climate change itself might interrupt), which would then naturally imply that the effective discount rate is higher than the real discount rate. Going back to what Weitzman was saying, it is perhaps the catastrophic nature of climate change that will deem discount rates entirely uninteresting, and perhaps then, the ethical arguments can resurface.

This discussion on discount rates is perhaps thus invalid since it leaves the discussion in a technical and theoretical domain, and not in a practical field. However, it is important to understand the discussions that are taking place in the literature if one were to propose another methodology of analysing the problem at hand. The proposed causal pathway analysis would move beyond mere discount rates and rather consider practical matters that are at stake when considering climate change mitigation, such as operational matters and a transition plan into a more stable path of economic development that addresses the concerns of climate change. Arguing about discount rates will not solve any problems, while analysing the problem from a practical solution and highlighting what is at stake and proposing a practical approach to dealing with the matter will.

3.3 Climate change policy outlining

Beyond that of considering some of the classic economic theory around scarcity and the models that are currently being used to estimate the socio-economic effects, we need to also consider how they contribute to global policy making; as the ultimate question revolves around the policy implications that are derived from the models that we use. By the end of the day, when policy makers decide on what course of action to take, they must consider the costs and associated benefits, given the set of assumptions that are employed in a given methodology. As was mentioned earlier, we are currently in a very lacklustre state of climate change policy making. Although the data and methodologies involved in the study of the climatic science improve with each AR, and consequently also the precision of the estimates, the political will to carry out policies is lagging. This subsection will briefly look at the reasons why climate policies might be difficult to carry out in light of the amount of evidence that exists.

Dieter Helm points out that it is not the lack of climate science based evidence that is causing our policies to lag, but rather perhaps a constrain in the political economy of matters (Helm, 2008). In other words, realising that the costs of dealing with climate change would be far higher than previous estimates could perhaps lead to paralysis and inaction, as the problem could seem insurmountable. What would actually be needed is more urgent and hard-hitting action, but in the face of ever tougher obstacles, it becomes difficult to even approach the problem. Thus, it is the interplay between political actions and the economic effects that could to a certain extent lead to inaction. Helm actually blames the Stern Review for having to some degree even impeded more than forwarded the cause of investing in climate change mitigation. Specifically, Helm takes issue with how the Stern Review addresses the impacts of climate change on economic growth, the costs of mitigation, and on discounting; or as Tol & Yohe (2006) put it: *"the policy implications of the Stern Review are [...] bleak. The damage estimates are, themselves, enough to undermine its ability to galvanize support for the near-term intervention."*

One of the main purposes of reports like the Stern Review is to provide policymakers with sound advice and tools that they could use. The cost-benefit analysis is potentially one of the most valuable tools at a politician's disposal. Robert C. Lind discusses the problem that was raised in the previous subsection with regards to the validity of even using a cost-benefit analysis at all when it comes to debating climate change (Lind, 1995). The

fundamental issue with the cost-benefit analysis is that it breaks down, much in the same way that the concept of a discount rate and net present value does when considering extreme events such as climate change. Not only is there a risk for cataclysmic effects as climate change intensifies, but the extreme events are also most likely going to occur in the future rather than today, since the effects of climate change are compounded over time. Due to both the fact that cost-benefit analyses are ill suited to deal with long time horizons as well as extreme, black swan-type events, Romer (2008) argues that a theory of justice is needed when trying maximise the welfare function of several generations.

Unfortunately the reality of the matter in terms of making climate change policy is that it is stuck at a stage where the needs of the planet are clear, and there exist concrete recommendations for what needs to be done, but we are unable to decide on who should bear what costs and achieve what by when. As was mentioned earlier, this should hopefully change by 2015 at the next COP meeting in Paris, France. The Stern Review, for example, contained a myriad of policy recommendations for almost every sector. While not going into in-depth detail for everyone, thought had nevertheless been given to the various needs of each sector. *E.g.*, for the climate change policies pertaining specifically to the ground transportation sector, the Stern Review sees that *"cost effective emission savings from transport are initially likely to come from improvements in the fuel efficiency of oil-based transport vehicles, behavioural change, and use of biofuels."* Furthermore, hydrogen and electric powered vehicles are seen as viable future technologies, as long as the electricity or hydrogen is generated in a low carbon way (Stern, 2007).

While the aforementioned recommendations are sound ways to consider mitigating climate change within the ground transportation sector, the more detailed story of how this would pan out goes missing. This is generally the problem with much of the literature that seeks to measure the economic costs of climate change. Even if the intent is only to measure the economic costs, the papers assessing these would be much more worthwhile if they were put in the context of carrying out certain, more specific policies instead of general emissions reduction targets. By looking at the general and thus skipping the crucial step of having a proper transition plan in place, much potential in providing politicians with additional tools is gone astray.

The issue of not considering a proper transition plan is also present in the Stern Review when considering the policy implications for the ground transportation sector; also, the recommended policies can often be overarching without necessarily considering the

intricacies of the sector in more detail. For example, if one were to consider the policy implications of Stern's recommendation, then whatever potential efficiency gains of the internal combustion engine would surely be dwarfed by the large car increase projections as more and more people enter the middle class around the world (Hurst & Gartner, 2013). Crunching some quick numbers would show that the efficiency of an internal combustion engine has in the past 40 years increased from an average of 15 miles per gallon to around 30 miles per gallon. Implying a doubling in the efficiency of a car engine in the past 40 years, which is compared to a doubling of the sales of new cars globally in the past 20 years (Pew Environment Group, 2011; The Economist, 2013). Thus, transition plans and reports are needed that go beyond the superficial and obvious.

One of the risks with the proposed form of systems thinking is that there is the risk that one would analyse interdependencies and dynamics *ad infinitum* and *reductio ad absurdum*, which itself poses a clear and definite danger as policy would get obfuscated in details which are successively less relevant – obviously something that should be eschewed. Thus, it is important to also limit the analysis. The proposed causal pathway analysis seeks to find this middle ground between practical policy considerations and detailed modelling. While the analysis at hand cannot be applied in the same general, macro-oriented fashion as the models that were described in the previous subsection, this analysis can however give more specific, practically oriented insights in the matters of climate change mitigation. Insights that are easily missed in the large IAMs. Looking back at the recommendations for the ground transport sector made in the Stern Review, the focus was for the most part put on the promise of what future technology could offer us. Any discussion about the pathway to these future technologies is glaringly omitted, whilst it arguably constitutes an equally important aspect of climate change mitigation. It is merely not about getting somewhere, but also about how one gets there.

4 Methodology

"Un bon mot ne prouve rien."[21]

- François-Marie Arouet (1694-1778), better known by his penname Voltaire

Some of the main limitations of the current approaches in estimating the socio-economic effects of climate change should have become more salient in the previous section; what is arguably the overarching theme is the fact that the models are based more on theoretical economics rather than physical facts. Thus, an alternative methodology is proposed in this thesis which is termed causal pathway analysis. The name comes from the fact that the methodology is embedded in systems thinking and what is of interest are the many dynamic mechanisms, feedback effects, and other interdependencies that one has to consider when analysing complex systems. Hence, the proposed analysis revolves around analysing the pathways that these aforementioned effects take, and the associated causes and effects.

To begin what was termed as the causal pathway analysis of platinum, firstly the thought behind it will be explained. Secondly, a system dynamics model of the platinum prices will be used in the next section (5) to analyse the price trend as well as to simulate the future price of platinum. This is done in order to get a grasp of the overall fundamental demand and supply drivers in the platinum markets, and the results will be later used when discussing the qualitative corollaries in section 6. The subsequent section (7) will cover the policy lessons based on the results of the system dynamics model as well as the discussion surrounding the results.

4.1 Causal pathway analysis

What prompted another methodology of analysis to be explored in this thesis was the fact that many of the current methodologies that are employed in assessing the socio-economic costs of climate change mitigation were not necessarily considering the effects of bottlenecking resources. By taking a more operational stance and looking more specifically at what climate change mitigation within the ground transportation sector depends on, another picture can be painted. Thus, another type of analysis would be carried out that

[21] Non-literal translation from French: "A witty saying proves nothing".

would widen the knowledge base of the current literature on estimating the socio-economic costs of climate change.

The proposed alternative is termed causal pathway analysis, and it was spurred by the need to embed the analysis in the physical, as opposed to the theoretical world. Many economic models do not generally consider the limitations of the physical world, as equilibrium theory would always ensure that all components find themselves in a balance. By employing other forms of analysis, such as using system dynamics and considering the interdependencies and dynamic effects in more detail, we can look beyond a mere theoretical construct at how the world actually works.

The analysis at hand was carried out both quantitatively by using a system dynamics model, as well as qualitatively, by focusing on the different societal knock-on effects that a platinum price hike might have. Before the actual analysis, a short primer on the different types of modelling techniques that exist will be presented so that the reader can better understand how to juxtapose the various methods of modelling.

4.2 A short primer on modelling techniques

In order to understand the place for alternative methodologies of analysis such as system dynamics, it is worthwhile to have a short discussion on modelling techniques, given that system dynamics is not something that is often encountered in economics, but rather a tool used by engineers. The tools that most economists find themselves familiar with are either general equilibrium type models, or analyses based on econometric techniques, or a combination of both such a Dynamic Stochastic General Equilibrium – more commonly known as DSGE – models.

Arguably, one of the primary reasons that numerical solving methods such as system dynamics has not gained traction is due to its lack of microfoundations (*i.e.* considerations of individual agents in the model). At the heart of system dynamic lie a set of coupled ordinary differential equations (equations that relate some function with its derivatives, *i.e.* the variables rates of change), and once these are solved using a variety of integration techniques (out of which Runge-Kutta is a popular one), an understanding of the stocks, flows, and rates of a complex system can be understood (these concepts are explained in more detail later on). This is in stark contrast to general equilibrium models which usually have a representative agent that has a specific utility function as well as a production

function which has two or more factors that are being maximised subject to some constraints. Econometrics on the other hand does not employ assumptions in the same way, but rather performs atheoretical operations on data to learn more about it.

At the heart of system dynamics lie stocks, flows, and rates, words which are not part of the usual economics jargon. A stock refers to an integral that captures what flows into it and what flows out of it. For example, the production of a good could be represented in this form, since the good would have a rate that it is being produced at, and once it is completed, it would be moved into the stock through a flow where it is stored until it would flow at another rate elsewhere. Whilst different stocks, flows, and rates could be defined to emulate microfoundations by having individuals passing through a system through time, the mathematical technique in itself is not based on economic theory. This would be in contrast to any general equilibrium model that has a utility maximising agent. The isoelastic utility function, such as the constant relative risk aversion (CRRA), ensures in the eye of the economist that there is human economic behaviour behind the model, while in practise it is merely a mathematically convenient tool to be able to utilise general equilibrium type models.

The greatest strength of system dynamics is perhaps, using the words of its founder, Jay Forrester, its ability to *"accept the complexity, nonlinearity, and feedback loop structures that are inherent in social and physical systems"* (Forrester, 1994). One of the highlighted benefits of modelling using system dynamics is that one is able to track which feedback mechanism or dynamic effect starts carrying the most weight in a model. With regards to understanding pricing decisions, many markets show high degree of complexity and non-linear behaviour, which warrants the use of system dynamics

System dynamics is ultimately an operational approach that seeks to understand an observable problem that can be defined. While a deeper philosophical discussion on modelling is warranted, it is beyond the scope of this text. One question that one may ask though is that while it may be useful to have a theoretical backing for a model, what ultimate purpose does it serve? Milton Friedman had quite a few thoughts on this as he argued that the thought behind the model was not as important as the results that came out of it (Friedman, 1966). This is clearly very dangerous, since if not enough attention is paid to how something is being modelled, then the results are at best spurious, and at worst catastrophic for those who make policy decisions based on them.

It is difficult to do justice to another type of modelling technique in such few words, which is why an example of the need for systems thinking will be used. The example is employed in Sterman (2000) to highlight the necessity of systems thinking, especially when juxtaposed to general equilibrium modelling. During the cold war era, economists had been asked to predict at what rate the U.S. economy would recover if it were hit with nuclear weapons. The general equilibrium models showed that the economy would regain most of its strength in only a few years. This result justified the build-up of an increasingly large arsenal of nuclear weapons, since if the U.S. could recover that quickly, so could the Soviet Union. A system dynamics model was later constructed to analyse the problem in more detail, and the result was quite the opposite. The model considered the effects of a nuclear weapon hitting energy supplies and the reverberating effects throughout the economy due to a reduced the amount of available energy. Based on the system dynamics model, it was enough to have a few nuclear weapons and to use them to hit important targets such as energy production that would cripple an economy. The feedback effect of a reduced amount of energy was not considered in the general equilibrium model, since the model ensures that the system has to be in equilibrium at all times, and thus artificially creates results that would indicate that the economy would be strong again sooner than what would be realistic.

5 Quantitative Price Analysis

"The man who does not read good books has no advantage
over the man who cannot read."

- Samuel Langhorne Clemens (1835-1910),
better known by his penname Mark Twain

This section will cover the quantitative analysis of the proposed causal pathway analysis that was established in the previous methodological section (4). Firstly the idea behind the model will be discussed, after which its constituent parts are documents and explained. The system dynamics model that will be used is an extension of a generic commodities model that was presented in Sterman (2000). After having established a model of interest it needs to be parameterised and calibrated. This process entails that firstly a set of exogenous parameters are determined and inputted into the model. For the parameters of interest that we cannot find exogenous values for (*i.e.* we have not been able to ascertain the parameter values from other reports, analyses, or industry experts), the values will be calibrated. Calibration implies that given all the other parameters, the parameters to be calibrated will be adjusted until the results that are produced are most like real world observations. Then the model will be used to create various pricing scenarios.

