The uncertain future of copper

An Exploratory System Dynamics Model and