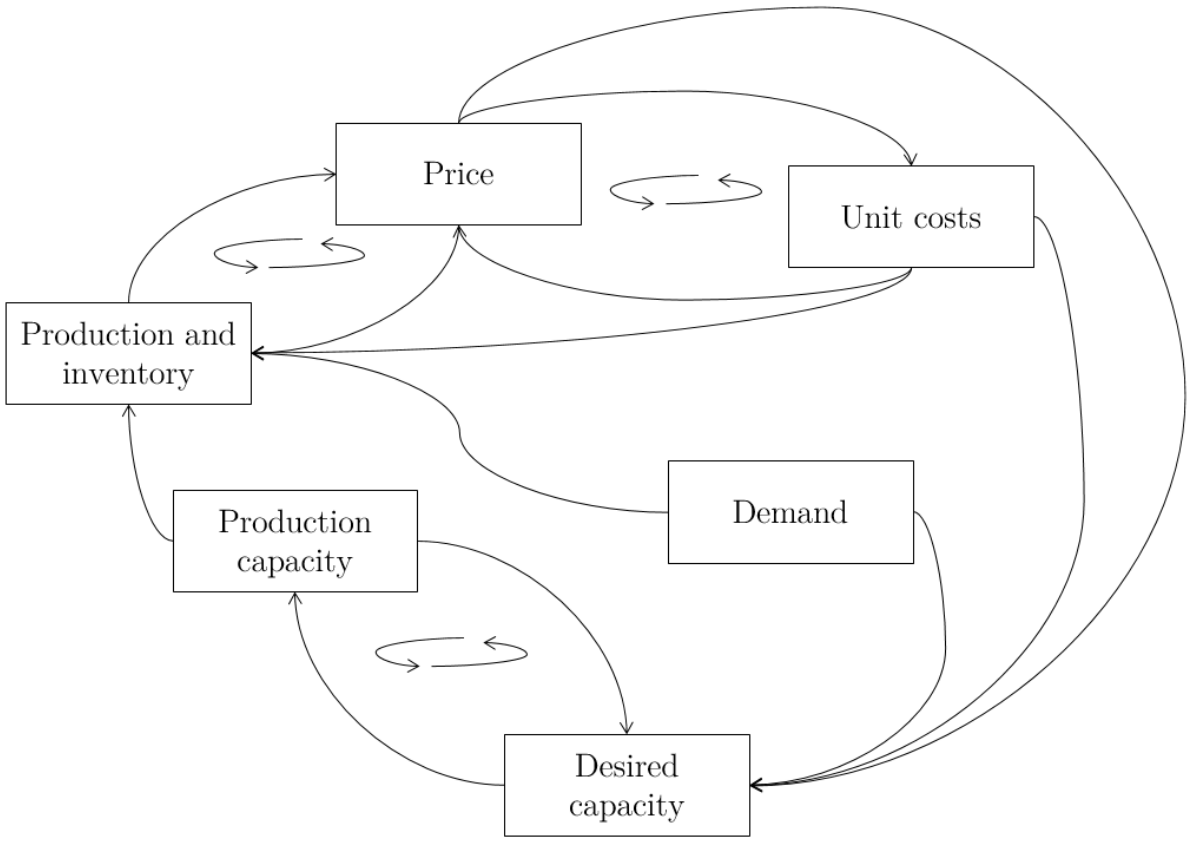
5.1 Model conceptualisation

When designing a system dynamics model, one follows a similar procedure to when designing almost any other model, such as *e.g.* a general equilibrium model or when setting up an econometric system. The fundamental units of tests have to be rooted in something observed or theoretical, and thus it is important to consider the underlying relationship in what one is studying. In our example, we are concerned with the price development of platinum, and the generic commodities model that will be introduced has been developed to cover a variety of factors that affect the pricing structure of commodities. There are, however, some differences when considering the model build-up, given that system dynamics is a more operational approach, as opposed to many theoretically oriented economic approaches.

Forrester (1994), the father of system dynamics, described the process of building a model as follows: Firstly, the system had to be described, as any attempt to analyse it would be futile without understanding the underlying fundamentals. Thereafter, this description needs to be turned into the equivalent mathematical concepts and notions, and in terms of a system dynamics model, these are stocks, flows, and rates. Stocks are integrals that contain everything that has flown into it, and the rate decides at what rate something flows into a stock. In addition, there are various other parameters and variables that determine other factors regarding the stocks, flows, and rates. In essence, one can describe a system very intuitively by merely considering a variety of parameters of interest and how they would affect each other mathematically. After defining the system, one can start simulating the model and checking for results. Upon the first simulations, alternative designs, policies, and structures should be considered. Upon learning more about the fundamental structures, and debating on various purposes, one can then implement new changes in policies and structures. Thus, the iterative process of building a system dynamics model continues.

In this study, the model that will be used in simulating platinum prices is an extension of a generic commodities model presented in chapter 20 of Sterman (2000), which in turn was inspired by Meadows (1970). The model presented in the textbook considers six different aspects of pricing a commodity, which are: cost, price, demand, inventory, production capacity, and desired capacity. All of these parts are interlinked and interwoven and make up the system dynamics model. The following figure depicts graphically the flow of information between the different sectors in the model.

Figure 7. Interdependencies across the system dynamics model



In such a model, the price is not determined explicitly, but rather implicitly through the interaction of many functions. The premise of system dynamics is to deal with the many non-linearities that arise in a complex world, and it is consequently very adept at dealing with many non-rational and adaptive behaviours. For this thesis, the generic commodities model was slightly altered to take into account the nature of platinum. The pre-built generic commodities model was constructed for cyclical commodities, while platinum cannot arguably establish an equilibrium in the same way as other cyclical goods due to the markets poor ability to adjust to the prevailing supply and demand conditions. Due to this, the demand structure had to be altered to reflect platinum's nature. The process is described in more detail in the following subsection.

5.2 Building a system dynamics model

When building a model, it is important to firstly consider what the model is trying to answer, and then to think of the parameters and variables that can be estimated and that are of interest. Given that a pre-built generic commodities model was used, the actual model did not have to be defined to the same extent in this exercise as would normally be warranted. This subsection will thusly describe the functioning of the pre-built commodities model and elaborate on the modifications that had to be made in order to make it reflect the realities facing the platinum market.

Given that the model does not consider individual firms, an aggregated industry is thus being emulated by using a representative firm. If needed, a system dynamics model could also be adjusted to include individual factors affecting each firm. In its entirety, the system dynamics model consists of six different parts or sectors that all take part in simulating a commodities market. The six parts or sectors are: cost, price, demand, inventory, production capacity, and desired capacity. Each of these parts are for all intents and purposes part of a larger model, however, they are separated in order to better understand how each part contributes to analysing a commodities market. Although the parts are in one way or another connected to another part in the model, each separate sector represents one separate group or action in the model.

The names are rather self-explanatory, however, an exposition might still be warranted. The cost part of the model determines the costs that the platinum manufacturers would face. It considers primarily the unit costs of producing a troy ounce of platinum, and the unit costs are determined as a fraction of the initialisation price, and the future unit variable costs are determined through a predetermined growth path in costs or through random noise.

The production and inventory sector is determined by a flow from a sink (a nebulous hole that either collects or releases inputs) through a work in process inventory stock to an actual inventory stock. This simulates the process of actually producing a unit of sellable platinum. The rate at which production starts is determined by the capacity utilisation, with some potential for a lag. The capacity utilisation in turn is determined by the short run expected price as well as the expected variable cost. The production rate, which is different from the rate that production actually starts, is influenced by both the manufacturing cycle time as well as the production start rate. The material leaves the

system through a shipment rate, back to the nebulous sink. The sinks function as a way of jumping into the middle of a model without defining a clear source and output, thus allowing the analysis of the production process instead of accounting for all the platinum that has been sourced and produced. Then finally, the rate at which shipments occur is dependent on the order fulfillment ratio, the inventory coverage, the maximum shipment ratio, as well as the desired shipment ratio.

The price is determined by a variety of actors as well. Primarily, it is a combination of the traders' expected price, which takes time to adjust (*i.e.* they are adaptive) and cost pressures, which are dependent on the sensitivity of the price to the cost, as well as the effect of the inventory coverage on the price.

The demand sector decides the amount of customer orders, which then get fed into the production function. The amount of orders is dependent on the relative prices and elasticities of each product. Given the design of the demand sector, short run fluctuations occur due to the elasticities being used. The normal generic model is designed for cyclic goods, whereby the elasticity is used to change the price and the production mechanism would shift to restore balance. Given that the platinum markets function differently, the generic commodities model had to be modified slightly.

The pre-built model was modified in two parts: firstly an exogenously determined growth factor, which was estimated in Alonso (2010) was built into the model. Then a second function was constructed whereby the percentage price differential between yesterday's and today's price that was not attributed to the exogenously determined growth projection, in conjunction with the product elasticity, determined the short run variability in sales. In the long run, however, the continuous exogenous growth factor would mask any short run effects from the price differential.

The production capacity is determined primarily by the interplay between the capital stock that is available to create capacity and to produce with, and the amount of orders that are being received. There are various feedback loops in place that govern the production process. Furthermore, there are many adaptive behaviours put in place, *e.g.* it takes time to adjust for both capacity and the supply line when more orders prompt the need for increased production capacity.

The desired capacity is based on the current price, the unit variable- and fixed cost, as well as the amount of capital stock. The interplay between these then determines the

amount of desired capital, which feeds into the production capacity sector and determines how much should be produced.

The formal diagrams and equations for this system can be found in the appendix. Also, a more thorough explanation of the dynamics in action can be found in Sterman (2000).

5.3 Parameterisation

After having considered the desired conceptual model as well as constructed the model of interest, one can start considering the values that need to be inputted. For the actual modelling, a programme called Vensim® vas used to amend the model (as the generic model presented in Sterman (2000) existed as a pre-built template for Vensim), and much of Alonso's (2010) previous work was used in terms of parameter inputs. This subsection describes the parameters of interest that were not calibrated (calibrated in this setting implies the values that could not be determined through reports, analyses, or industry experts, but had to rather be mathematically evaluated by minimising the difference to the actual witnessed price); these parameters were rather exogenously inputted from other sources.

Firstly, the set of exogenous parameters that had been determined previously by Alonso (2010) were inputted. These were demand factors that included elasticities, growth rates, as well as demand adjustment delays that had been calculated separately for different goods (in this model, only catalytic converters, jewellery, and others were considered). The following table highlights these values. As with the remaining tables describing the parameters, if there is no unit after the parameter value, this implies that the value is dimensionless.

Table 3. Exogenous parameters previously determined

Sector	Parameter name	Parameter value
Demand	Jewellery Demand Elasticity	0.55
Demand	Catalytic Converter Demand Elasticity	0.1
Demand	Other Industry Demand Elasticity	0.6[22]
Demand	Jewellery Demand Growth	3.17% per annum / 0.26% per month
Demand	Catalytic Converter Demand Growth	5.61% per annum / 0.46% per month
Demand	Other Industry Demand Growth	1.98% per annum[23] / 0.16% per month
Demand	Jewellery Demand Delay	1 year
Demand	Catalytic Converter Demand Delay	15 years
Demand	Other Industry Demand Delay	9 years[24]

Source: Alonso (2010)

The values presented in the former table had been analysed and determine in earlier work, and was consequently a natural stepping stone when parameterising the model in this thesis. These values were econometrically estimated based on historic data. Alonso (2010) describes in more detail how these parameters were determined. The following table contains another three parameters that were exogenously inputted. These values are not as much based on any specific previous work, theory, or observation, but rather on the stability of the model.

A capital productivity of one is a subjective choice, and in this thesis it was determined that capital would have a standard, normalised productivity level. The two parameters concerning the minimum order processing time in the production and inventory sector and coverage perception time in the price sector had to be within a certain interval for the model to not start looping excessively. What this means is that the time spans for these two parameters would not correspond enough to other parameters in the model, and consequently start creating ludicrous cycles in the model (the potential issues with this are addressed in the robustness checks subsection). With the current parameters the model is stable and produces much more reliable and believable results.

[22] This is a weighted average based on the other sectors' size of the total platinum market.
[23] Ibid.
[24] Ibid.

Table 4. Exogenously inputted parameters

Sector	Parameter name	Value
Production and Inventory	Minimum Order Processing Time	0.175 months
Price	Coverage Perception Time	0.167 months
Production Capacity	Capital Productivity	1

The final table contains what are called the reference values, but for all intents and purposes are equivalent to initialisation values. The model starts from January 1975 and the simulated values are collected monthly, albeit the model simulates at a finer level of detail than that (the time step, as the rate of simulation is called, is set at 0.0625 out of one month). The reference values that are noted below are the values that were observed in the real world at this point in time and were thus used to initialise the model before simulating.

Table 5. Reference values (*i.e.* the initialisation values)

Sector	Parameter name	Value
Price	Initial price	150 USD
Price	Reference Inventory Coverage	0.2[25]
Unit Costs	Initial Variable Cost Fraction	0.6[26]
Demand	Reference Price	150 USD
Demand	Catalytic Converter Reference Demand	360 oz t[27]
Demand	Jewellery Reference Demand	1210 oz t
Demand	Other Industry Reference Demand	2070 oz t

Source: Johnson Matthey (2013); Alonso (2010); Kitko (2014); Anglo American Platinum (2012)

The parameterisation process that was outlined above could have obviously been done differently, however, this process ensured that realistic and reasonable values were used. One major point of criticism are the exogenous parameters that are used to ensure the

[25] Reference derived from Alonso (2010).

[26] Calculated on the basis of Anglo-Platinum's annual report.

[27] Troy ounce, the standard measurement for precious metals. One troy ounce is roughly 31 grams.

stability of the system, and partially reflect the fact that the system as a whole might not be as well behaved as it ideally should be. Nevertheless, we are still able to use the modelling setup to simulate the future prices as the remaining parameters of interest can be calibrated to the observed prices.

5.4 Calibration

There are a variety of components in the model that would be difficult or practically impossible to ascertain, and these can be estimated using calibration techniques. The general method for parameter calibration is built on trying to find a set of parameters that will ensure that the simulated price is as close as possible to the observed price. We can never account for random, exogenous events so there will always be some level of variability even when optimising. How good a model is, is to some degree dependent on how closely it can follow the actual witnessed prices. Given that the generic commodities model that was used did not take into account the many intricacies that are present in the platinum markets (as is for example seen in Alonso (2010)), one is inevitably left with a model which can give an indication of the long term, overarching trend, as opposed to a minutiae estimation.

The calibration procedure works by adjusting the values for a set of parameters between a predetermined boundary and consequently minimising the difference to the observed prices using Powell's minimisation[28]. The parameters that are being calibrated for, generally fall into two categories: those that would have ideally been based on more concrete industry observations, and those that can be more realistically estimated through a minimisation algorithm.

The parameters that involve adjusting to price and cost expectations are arguably better estimated through minimisation techniques as opposed to inquiring industry experts for the simple reason that it is an aggregated market behaviour that we are interested in measuring, something that the market participants might not be that aware of. This is in contrast to, for example, inquiring about manufacturing cycle times, which are going to be known by the companies that engage in the trade. These values were not acquired for this study, but should have ideally been explored for the model.

[28] Powell's minimisation is a mathematical algorithm that can efficiently find parameters that minimises the difference to the values that are being compared.

The following tables go through the parameters that were calibrated most closely to the real world data. The boundaries are also stated before the calibrated value. When initially optimising, the payoff function performed much worse as there is an inherent trial and error process involved with optimisation. Through time, and through the standard scientific process of trial and error as well as utilising logic, a set of boundary equations were established that were not too prohibitive computationally. The calibrated values are the best guesses given the model setup, the exogenous parameters, and the model boundaries.

Table 6. Calibrated parameters: desired capacity sector

	Boundary		
Parameter name	Lower	Upper	Value
Time to Adjust Expected Costs	0	12	12 months
Time to Adjust Long Run Price Expectations	3	12	3 months
Sensitivity of Investment to Exp Profit	0	1	1

Table 7. Calibrated parameters: production and inventory sector

	Boundary		
Parameter name	Lower	Upper	Value
Time to Adjust Short run Price Expectations	0	3	2.6 months
Time to Adjust Expected Variable Costs	0	12	1.7 months
Manufacturing Cycle Time	0	12	1.6 months
Utilisation Adjustment Time	0	3	0.3 months

Table 8. Calibrated parameters: production capacity sector

	Boundary		
Parameter name	Lower	Upper	Value
Supply Line Adjustment Time	0	12	3.8 months
Capacity Acquisition Delay	0	12	5.9 months
Capacity Adjustment Time	0	12	1.7 months
Average Life of Capacity	12	120	23 months

Table 9. Calibrated parameters: price sector

	Boundary		
Parameter name	Lower	Upper	Value
Time to Adjust Traders' Expected Price	0	12	1.2 months
Sensitivity of Price to Costs	0	1	0.3
Sensitivity of Price to Inventory Coverage	-1	0	-0.8

All of the calibrations were done with a 2.5% unit cost increase embedded into the model. The cost increases were then varied when doing the scenario simulations in order to assess the effects of cost increases on the simulated price.

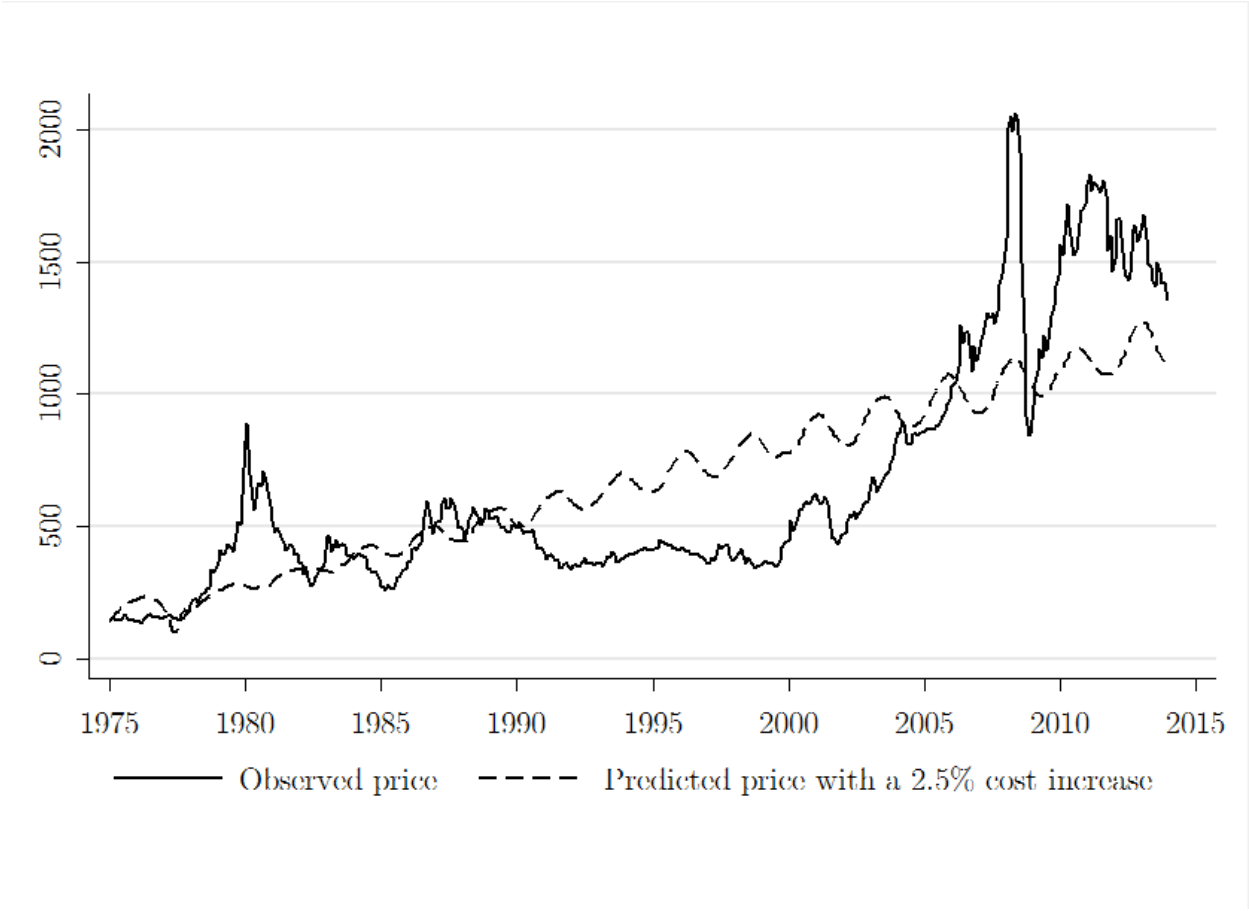
5.5 Scenario simulations

After the parameters were calibrated to match as closely as possible to the actual price, a variety of pricing simulations were conducted. The simulations were carried out by firstly initialising the system to the reference values, and then letting the system's internal dynamics and feedback mechanisms generate the simulated prices over time by always using inputs from the previous periods within the model; this is in contrast to many general equilibrium models where each period by itself is calculated to ensure that equilibrium is reach in said period. The downside of the general equilibrium methodology is that the internal dynamics of how variables affect each other within a period are missing; merely having one or two previous result affect the current values is not truly dynamic.

For the following price simulations, three different unit cost increases were used, which were: 0%, 2.5%, and 5%. Furthermore, all simulations had white noise fed into both the demand sector as well as the variable cost sector in order to create some random effects more akin to real markets. The white noise seed standard deviation was set at 0.25.

The first of the following two graphs shows the actual observed prices since 1975 with the predicted price from using the parameters that were described in previous subsections. Furthermore, it used the 2.5% marginal cost increase that the parameters were calibrated to. The second graph shows the future price predictions with either a 0%, 2.5%, or a 5% marginal cost increase.

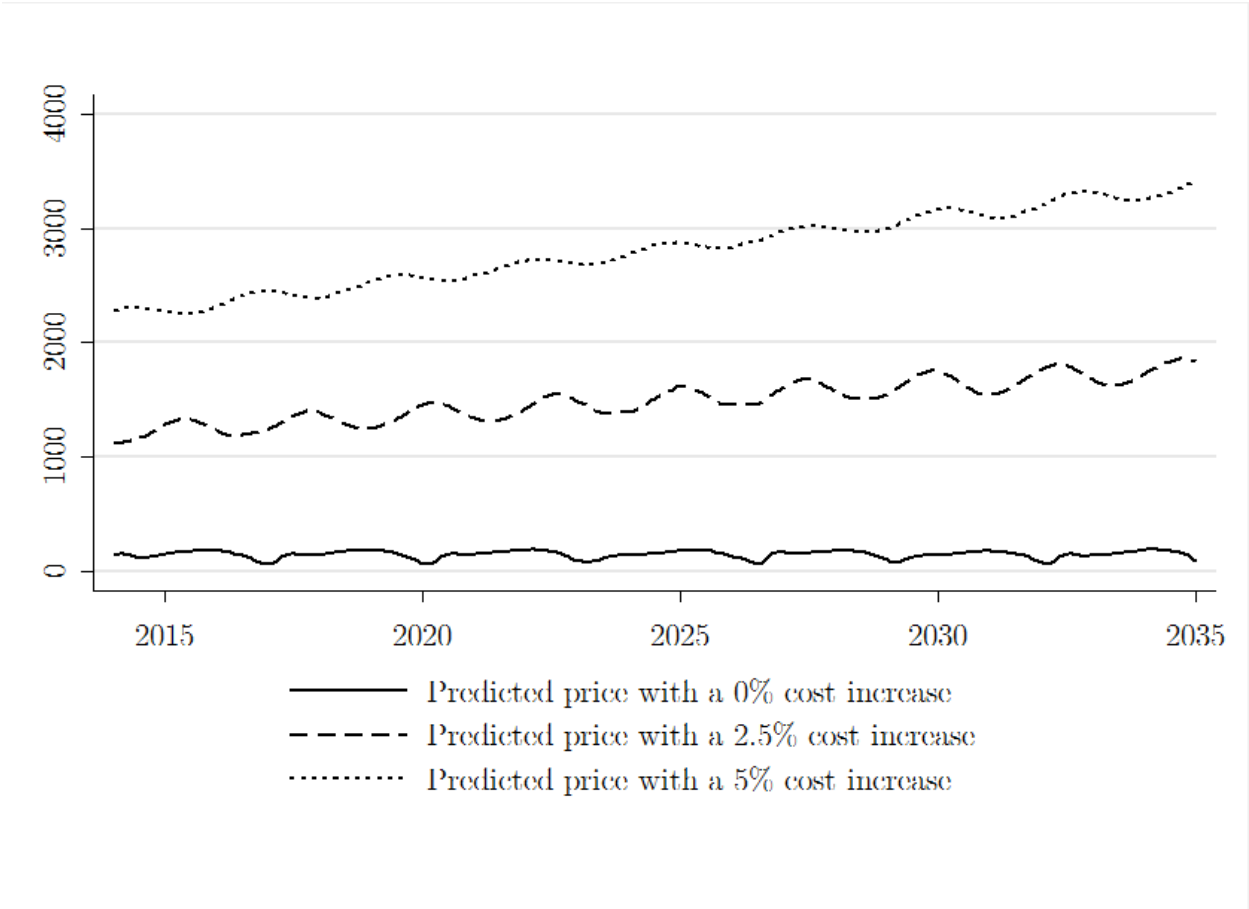
Figure 8. Observed and predicted prices in nominal USD per troy ounce



The predicted values are business as usual predictions, that is to say, this is the prediction based on historic trends a well as a mathematically optimised market structure.

The platinum dependency in climate change mitigation and the potential effects are not explored endogenously within this model.

Figure 9. Predicted future platinum prices in nominal USD per troy ounce



The graph above (Figure 10), shows the predicted prices with various cost increases. The cost increases were set to begin at the point of initialisation, which explains the discrepancy in the future predictions. With no increasing marginal costs, the model is built around being able to increase the amount of supply that is available to compensate for the increased demand. Since there are several supply issues with platinum sourcing, as has been mentioned throughout this thesis, an increasing marginal cost is used to simulate the fact that it will be more expensive to source PGMs form worse ore grades as well as from deeper mines.

5.6 Robustness checks

Like with any modelling approach it is worthwhile to carry out robustness checks to assess the model that was created. While statistical tests can provide some insight into the model, it is important to remember that given the nature of models, they can never be fully validated or verified. The following table contains a variety of tests that have were recommended by Sterman (2000) and that will be considered in light of the system dynamics model.

Table 10. Robustness checks for system dynamics models

	Test	Purpose
1	Boundary adequacy	To test if the important concepts are endogenous to the model.
2	Structure assessment	To assess whether the structure of the model is sound, realistic, and consistent with the laws that are observed. Also, whether the level of aggregation is appropriate.
3	Dimensional consistency	To check if all of the equations are dimensionally consistent.
4	Parameter assessment	To explore if the parameter values are consistent with relevant descriptive and numerical knowledge of the system, and if all of the parameters have real world counterparts.
5	Extreme conditions	To test how the model responds to extreme events.
6	Integration error	To assess whether the result are sensitive to the choice of time step or numerical integration method.
7	Behaviour reproduction	To check if the model reproduces the behaviour of interest in the system both qualitatively and quantitatively.
8	Behaviour anomaly	To explore whether anomalous behaviour occurs when changing the assumptions of the model.
9	Family member	To test whether the models generates the behaviour observed in other instances of the same system.
10	Surprise behaviour	To assess if the model generates previously unobserved and unrecognised behaviour.
11	Sensitivity analysis	To check how sensitive the system is to the values that are used and the behaviour that is emulated.
12	System improvement	To explore whether the modelling process helped change the system for the better.

Source: adapted from Sterman (2000), who adapted and extended it from Forrester and Senge (1980)

The tests that were mentioned in the previous table could be divided into three larger groups, namely those tests that concern themselves with the structure of the model, how the model is used, and how the model performs. When performing checks on the model, they will be done according to this three group classification. The first group of tests would include boundary adequacy, structure assessment, system improvement, and parameter assessment. The questions that these individual tests seek to answer are explored throughout the thesis. In short, there are severe drawbacks to the structure of the model, and as such it has relatively limited use. While a more sophisticated proper model would account for many of the qualitative corollaries that are discussed in the next section (6), the current model setup is good enough for considering long term price changes.

The second group of tests would include behaviour anomaly, family member, surprise behaviour, and extreme conditions. All of these tests seek to stress test the model at hand. As was earlier noted, certain exogenous parameters had to be used to ensure the stability of the system. This clearly shows that there are some problems in the behaviour of the model when certain parameters are adjusted. While the results that are presented when using appropriate demand drivers and initialisation values are sane, it is still troublesome that when the model is stress tested, it does perform rather badly and produce some spurious results.

The third and final group of tests consists of dimensional consistency, integration error, sensitivity analysis, behaviour reproduction. These tests are designed to check how well the model performs. The model was tested for integration errors and dimensional consistencies, of which there were none. The other statistical tests of interest are detailed more carefully below. Three standard statistical tests will be carried out, namely determining the coefficient of determination, calculating the mean square error, and then performing a serious of tests named Theil's inequality statistics which are designed to assess the properties of the data and the model. This inequality statistic decomposes the MSE into three components: a bias, an unequal variation, and an unequal covariation. These tests are formalised below (where $\bar{X}$ is the mean of the variable and $\boldsymbol{s}$ refers to the standard deviation):

Equation 4. Coefficient of determination:

$$R^2 = r^2; r = \frac{1}{n}\sum \frac{(X_d - \bar{X}_d)(X_m - \bar{X}_m)}{s_d s_m} \quad (4)$$

Equation 5. (Root) Mean square error:

$$MSE = \frac{1}{n}\sum (X - X_d)^2; RMSE = \sqrt{MSE} \quad (5)$$

Equation 6. Theil's inequality statistic – the bias component:

$$U^M = \frac{(\bar{X}_m{}^2 - \bar{X}_d{}^2)}{MSE} \quad (6)$$

Equation 7. Theil's inequality statistic – the unequal variation component:

$$U^S = \frac{(s_m{}^2 - s_d{}^2)}{MSE} \quad (7)$$

Equation 8. Theil's inequality statistic – the unequal covariation component:

$$U^C = \frac{2(1-r)s_m s_d}{MSE} \quad (8)$$

Table 11. Summary statistics for assessing the model fit to the data

Metric		Value
R^2		0.63
R(MSE)		281
	Component	
Theil's inequality statistics	Bias	0.23
	Unequal variation	-1.4
	Unequal covariation	0.7

Theil's inequality statistics usually indicate that there are problems with the model if the values start approaching one. Given that the values for both the bias and unequal variation are low, we know that there are no systemic biases nor any issues with trends and how the data is followed. The relatively high value for unequal covariation could indicate a systemic error if phasing is important to the purpose and if the model is driven by historic data. It is, however, unsystematic if the model is driven by noise. For our model, the phasing is not important, since there are no specific cycles in the platinum market, however, the model is driven by historic data. Furthermore, many of the small changes are driven by noise. Albeit the value of unequal variation is high, it does not necessarily indicate a systemic error given the type of data that is used and the type of model.

Based on the summary statistics, the model does for the most parts behave well enough. There were several problems that were addressed earlier with regards to the behaviour and the structure of the model. These do remain problematic and are ultimately indicative of the fact that more emphasis should be put on model building. That being said, the predicted prices have a relative high coefficient of determination and are otherwise behaving numerically rather well. Ultimately, a model has to also be judged by its purpose as well as the summary statistics, and given that we were interested in some simple, macro oriented, long term pricing scenarios for platinum, the model functioned well enough.

5.7 Summary

The quantitative price analysis using a system dynamics model was used to assess the pricing structure of platinum as part of the causal pathway analysis. An approach was taken whereby a usable prediction would be simulated with a fraction of the complexity (and thus also the detail) compared to Alonso (2010), thus focusing on broad, long run scale projections. It is rather obvious from the scenario simulations that there are deterministic trends at play as Alonso's long term growth rates were used for the various demand side industries. Thus, while the model does create endogenous demand in the short run, the long run effects are exogenously determined, and thus start carrying much more weight. This aside, the model can at least consider on a very superficial level some of the dynamics at work within the platinum market. Although, it goes without saying that the system dynamics analysis at hand is at most meant to guide and provide some insight on future trends, not actually predict exact values.

The actual accuracy could be increased significantly due to system dynamics' non-linear nature. Consequently, a much more advanced model could be built that would consider the full sourcing of platinum, and all of the associated complexities. While a system dynamics model could take into account many short- and long term behaviours and trends, larger exogenous effects are notoriously difficult to model. Big changes such as innovations are very difficult to endogenise since they are by nature unpredictable and far-reaching. While not being able to account for these types of extreme events, Alonso (2010) wrote for her PhD thesis a rather impressive system dynamics model that could follow the pricing of platinum much more accurately than the model that was used here.

But as with all models, one gains and loses as one goes from the general to the specific. Furthermore, in this case, we were merely interested in the future trend given simple descriptions of market actors and structures. For the task at hand, it seems to have sufficed as the key components of a commodities market were in place, and the proper demand drivers were also included. Increasing extraction costs or scarcity was also considered through using a higher unit variable cost as a proxy. Thus, many different components were simulated through indirect means.

While it could be worthwhile to provide a sense of the costs associated with not considering the potential supply bottlenecks and competing demand for platinum, it would in equal parts be slightly futile, outside the scope of this thesis, and also defeat the purpose

of this thesis. This thesis seeks to highlight the fact that we need to have operational considerations when addressing the issue of climate change mitigation (which has unfortunately been mostly unachievable in the world of politics and academia).

6 Qualitative Corollaries

"So I think there are more politicians in favor of electric cars than against. There are still some that are against, and I think the reasoning for that varies depending on the person, but in some cases, they just do not believe in climate change — they think oil will last forever."

- Elon Musk, CEO of Tesla Motors

The scenario simulations that were conducted in the previous section speak mostly for themselves – based on the demand drivers as well as increasing marginal costs, platinum prices are set to increase in the future. Obviously, the results are dependent on the model structure; however, similar – although much more elaborate – model structures for example in Alonso, Field & Kirchain (2008) and Alonso (2009) as well as van Vuuren, Strengers & de Vries (1999) do to a large degree validate the expected price rise seen in the previous section. The question that must now be considered is what the corollaries are beyond that of a mere platinum price hike.

The quantitative part of the causal pathway analysis, which involved using a system dynamics model, addressed the future of the platinum markets, and by considering the qualitative interdependencies as well as the causes and effects, we can map out how the model results would factor into various facets of society. Through this process we would consider beyond the internal dynamics and feedback mechanisms of the price changes, and consider the dynamics and feedback mechanism at work in society at large. The following qualitative analysis would have ideally been endogenised, however, the complexity involved in building such a model would have taken the focus away from looking at platinum's role in climate change mitigation. A major focus on building a more extensive model would have been slightly outside the scope of this master's thesis as well, as the thesis itself is not focused solely on building a model, but rather exploring the role of a mission-critical resource in climate change mitigation.

Given that the aim of the thesis is to analyse platinum's role in climate change mitigation, a qualitative counterpart does allow a more diverse and varied analysis in a shorter timeframe. Also, it is worthwhile to qualitatively consider a variety of pitfalls and opportunities that exist as a result of the quantitative result. By exploring the various issues

at hand qualitatively instead of focusing on endogenising them in the quantitative model, we are allowed more room to explore the corollaries in-depth. The following subsections will go through five different qualitative facets that are being considered as part of the causal pathway analysis; they are: the economic consequences, the political ramifications, the geographic implications, the social and ethical considerations, and finally the environmental impacts.

6.1 Economic consequences

When considering the following corollaries, it is important to put them all in terms of the focus of this thesis, namely climate change mitigation. With this in mind, the key issue to consider in terms of the economic consequences is not the price increase of platinum *per se*, which would affect climate change mitigation efforts, but rather the knock-on effects that it would have on current and future products that are dependent on platinum usage. The potential implication would be that not only do current environmental projects become more expensive, but future ones would as well.

To understand platinum's development better, it is crucial to understand the underlying demand drivers. Since the primary use for platinum is either in catalytic converters or in jewellery (accounting for 38% and 34% respectively in 2012), and with only minimal use, proportionally at least, in other high-tech industries (combining chemical, medical, electrical, and petroleum would lead to 13%), the pure price analysis becomes rather limited in scope (Johnson Matthey, 2013). This is because there are really only two key primary demand drivers; thus, what is interesting in this context are the relative elasticities for the two primary products. Jewellery, by its very definition would be seen as a luxury good, which tend to be rather elastic (*i.e.* price sensitive) (Perloff, 2011). This is in stark contrast to catalytic converter use, which is arguably almost perfectly inelastic, since its use is established by environmental regulation (obviously differing between countries). Conversely, car purchases would have an elasticity somewhere between the two, and it would come as no surprise if higher platinum costs would be pushed onto the consumer, as manufacturers could easily justify it due to the environmental regulatory framework.

A recent analysis considered the immediate future's vehicular demands (The Economist, 2013). The data shows that that there were roughly five million units of light-vehicles sold per year in China in 2005, and in 2020 they are predicted to hit 30 million units per year.

North America, Western Europe, as well as Japan and South Korea have not seen dramatic changes and are for all intents and purposes satiated markets, so while new cars are being bought to replace ageing ones, this is still vastly different from much of developing Asia that is seeing many of their first car purchases. Considering what the future will hold, it is highly likely that there would be a dynamic process whereby there would not only be an increased demand for vehicles but also potentially higher environmental standards (as cars in Asia only use around two grams of PGMs on average, compared to their European counterparts where six grams is used and in the United States where on average four grams per car is used), which cause the price to successively rise in conjunction (Stillwater Mining Company, 2012). The combined effect of the two is obviously an upward price pressure, but how much either aspects ends up affecting the other remains to be seen.

Car sales might slow down due to the knock-on effect since they would be more price elastic than the catalytic converters themselves. However, using the words found in the AR4, modes of transportation such as car use are seen as something of a right (IPCC, 2007). Furthermore, a growing middle class around the world will want the transport capacity that a car brings, thus one could assume that the price hikes for cars as a result of the increased costs of platinum would be tolerable (or nonexistent if environmental standards are not in place). A price increase would furthermore lead to platinum's importance in jewellery diminishing due to jewellery being more elastic than catalytic converters, which would free up some supply that could be used elsewhere. This would then ease on the upward demand pressure (at least based on the estimated elasticities presented in the previous section).

While the good news might be that there is some maneuverability in the price, since not all demand is highly inelastic, there is still the danger involved with having markets for a resource whose primary use is in an inelastic good. One worry to consider would be that since the odds of environmental standards getting less stringent are rather small (we as human beings do not like giving up entitlements, and clean air is an entitlement that the catalytic converter was devised to provide), there would be a baseline demand for platinum that is only set to increase. Although palladium and rhodium can substitute platinum to some degree, no full market substitutes exist (Stillwater Mining Company, 2012). With no real marketable substitutes in place, inefficiencies can be spurred as the industry does not have the same incentives to be more effective since catalytic converters are inelastic by nature (Glaister & Mudd, 2010). The longer term consequence of this is of course even

higher prices, as the industry would not be as flexible when it comes to the pricing structure since there has not been the same demand to innovate and stay ahead of the cost curve.

Ultimately, given catalytic converters' highly inelastic nature, it is safer to assume that much of the development for their use will dictate the near-term future of platinum prices. Furthermore, since there is some level of substitutability between platinum and palladium in catalytic converter use, there is some supply slack that can also dampen the increased demand (Stillwater Mining Company, 2012). In the end, given that natural resources that are not used as general hedging alternatives (investment only accounts for about 6% of the total market) tend to be priced according to their long run supply and demand characteristics, the key economic consequences were those of the aforementioned knock-on effects (Hotelling, 1931; Hanson, 1980; Kneese, 1988; Pindyck, 1978; Johnson Matthey, 2013). As has been mentioned earlier, the longer-term effects would come in where platinum could be a primary ingredient in another product, and the example that we have been referring to is the use of platinum in PEM fuel cells. PEM fuel cells would of course be bringing in another problem, as the implementation of PEM fuel cell solutions, while good for the environment from a climate change perspective, would simultaneously increase the demand for platinum, which might increase the costs of cars due to a more expensive catalytic converter, which could lead to a negative view on environmental efforts.

6.2 Political ramifications

When considering the political ramifications, it is important to put them in light of what we are discussing, and also, what level we are discussing on. When analysing the political implications in terms of the causal pathway analysis, it would be rather spurious to suggest that there are direct political implications of rising platinum prices. To suggest, however, that there might be environmentally related policy impacts due to rising platinum prices, which in turn have political implications, is hardly as absurd. Thus, while the direct effect of rising platinum prices hardly has any political ramifications, the feedback mechanism and dynamics at play could easily affect the policy process.

A prime example of this would be with the promise of a green good. With a larger focus on providing environmental goods in many parts of the world, politicians could promise a certain amount of improvement in, *e.g.* the air quality due to a new environmental standard, which would obviously come at a cost since solutions like catalytic converters have a price.

The populace at large might be willing to accept an environmental good at a certain cost, however, if the cost starts spiraling out of control, then the public support for said project might deteriorate rather fast[29].

While cost overrun analyses are nothing new, and something that can quite often be observed as an argument against stricter environmental policy (or against any public policy really), it is nevertheless the extent of the backlash that this type of analysis could provide that is interesting. This also takes us back to the debate about costs vs benefit which were discussed in section 3 as the problem within current climate change mitigation policy making. Considering the previous example, if a stricter inner-city clean air policy would be implemented in a developing country, this would inevitably mean that either catalytic converters would have to be installed on more cars, or that higher amounts of platinum would have to be utilised (Esty & Porter, 2001; Carter, 2013). In many parts of the developing world, politicians also need to ensure sustained economic growth, and balancing the two might prove to be rather difficult, and lead to reneged promises on the part of politicians.

Politicians have many primary objectives to attain, and besides whatever personal motives are on the table, sustained economic growth usually ranks high on the list of important policy agendas. The fact that there is some potential for a current investment in higher environmental standards to lead to other knock-on effects that reduce general economic growth could lead to voter resentment. This comes back then to the questions of inter-temporal preferences and the choice of a discount rate. A more realistic non-zero discount rate would lead to individuals appraising current consumption more than a potential future benefit. If there would be a government led effort to redistribute current consumption for future generations, it would not be unimaginable to envisage voter resentment. Furthermore, had the current investment rather gone to invigorate the economy (in some vague sense), then this investment could yield more capital for new investments due to the spurred economic growth. The new capital could then be significant in investing in even more expensive and newer environmentally-friendly technologies. Thus, there is an inter-temporal and also an intra-temporal allocation consideration between using current

[29] Examples of this are aplenty, *e.g.* more or less any Olympic games have had cost overruns. Public cost overruns are not something new, but it is important to consider the fact that it is easier to reverse environmental policy as opposed to an almost completed infrastructure project.

stocks to address a current issue and using current stocks to potentially gain a larger future benefit that cannot be ignored.

Looking at this specifically in terms of the platinum markets and assuming a future higher platinum price (due to both a combination of increased cars and higher environmental standards), political promises to increase environmental standards further would put even more upward pressure on the price of platinum in the absence of good substitutes. Also, an increase in the price of platinum could further hamper political will to undertake environmental projects due to the large costs. Furthermore, old potential complications with unforeseen higher input prices might lead to a lack of political will in the future to undertake similar projects, which might affect current and future climate change mitigation efforts. As an example, potential political projects to support future technologies to replace PGMs' catalytic properties could end up never materialising. In the end, this discussion mostly highlights the need to divert money into research and development for technologies such PEM fuel cells.

6.3 Geographic implications

Given that climate change mitigation in the ground transportation sector is dependent on a steady supply of inputs, one of the more unique factors that need to be taken into account when analysing the PGM markets is the high concentration, both in terms of the amount of companies that are involved in mining as well as the geographical proximity. Since South Africa covers 72% of all current platinum production, and since they sit on 95% of all known global reserves, their role in the future of the platinum markets is rather unique (Loferski, 2013; Johnson Matthey, 2013).

There are real supply chain concerns that could severely affect the pricing structure. One real worry is that in light of the workers' strikes that occurred in 2012, we might see some similar action in the future (Yager, Soto-Viruet, & Barry, 2013). There are two factors that are increasing the risks for the possibility of a strike: one is that if platinum prices are higher, then workers have a higher incentive to strike since either the company would have the ability to pay them more (although the firms are currently rather unprofitable), or the workers would have a better bargaining position (Johnson Matthey, 2013). This is obviously dependent on the local conditions, and on the availability of substitute labour (for example from neighbouring Zimbabwe), but put in the light of industrial action in the country, it is

nevertheless a real concern that might have global implications in terms of environmental policy.

The second worry is that the South African regime might see an opportunity to give itself more control of the local platinum market. Although takeovers like this are not unheard of in the developing world, South Africa has not had the same legacy with them, although discussion of mine nationalisation has come up before (Rowley, 2013; Reuters, 2012). If a substitute to platinum is not found, and the price continues to increase, then there might even be incentives to engage in a zero-sum game to obtain valuable resources – to everyone's detriment as this would hamper global environmental mitigation efforts in the ground transportation sector.

6.4 Social and ethical considerations

One of the many considerations of the Kyoto protocol has been the question of ethics – namely who gets hit the hardest by the effects of climate change (IPCC, 2007). Unfortunately, as often is the answer, it is the developing countries, and even in them, the poor usually fare worse than the rich (Stern, 2007). This is not a new result, nor a result that is particular to the modelling choice at hand; however, it is still important to go through the social and ethical considerations as a result of the model output.

This specific climate change mitigation avenue – the use of platinum in catalytic converters – is going to hit anyone who is interested in using a motorised vehicle as transport and who lives in a country with environmental standards; or if there are no environmental standards in place, there will most likely be in the future, and that will bring additional costs with them.

Looking more specifically at developing countries, since a car is considered a rather quintessential middle class item in many places, it will put a lot of pressure on a societal class that can often be rather dependent on this mode of transport (IPCC, 2007). Increases in the price of platinum will not only impede the ability for the middle class to gain access to, or maintain access to a motorised vehicle, but might have more economy-wide implications as it is an integral part of the modern economy. As often happens, any price hikes obviously hurt the lower income brackets more, since their marginal propensities to consume are much higher. If it is determined that a specific environmental policy would hit the lowest echelons of society the hardest, then it might be ethically questionable to see it

through, which would dampen the upward price pressure. Furthermore, this might make it more difficult to drive through more restrictive environmental policy as it becomes a luxury of the rich.

6.5 Environmental impacts

The environmental impacts of higher platinum prices are quite straightforward as platinum would be needed as an input for catalytic converters to ensure that we are able to curb the effects of having a primarily fossil fuel based transportation sector. Any increases in the price of platinum would most likely be pushed onto the products that involve platinum, and in this case that would entail the catalytic converter. Given the discussion on elasticities in the first subsection concerning the economic consequence of a platinum price rise, it is safe to say that efforts to mitigate the effects of climate change would become more expensive.

With regards to actual causes and effects of climate change mitigation plans, most of the general recommendations that should be heeded vis-à-vis mitigating climate change have already been covered in AR1-4 as well as the Stern- and Garnaut Reviews. However, there are some additional considerations that should be considered in light of the causal pathway analysis. Considering the workings of the model, some of the key environmentally related take-home messages are tied to the sourcing and using of platinum.

The need to increase the amount of available source material is an absolute necessity as it has direct implications on the supply of the material. This can happen through a variety of avenues, the most obvious of which include recycling, where platinum is well poised since it can practically be cycled in perpetuity (at a cost) (Graedel T. E., *et al.*, 2011). Other considerations include redesigning and dematerialisation, which both relate to the potential efficiency gains that can be made by ensuring the same output by either using less of the input, or another combination of materials that are less scarce. These and related practises could easily ease the upward price pressure.

The amount of platinum that is being recycled has already increased significantly in the past decade (Johnson Matthey, 2013). This has partially been prompted by technological improvements, but it has also been driven by the high demand for platinum's catalytic properties. The same driving factors have also led to dematerialisation, which has also helped with the upward price pressure. One of the most promising avenues, however,

is the prospect of redesigning. Throughout this thesis, much emphasis is put on the need for increased research and development. While there are many ways that innovations could occur within this sector, the process of redesigning is quite fascinating. What it implies is that products would be designed so that they could be more easily and cheaply be reused and recycled. This is more an operational and engineering question, but shows another avenue whereby the smarter use of materials can lead to the increased availability of a precious metal.

In the end, all of the prospective effects of a platinum price rise do not need to be purely negative. There are many innovations, behavioural changes, and new practises that arise as a consequence of necessity. Within our example of platinum, we will need to use catalytic converters as long as the transportation sector is fossil fuel based, and anything that would incentivise efforts to either move beyond the need of using a catalytic converter, or improving its use would have a positive effect as that would ease the price pressure. This would consequently also make it easier to carry out climate change mitigation policies within the ground transportation sector.

7 Policy Lessons

"The climate change argument is absolute crap, however the politics are tough for us because 80 per cent of people believe climate change is a real and present danger."

- Tony Abbott, Prime Minister of Australia

The key purpose of using a causal pathway analysis to assess a mission-critical component – such as the use of platinum to ensure climate change mitigation – is to map out what systemic effects such an essential instrument could have. Through this analysis, it is hoped that some lessons could be discovered that would have potentially gone unnoticed in the mere top-heavy analytical approach – which really begets the question: what can we learn from the causal pathway analysis and bring back to the global scale and use in policy outlining? By taking the discussion away from issues of discount rates and other theoretically oriented questions that were prevalent in the review in section 3, an operationally focused transition plan can be presented that could serve as a foundation for future policy making.

7.1 In the short to medium term: structural measures

The key policy lesson for the short term from both the quantitative as well as the qualitative part of the causal pathway analysis of platinum is that having a transition strategy is of the utmost importance. This is due to the one unequivocal result of the causal pathway analysis: markets and market actors are imperfect. Through the system dynamics model we could see that with the most fundamental demand and cost assumptions, prices are set to increase. Thus this modelling result is a consequence of the model construct and design and as such, this is a foregone conclusion as it is an inherent component of the model. After all, there is no variable included that would regulate the market's conscience in terms of being able to provide an affordable environmental good[30] (platinum for catalytic converters in this case). This conclusion does, however, reflect the real problems that we

[30] Or in more formal terms, there is no included elasticity for an environmental effect, whereby higher prices would induce a kickback loop that would encourage either the supply to increase (at a lower cost than what the elasticity would dictate) or demand to drop to ease the upward pressure. This would be another component that a more advanced model could test.

have in terms of the supply, demand and pricing characteristics of mission-critical resources, such as platinum in climate change mitigation in the ground transportation sector.

Moving outside the system dynamics model and considering the situation in more practical terms: the inherent structural issues arise from market actors not seeing beyond the pricing mechanism. Considering Stern's statement of calling climate change *"the greatest market failure the world has seen"*, it comes as no surprise to see this market failure extended to what we deemed to be a mission-critical resource (Stern, 2007). *Ergo*, beyond not pricing the environmental consequences of using fossil fuels according to the environmental damage that is done, markets would also not price a natural resource in its strategic importance in climate change mitigation. On the other hand, to suggest that a price could reflect the importance of a strategic resource is of course an absurd proposition, since it ultimately cannot. The only way this could work in practise is if market actors would decide not to buy a resource in order to lower the price point, but considering the dynamics at work, this would of course lead to less supply which could imply higher prices – the reason why system dynamics exists is to explore questions like this; and the proposed causal pathway analysis is carried out to consider the many interactions and interdependencies across the issue at hand.

Thus the question of what measures could be taken to counteract the fact that markets do not inherently consider the strategic importance of platinum in climate change mitigation comes into the fray. As far as command and control approaches go to ensuring a constant supply at a price with low volatility, they would vary from trying to control the supply in a draconian fashion to merely being an active market agent. The ramifications for the two extremes would of course vary.

If one were to look at historical examples, the cobalt crisis witnessed in the 1970s could perhaps be something that one could learn from (Alonso, 2010). Zaire stood for the lion's share of the global cobalt production in 1978 and in the same year, its copper-cobalt mining region was invaded, which caused prices to rise by up to 380% (Shedd, 1998). Although there were U.S. government stockpiles, they had been sold off in the decade prior, and had to now be reintroduced as it was deemed a strategic resource input for military applications (Alonso, 2010; Shedd, 1998). The effects of the transition period in building up stockpiles and finding substitutes can be costly and warrants careful reflection. Using the same language that has been employed throughout this thesis, cobalt was mission-critical for U.S.

military applications, much in the same way that platinum is mission-critical to climate change mitigation efforts in the ground transportation sector.

On the note of stockpiles, U.S. government stockpiles of platinum already existed since the first values were reported back in 1960 (Kelly & Matos, 2012). They were fairly constant until 1996 when they were sold off over an 8 year period. Thus, the idea of stockpiling important natural resources – platinum specifically – to either stabilise markets due to supply disruptions or due to a specific national interest such as military applications is nothing new. This might even be heralding of what could be needed as a medium term solution if markets are unable to price the environmental importance of platinum. When considering strategic stockpiles, this is obviously not the only stockpile of strategically important resources. The U.S. also boasts strategic grain reserves, strategic petroleum reserves, and strategic national stockpiles of medicinal equipment – Canada even has a strategic maple syrup reserve. An international strategic stockpile of natural resources that are mission-critical and of the utmost strategic importance in mitigating climate change does not sound as absurd in light of the aforementioned. Realistically, national politics would probably come in the way; however, the idea of an international stockpile is nevertheless not ludicrous. It would, however, require an unprecedented amount of cooperation.

The larger question that this begets is whether there is a place for platinum reserves in modern markets. There are reports stating that car manufacturers are sitting on stockpiles of platinum as they usually sit on longer contracts with miners and any given economic detraction and an associated car sales slowdown would naturally lead to a build-up in stockpiles of material inputs (Mining Journal Online, 2013). Lengthier contracts by themselves spell less volatility as short market fluctuations are ironed out. However, the fact that car manufacturers themselves sit on platinum reserves is in itself a short term solution, and before we can rely on our hopes and dreams on the technologies of the future, we need to have an understanding, as well as a plan to deal with the medium term business dynamics. This would arguably require more action than what the car manufacturers themselves could accomplish.

The aforementioned examples clearly show that being an active market agent and stockpiling a resource for ulterior motives by harnessing the markets is feasible and reasonable. However, the price differential (*i.e.* the extra cost that will be involved with actively buying a resource and thus indicating a near zero demand elasticity, which

obviously incentivises the sellers to raise prices) will always be picked up by the market agent, and in the case of national strategic stockpiles, tax payers are the ones who would foot the bill. This is not a problem *per se*, although it is nevertheless important to remember that someone would have to pay for the stabilisation efforts; who would pay, in what amounts, and whom it would affect would all depend on the form of stabilisation.

The other extreme type of stabilisation effort that was briefly mentioned is that of physically controlling the markets; albeit implausible, it could in theory function – the mechanisms however, would depend on a tragic amount of optimism to actually work. The reason why this could function in theory is that while platinum markets are global in the sense that local prices do not exist that would allow arbitrage, sourcing locations are extremely localised in the sense that the repositories are located in a relatively small geographic area. Hence, a global authority could be needed to regulate the markets for the sake of the environmental benefit. On the bright side, since South Africa would not need to negotiate with the rest of the world, they could end up acting as the good steward and regulate the markets more intelligently. In practise, the odds of a monopoly acting as a good steward are not in anyone's favour; however, the geographic antecedent is at least in place to control the supply.

But what would this mean in practise? From a purely environmental perspective, it would imply that the resource should be diverted for environmental use in order to ease the upward price pressure. This would allow us to have an economically viable and environmentally sustainable resource to use to mitigate climate change within the ground transportation sector. However, this could have the unfortunate side effect of affecting the supply side and riddle it with inefficiencies and other externalities, which might end up causing more harm than the good intentions that the plan was conceived under. Consequently, a very difficult approach to undertake.

When considering resources, Robert Solow concluded that *"the market for exhaustible resources might be one of the places in the economy where some sort of organized indicative planning could play a constructive role."* He also made it clear that it was *"not an endorsement of centralized decision-making, which is likely to have imperfections and externalities of its own."* Indeed, according to him *"it might be enough to have the government engaged in a continuous program of information-gathering and dissemination covering trends in technology, reserves and demand."* (Solow, 1974) This thesis seeks to

promote this last statement, namely that more extensive information gathering is necessary for mission-critical resources when considering climate change mitigation.

Although it is clear that some sort of structural approach would be warranted in the short- to medium term, what the shape of it would be is up for debate. More draconian approaches of controlling markets can be difficult to justify as well as meet political resistance. On the other hand, doing nothing might cause severe price fluctuations that would have reverberating systemic effects that could in the medium term threaten environmental projects that aim to mitigate the effects of climate change. Maybe the tried and tested methods of governments building up stockpiles would be seen as a reasonably justified method that does not interfere too much in the inner workings of markets.

The extreme options of either controlling the markets or being an active market agent could be seen as unreasonable or too draconian and would be extremely impractical to implement on a coordinated global scale, however, one can ask the simple question: is it any saner to allow markets to ignore the environmental externalities that have been created since the dawn of the industrial revolution? Is it any more rational to not consider a resource in terms of its long term feasible extraction rate and impact on the eco-system rather than the short term profit?

7.2 In the long run: advancing research and development

One has to also consider what comes beyond that of the short- to medium term conclusion of either having an active agent that could intervene in the market with an environmentally beneficial agenda or by controlling the supply of the resource by deeming it to be mission-critical and thus of international-interest. Taking an active part in markets by influencing the supply, demand, and price characteristics come with a significant cost[31] as an agent would have to actively buy stocks regardless of the price. Controlling markets on the other hand comes with a plethora of other problems that are inherent to any type of centralised economic structure, and history has generally not been kind to such levels of control over human activities[32]. Thus, structural solutions are not optimal, and should only be considered as part of a short- to medium term strategy in transitioning to a longer term

[32] Any example of a controlled economy under Communism comes to mind.

plan – even if structural plans are suboptimal, they might be the lesser of two evils when considering the consequences of inaction.

The real salvation when considering strategically important resources is to explore alternatives. Thus, given the market failures that do occur, and which it is safe to assume will continue to exist, it becomes important to consider beyond mission-critical resources. Deeming a resource to be mission-critical is a significant bottleneck, and the easiest way to move away from said bottleneck is by finding a substitute. One of the ways that markets actually work to promote this is through higher prices. When industries are facing increasing prises, there is a certain threshold after which it cannot make a profit unless it can find a substitute. Thus, higher prices incentivise further research and development. However, in this case, there is the added goal of being able to economically produce an environmental good that can be used to currently mitigate climate change; so while higher prices might spur technologies that could help in the future, it might be at the cost of current environmental efforts.

There are examples abound of this process of innovation, but using the same example of cobalt as before: during the crisis years when the price increased by up to 380%, the magnet industry, which was heavily reliant on cobalt, found alternatives that were cheaper as a consequence of the severe price hike (Alonso, 2010; Shedd, 1998). There are other examples of environmentally friendly innovations that do not come with an associated price hike. Take the classic example of chlorofluorocarbon use in refrigerators, and how they were replaced by hydro fluorocarbons once the chlorofluorocarbons' role in ozone layer depletion was confirmed and the Montreal protocol put in place (United Nations Environment Programme - Ozone Secretariat, 1987). With regards to any innovation, it can really be made on either the supply or the demand side, and when considering strategically important resource in abating climate change, both are equally welcome, though supply side changes can be more revolutionising.

Supply side innovations include introductions of new materials that could be used as substitutes for platinum, and are hence competing in terms of being the supply input into an application. Within this domain, there is great promise on a few alternative technologies to platinum, *e.g.* Stanford scientists have studied the use of carbon nanotubes as a low-cost alternative that mimics the catalytic properties of platinum (Stanford Report, 2012). Another innovation involved a metal-free catalyst that outperforms platinum in a fuel cell.

A team of scientists came up with this novel material that was constructed using graphene nanoparticles edged with iodine (Case School of Engineering, 2013).

On the demand side, *i.e.* technologies that allow the same effect with less platinum, recent innovations in Denmark have cut the amount of platinum needed in hydrogen fuel cells by up to 80% (The Copenhagen post, 2013), one of the primary new demand drivers in the future. Also, a novel aerogel catalyst has been in the works in Germany that uses both platinum and palladium in an innovative way to achieve much higher rates of catalytic action, leading to lower use of platinum (phys.org, 2013). It is important to remember that technological innovation is a constant process, and although we might focus on the technology that seems immediate and achievable, it might not be the most optimal. Moving beyond fuel cells that use platinum is perhaps something that should also be considered giving the market issues involved that have been discussed throughout this thesis. Furthermore, one of the biggest problems currently with fuel cell production is also its scalability, where the high use of platinum has been a bottleneck (Holton & Stevenson, 2013). While demand side technologies that reduce the needed amount of platinum are helpful in this regard, better technologies that does not even use platinum might be behind the corner and more deserving of focus.

To summarise, aimless research and development to find substitutes for current mission-critical resources in climate change mitigation should not be carried out. Rather, technologies should be assessed and then compared in terms of how far away we are from materialising the innovation, of turning it into a product, being able to scale it so that we can have a significant impact in abating climate change, and also being able to convince markets to adopt the innovation. The answer to the aforementioned proposition is not always the easiest. Jonathan Adler concludes that neither traditional support for research and development nor command and control regulations are likely to spur sufficient innovation in the time period that is required to stabilise CO_2 emissions (Adler, 2011). He argued that prizes would be a rather good reward in this context to increase the rate of innovation, something that should perhaps bring in the possibility of crowdsourcing innovations as opposed to focusing on merely a few promising projects.

Going back to considering structural approaches, national and global legislation could also be helpful here. Much like environmental standards that were enforced with the introduction of the catalytic converter, similar environmental standards could be enforced with the use of fuel cell vehicles. While this is not currently relevant, it might be part of

the next big policy step to address climate change mitigation in the ground transportation sector. This would be beyond that of only relying on markets to develop biofuels, fuel cells, and to encourage changes in human behaviour as suggested in the technical annex regarding ground transportation in Stern (2007). A significant blunder is made in the Stern Review, with regards to policy lessons, when not considering the fact that by putting too much hope in future technologies, we might ignore the action that has to be taken now that would lead to said future technology.

8 Recommendations for Future Studies

It goes without saying that no study is ever all-encompassing and that there is always much room for improvement. Within the scope of this thesis, the three avenues that would be worthwhile to explore in future studies concern themselves with the modelling approach, choice of sector, as well as the policy considerations.

There are a variety of modelling techniques that could be used to solve a problem. For the task at hand, system dynamics was chosen for its ability to use feedback loops, as well as stocks and flows when analysing non-linearities in complex systems. Estimating platinum prices could have also been done through other numerical means. In terms of regression models, the problem could also have been analysed by building a nonparametric two-stage least squares model to overcome some of the hurdles of price non-linearity and endogeneity; on the other hand, using a general equilibrium model could provide with results that are more micro-founded, and thus more justifiable in terms of mainstream economics. Thus, it could be worthwhile to study the same question using other modelling techniques in order to provide a richer and fuller picture of the issue at hand; and even to compare the results using different modelling approaches to provide further insight into modelling in general.

What is deemed a causal pathway analysis throughout this essay is merely a term to describe a mode of thinking inspired by systems thinking that focuses on the many interdependencies throughout a system. This line of thinking would allow the focus of this study to shift more onto the dynamics and feedback effects that are at play in the sector of choice. This was done both quantitatively by using a system dynamics model, as well as qualitatively, by focusing on the different societal knock-on effects that a platinum price hike might have. All of these qualitative facets of a platinum price hike could also have been modelled using system dynamics, and this would be an interesting future project. This would however be a much larger project than the current thesis. While the model itself could be built as part of a thesis at this level, the associated analysis within the context of climate change would increase the project size significantly.

This analysis was carried out using data pertaining to the ground transportation sector, and more specifically, to the use of a catalytic converter. There are many other avenues that warrant a similar study, especially in the energy producing sector as electricity drives all other types of economic activity. Similar analyses could also be carried out in other sectors such as the agricultural or residential sectors. When analysing the various sectors

that greenhouse gas emissions emanate from, it becomes apparent that there is no one sector that is the primary cause, but rather that the emissions are relatively evenly spread across various economic sectors.

Perhaps the most important facet of this interdisciplinary problem is to understand the policies that need to be carried out in order to mitigate climate change. Analyses, simulations, and advice are moot if there are no clear ways of feasibly implementing a stage-wise multifaceted plan that would further climate change mitigation; studies that could provide such a plan would be of much use in the future. While a variety of methodologies were employed in this thesis to analyse platinum's role in climate change mitigation, the real need is for realistic future policy outlining; more specifically, proper transition plans are needed. This was attempted with the policy lessons. However, these could be done much more in-depth, considering for example country specific characteristics.

Finally, something that would be extremely ambitious, although worthwhile from a policy, economic, and environmental perspective, would be to estimate the willingness to pay for a common good such as the environment. Also, to estimate the rate that individuals are willing to substitute current private consumption for a future public or common good would be very interesting. These would, however, require a significant amount of work. Ultimately, there is still much work left to be done within the scope of climate change, especially works that would consider the society-wide costs and implications as well as the associated policy implications.

9 Concluding Remarks

The primary aim of this thesis was to explore the role of platinum in mitigating climate change within the ground transportation sector. This was, however, not the only aim of this thesis, as it explored many other associated aims as well. The main related aims were: addressing the need of systems thinking when considering causes and effects, as well as analysing and questioning the premises of the many models that are used and understanding their limitations due to the modelling structure. These aims were by analysing the platinum market quantitatively and considering it in the context of climate change qualitatively, as well as by going through policy considerations that were constructed in light of the proposed causal pathway analysis.

This thesis was prompted by a dearth in the literature of considering mission-critical resources within climate change mitigation. Furthermore, this thesis served the function of being more of an operational and practically-oriented paper in contrast to many of the other cost modelling papers. Thus, it really serves to further climate change mitigation efforts, albeit from a different lens than many other papers that are available. The thesis itself did this by firstly considering climate change in the larger scope and then focusing down on one aspect, which was platinum in this case. By considering platinum's role in the larger climate change mitigation effort, this thesis was able to provide a new perspective to the literature that had not, to the author's best knowledge, been available before.

The main purpose of this thesis was to highlight a different set of dynamics that are at play when considering mitigating climate change, or more specifically in this case: not exacerbating the effects of climate change. The causal pathway analysis that was performed in this study was composed of two components: a quantitative and a qualitative aspect. Both are rooted in systems thinking, as that has been one of the main drivers throughout this study. For the quantitative aspects, an extended generic system dynamics commodity model that was presented in Sterman (2000) was used, and for the qualitative aspects, the economic, political, geographic, societal and ethical, as well as environmental facets were considered. Both of these methodologies furthered the deliberation on the dynamic effects and feedback mechanisms that are inherent in complex systems.

The focus throughout this study was on what was deemed a mission-critical resource – platinum – in its role in climate change mitigation. Platinum is an essential part of climate change mitigation in the ground transportation sector as it is the primary component in the

catalytic converter. The catalytic converter is of course in charge of cleaning up tailpipe exhaust, but it also has the added effect of turning gases with higher GWPs to gases with lower GWPs, thus serving a dual role of providing a palatable environmental benefit as well as mitigating climate change.

By analysing in-depth how the role of a bottleneck resource could affect climate change mitigation efforts, another light was shed on the socio-economic cost calculations of the effects of climate change. As the analysis showed, platinum prices are set to increase and could have reverberating effects for many climate change mitigation efforts. This added cost of not considering the bottlenecks of a mission-critical resource would potentially make climate change mitigation efforts much more expensive and difficult to carry out. Action is required and this thesis seeks to shed light on the aspects that might need to be analysed more in-depth when thinking of an appropriate operational and transitional plan.

The need for the type of analysis that was conducted in this thesis was prompted by the fact that most of the economic cost analyses that are in the vanguard are top-down models, which inherently miss out on the many dynamic feedback mechanisms, interdependencies, and interplays of complex systems. When it comes to something as crucial as mitigating climate change, it is important to recognise those aspects which bear more weight, and the current top-down models are not conducive to this. For this reason, the current causal pathway analysis was used. Thus, this study serves to fill a gap that exists within the current body of literature concerning with how the economic costs of climate change mitigation are measured and considered.

The main contribution of this thesis came from identifying a crucial resource for mitigation the effects of climate change in the ground transportation sector and analysing its significance and role. While this thesis sought to contribute to the question of how to model socio-economic costs in climate change mitigation, it inevitably also contributed something to the question of climate change. The endgame contribution is of course though the analysis of a small subsection of the whole climate change problem – namely the role of platinum in climate change mitigation within the ground transportation sector.

The quantitative system dynamics analysis shows rather unequivocally that given the expected supply and demand conditions in the platinum market, we are bound to see price increases in the future. The price increase will have effects that will reverberate through many different pathways. The qualitative analysis considered the economic effects of an increasing price, which could dampen future environmental projects such as fuel cell

production. It also covered the difficulty in carrying out politically motivated environmental projects if there is backlash from an increase in the price of platinum; higher prices might also increase the geopolitical risk involved given the high concentration of mining operations. Given that catalytic converters are used in motorised vehicles – a middleclass good – there are also societal and ethical considerations to be made. Finally, and hopefully, environmentally-friendly practises of higher recycling, redesigning, and dematerialisation could occur due to higher platinum prices.

In terms of policy suggestions, this study sought to clarify the dynamics effects and feedback mechanisms involved within the platinum markets and more specifically the effects that would be had on climate change mitigation; these were then extrapolated into wider policy lessons. The policy lessons were separated into both a short- to medium term-, and a long run recommendation. For the short- to medium term, given the market imperfections that exist, it might be warranted to consider some type of command and control policies which could work by either controlling the supply or by deeming the material of international-interest and in the process stockpile it for environmental use. Given that platinum stockpiles have existed in the U.S. before, they might be needed again before we can rely on future technologies that would either lower our demand for platinum, or supply materials that would completely replace platinum's catalytic function. In the long term, we need to find alternatives that do not have as restrictive supply characteristics. Thus, research and development is needed to find substitute materials.

It is important to remember to consider these conclusions in the larger scale. This study has the added function of encouraging other forms of analysis, and hopefully spurring a discussion on how some modelling aspects could be done differently. As such, it has a larger economic scope in questioning the methodologies and practises that we use, and even inviting other forms of analysis to the table. The analysis at hand was conducted to show that there might be knock-on effects that current top-down models are unable to capture, which could nevertheless reverberate and have systemic effects, and would thus be of importance to consider in the analysis.

Finally, it is also important not to see the conclusions in the sense of there being any particular material that we would run out of which would cause cataclysmic destruction. The story to consider rather, is that by mismanaging our current resource pool, we would make it much more difficult for ourselves to carry out reasonable environmental policy in the near future. In other words, it would be easier and cheaper to tackle this problem head-

on sooner, rather than dealing with all the consequences that would most likely make mitigation efforts more expensive later on. Luckily though, there are good promises on the research and development front when it comes to alternatives to platinum catalysts – we just need to get there without wrecking ourselves or the environment.

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10 Appendix

A1. Formal framework of the system dynamics model

Mathematically speaking, there are two parts to solving a system dynamics model. Firstly, individual relationships within the system have to be defined in terms of coupled ordinary differential equations. These coupled ordinary differential equations form a system of equations that has to be defined by outlining the relationships between the variables. The following is a mathematical definition of a system of ordinary differential equations:

If y is a vector whose elements are functions as in (4):

$$y(x) = \left[y_1(x), y_2(x), ..., y_m(x) \right] \tag{1}$$

And F is a vector valued function of y and its derivatives, as in (5):

$$y^{(n)} = F(x, y, y', y'', ..., y^{(n-1)}) \tag{2}$$

Then (6) is an explicit system of ordinary differential equations of order m:

$$\begin{pmatrix} y_1^{(n)} \\ y_2^{(n)} \\ \vdots \\ y_3^{(n)} \end{pmatrix} = \begin{pmatrix} F_1(x, y, y', y'', ..., y^{(n-1)}) \\ F_2(x, y, y', y'', ..., y^{(n-1)}) \\ \vdots \\ F_3(x, y, y', y'', ..., y^{(n-1)}) \end{pmatrix} \tag{3}$$

When closed form solutions do not exist to solve systems of ordinary differential equations, one can employ iterative methods to approximate a solution. There are a variety of techniques that can be employed, one of the more common, and the one that is used in the current simulation, are called the Runge-Kutta methods. They function as follows:

Let the following be an initial value problem

$$\bar{y} = f(t, y), \; y(t_0) = y_0 \tag{4}$$

In (7), y is an unknown function dependent on time that we would like to approximate. We know that y prime, which is the rate that y changes at, is a function of both time and y itself.

When initialising at t = 0, the corresponding y value is also 0. The function f and the data t_0,y_0 are given.

Now pick a step-size h, where h>0, and define the following:

$$y_{n+1} = y_n + \frac{1}{6}h(k_1 + 2k_2 + 2k_3 + k_4) \tag{5}$$

$$t_{n+1} = t_n + h \tag{6}$$

Then for n = 0, 1, 2, 3, …, and using:

$$k_1 = f(t_n, y_n) \tag{7}$$

$$k_2 = f(t_n + \frac{1}{2}h, y_n + \frac{h}{2}k_1) \tag{8}$$

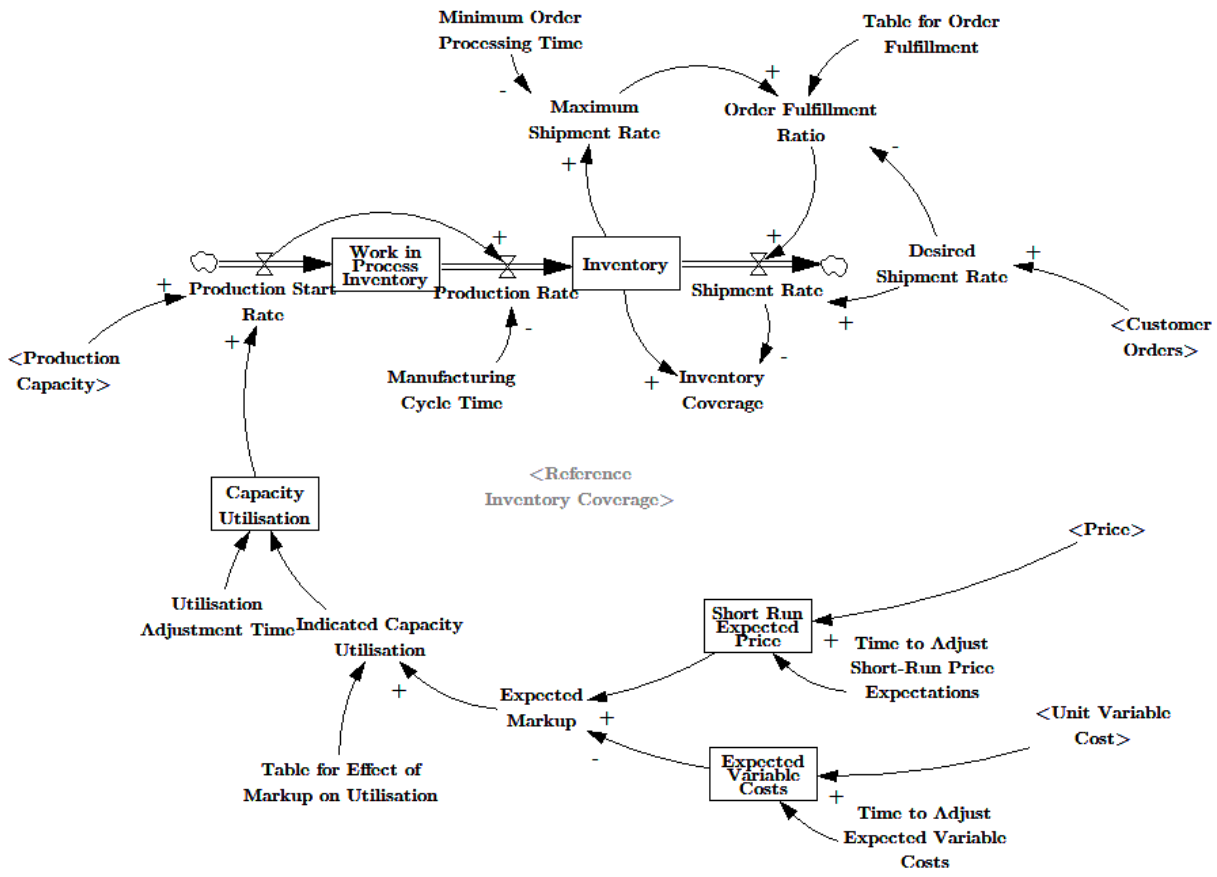
$$k_3 = f(t_n + \frac{1}{2}h, y_n + \frac{h}{2}k_2) \tag{9}$$

$$k_4 = f(t_n + h, y_n + hk_3) \tag{10}$$

The next value of y, y_{n+1} is the RK4 (that is the fourth-order Runge-Kutta) approximation of $y(t_{n+1})$. The value that follows, y_{n+1}, is determined by the present value y_n and the weighted average of four increments, where each increment is the product of the size of h, which is the interval, and an estimate slope specified by a function f on the right-hand side of the differential equation. Thus the model solves for functions which contain the function itself. This is an overly simplified explanation of the mathematical concepts at work; for a full derivation, please see a differential equations textbook.

A2. System dynamics model blocks and equations

A2.1 Production and inventory



$$\text{Maximum shipment rate} = \frac{\text{Inventory}}{\text{Minimum Order Processing Time}} \tag{1}$$

$$\text{Order Fulfillment Ratio} = \text{Table for Order Fulfillment}\left(\frac{\text{Maximum Shipment Rate}}{\text{Desired Shipment Rate}}\right) \tag{2}$$

$$\text{Shipment Rate} = \text{Desired Shipment Rate} * \text{Order Fulfillment} \tag{3}$$

$$\text{Inventory Coverage} = \frac{\text{Inventory}}{\text{Shipment Rate}} \tag{4}$$

$$\text{Inventory} = \int (\text{Production Rate-Shipment Rate}) \tag{5}$$

$$\text{Production Rate} = \text{DELAY3}(\text{Production Start Rate}, \text{Manufacturing Cycle Time})^{33} \tag{6}$$

$$\text{Work In Process Inventory} = \int (\text{Production Start Rate - Production Rate}) \tag{7}$$

$$\text{Production Start Rate} = \text{Production Capacity} * \text{Capacity Utilisation} \tag{8}$$

$$\text{Capacity Utilisation} = \text{SMOOTH}(\text{Indicated Capacity Utilisation}, \text{Utilisation Adjustment Time})^{34} \tag{9}$$

$$\text{Indicated Capacity Utilisation} = \text{Table for Effect of Markup on Utilisation}(\text{Expected Markup}) \tag{10}$$

[33] DELAY3 refers to a third-order delay function.
[34] SMOOTH refers to an exponential smoothing function.

$$\text{Expected Markup} = \frac{\text{Short Run Expected Price}}{\text{Expected Variable Costs}} \tag{11}$$

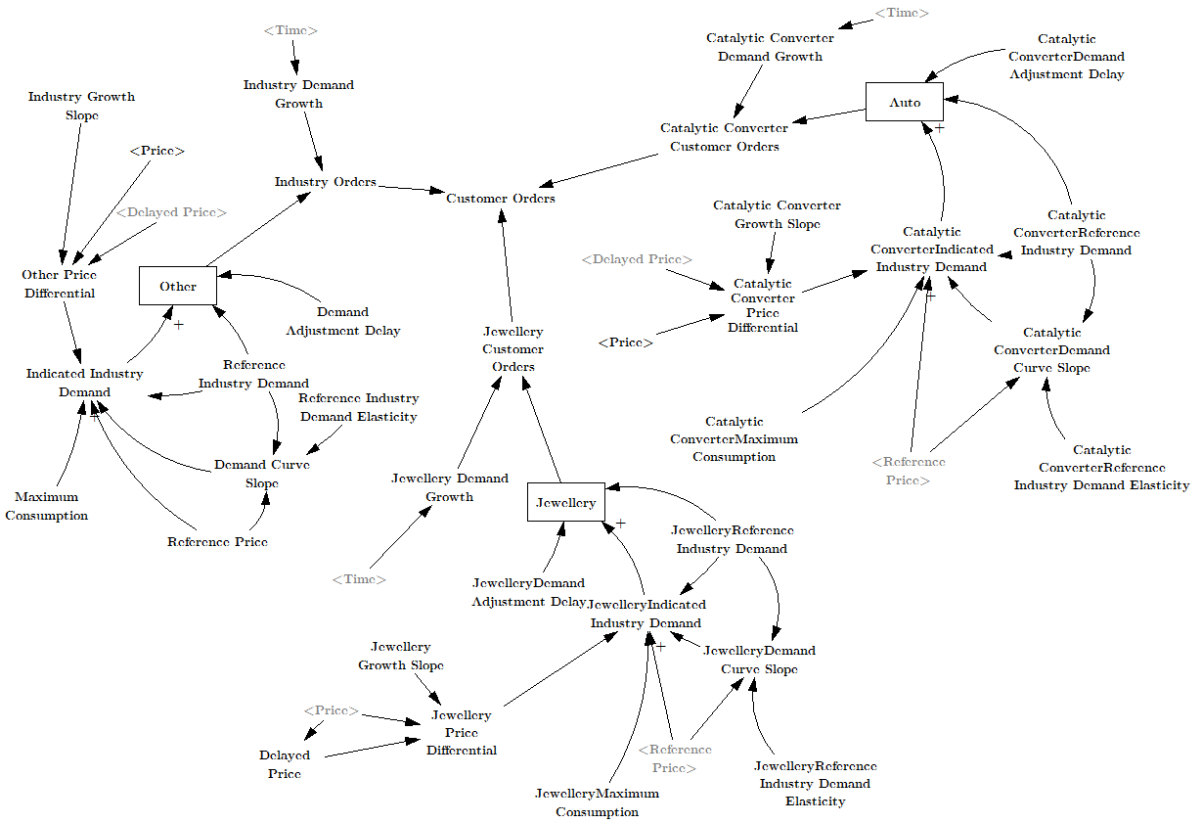
$$\text{Short Run Expected Price} = \text{SMOOTH(Price,Time to Adjust Short-Run Price Expectations)}^{35} \tag{12}$$

$$\text{Expected Variable Costs} = \text{SMOOTH(Unit Variable Cost,Time to Adjust Expected Variable Costs)}^{36} \tag{13}$$

[35] Ibid.

[36] Ibid.

A2.2 Demand



Customer Orders =
Industry Orders + Catalytic Converter Customer Orders + Jewellery Customer Orders (1)

The following equations are the same for all three products (jewellery, catalytic converter, and other), and are consequently expressed generically.

Price Differential = (1+(((Price-Delayed Price)/Delayed Price))- Growth Slope)*Price (2)

Industry Demand =
SMOOTHI(Indicated Demand, [37]
Demand Adjustment Delay,Reference Demand) (3)

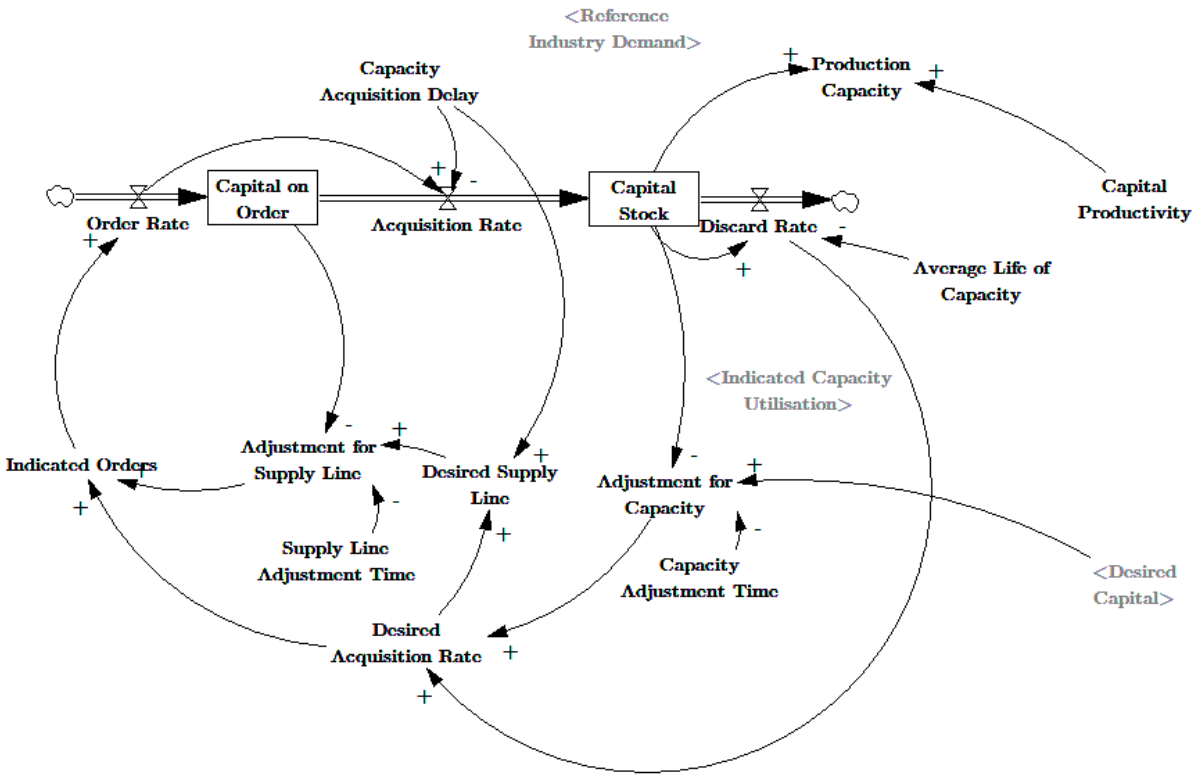
Indicated Demand =MIN(Maximum Consumption,
Reference Demand * [38]

$$\text{MAX}\left(0,1+\text{Demand Curve Slope} * \left(\frac{\text{Price Differential - Reference Price}}{\text{Reference Demand}}\right)\right) \quad (4)$$

$$\text{Demand Curve Slope} = \frac{\text{-Reference Demand} * \text{Reference Demand Elasticity}}{\text{Reference Price}} \quad (5)$$

[37] SMOOTHI refers to an exponential smoothing function.
[38] MIN refers to the minimum value of the inputs; MAX refers to the maximum value of the inputs.

A2.3 Production capacity



Order Rate = MAX(0, Indicated Orders)[39] (6)

Indicated Orders = Desired Acquisition Rate + Adjustment for Supply Line (7)

Capital on Order = $\int$ (Order Rate-Acquisition Rate) (8)

[39] Ibid.

$$\text{Acquisition Rate} = \text{DELAY3}(\text{Order Rate}, \text{Capacity Acquisition Delay})^{40} \quad (9)$$

$$\text{Capital Stock} = \int (\text{Acquisition Rate} - \text{Discard Rate}) \quad (10)$$

$$\text{Production Capacity} = \text{Capital Stock} * \text{Capital Productivity} \quad (11)$$

$$\text{Discard Rate} = \frac{\text{Capital Stock}}{\text{Average Life of Capacity}} \quad (12)$$

$$\text{Adjustment for Supply Line} = \frac{\text{Desired Supply Line} - \text{Capital on Order}}{\text{Supply Line Adjustment Time}} \quad (13)$$

$$\text{Desired Supply Line} = \text{Expected Acquisition Delay} * \text{Desired Acquisition Rate} \quad (14)$$

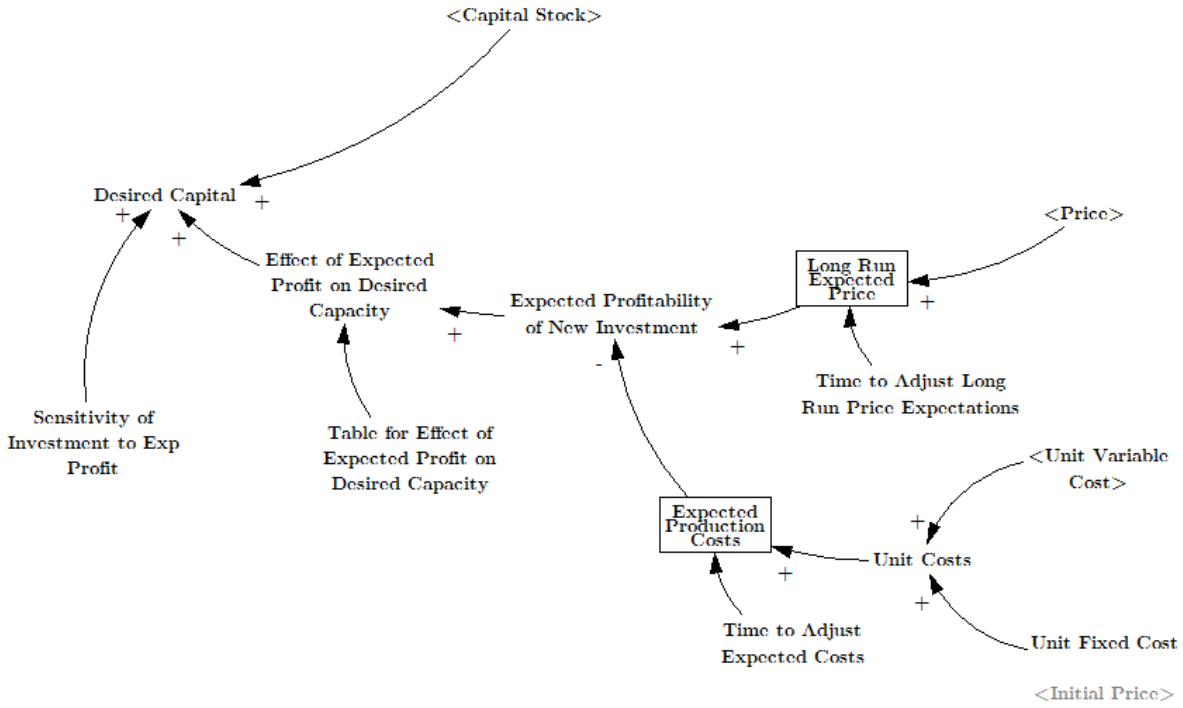
$$\text{Desired Acquisition Rate} = \text{MAX}(0, \text{Expected Discard Rate} + \text{Adjustment for Capacity})^{41} \quad (15)$$

[40] DELAY3 refers to a third-order delay function.

[41] MAX refers to the maximum value of the inputs.

$$\text{Adjustment for Capacity} = \frac{\text{Desired Capital - Capital Stock}}{\text{Capacity Adjustment Time}} \tag{16}$$

A2.4 Desired capacity



Desired Capital =
Capital Stock*(1+Sensitivity of Investment to Exp Profit
*((Effect of Expected Profit on Desired Capacity)-1)) (17)

Effect of Expected Profit on Desired Capacity =
Table for Effect of Expected Profit on Desired Capacity [42]
(Expected Profitability of New Investment) (18)

$$\text{Expected Profitability of New Investment} = \frac{\text{Long Run Expected Price - Expected Production Costs}}{\text{Long Run Expected Price}} \quad (19)$$

[42] Values are drawn from a reference table, see Sterman (2000).

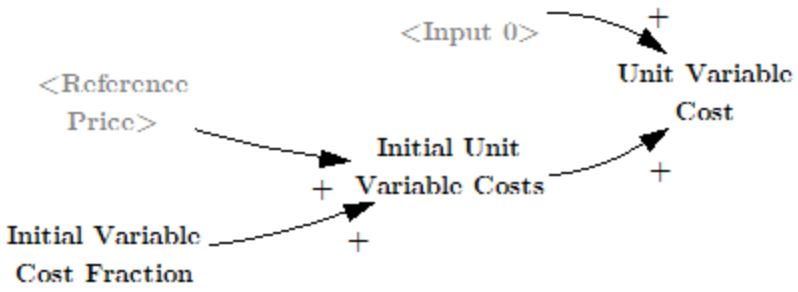
Long Run Expected Profit =
SMOOTH(Price,Time to Adjust Long Run Price Expectations)[43] (20)

Expected Production Costs = SMOOTH(Unit Costs,Time to Adjust Expected Costs)[44] (21)

Unit Costs = Unit Fixed Cost + Unit Variable Cost (22)

[43] SMOOTH refers to an exponential smoothing function.
[44] Ibid.

A2.5 Unit costs

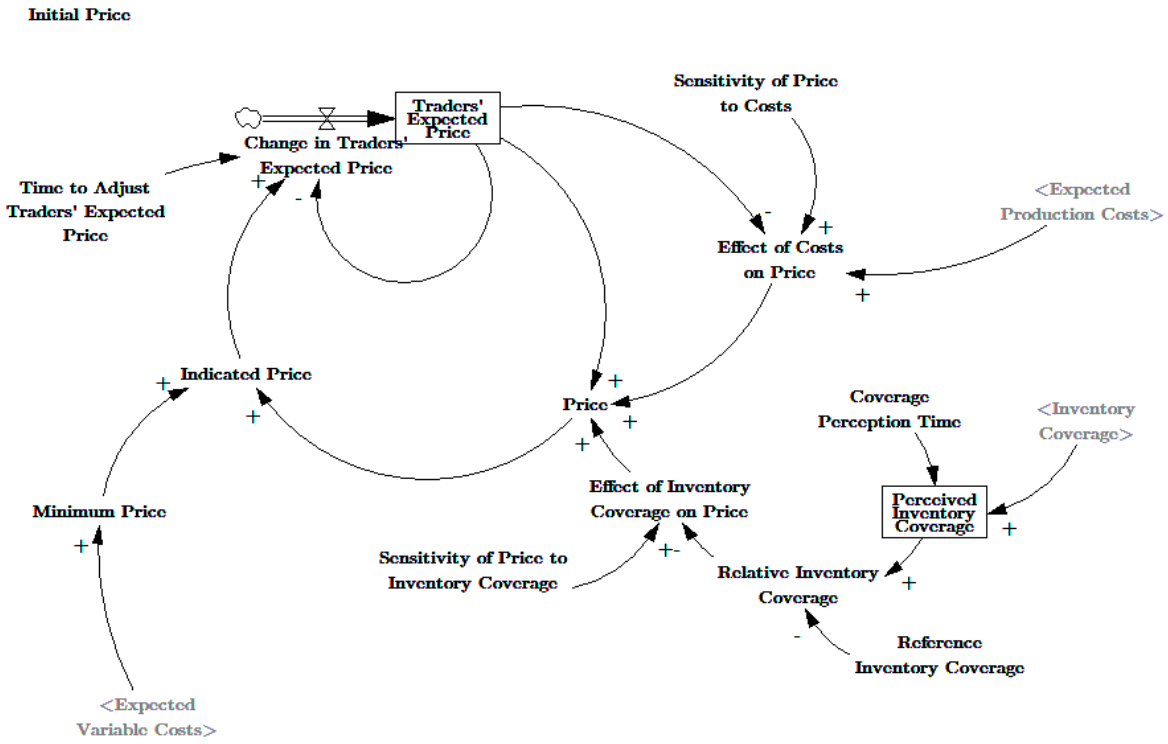


Initial Unit Variable Cost = Initial Variable Cost Fraction * Reference Price (23)

Unit Variable Cost = Initial Unit Variable Costs * Input 0[45] (24)

[45] Input 0 refers to an exogenously controlled marginal cost value.

A2.6 Price



$$\text{Minimum Price} = \text{Expected Variable Costs} \tag{25}$$

$$\text{Indicated Price} = \text{MAX}(\text{Minimum Price}, \text{Price})\ ^{46} \tag{26}$$

$$\text{Change in Traders' Expected Price} = \frac{(\text{Indicated Price} - \text{Traders' Expected Price})}{\text{Time to Adjust Traders' Expected Price}} \tag{27}$$

[46] MAX refers to the maximum value of the inputs.

$$\text{Traders' Expected Price} = \int \text{Change in Traders' Expected Price} \tag{28}$$

$$\text{Price} = \text{Traders' Expected Price} * \text{Effect of Inventory Coverage on Price} * \text{Effect of Costs on Price} \tag{29}$$

$$\text{Effect of Inventory Coverage on Price} = \text{Relative Inventory Coverage}^{\text{Sensitivity of Price to Inventory Coverage}} \tag{30}$$

$$\text{Effect of Costs on Price} = 1+\text{Sensitivity of Price to Costs}* \left(\frac{\text{Expected Production Costs}}{\text{Traders' Expected Price}} -1 \right) \tag{31}$$

$$\text{Relative Inventory Coverage} = \frac{\text{Perceived Inventory Coverage}}{\text{Reference Inventory Coverage}} \tag{32}$$

$$\text{Perceived Inventory Coverage} = \text{SMOOTH}(\text{Inventory Coverage}, \text{Coverage Perception Time})^{47} \tag{33}$$

[47] SMOOTH refers to an exponential smoothing function.

A2.6 Lookup tables

Table for effect of markup utilisation

Input	Output
0	0
0.5	0
0.75	0.05
1	0.5
1.25	0.68
1.5	0.75
1.75	0.8
2	0.84
2.25	0.87
2.5	0.9
2.75	0.93
3	0.96
3.25	0.985
3.5	0.995
4	1
4.5	1
5	1

Table for Order Fulfillment

Input	Output
0	0
0.2	0.2
0.4	0.4
0.6	0.58
0.8	0.73
1	0.85
1.2	0.93
1.4	0.97
1.6	0.99
1.8	1
2	1
2	1
4	1

Table for Effect of Expected Profit on Desired Capacity

Input	Output
-1	0
-0.75	0.1
-0.5	0.3
-0.25	0.67
0	1
0.25	1.25
0.5	1.45
0.75	1.6
1	1.7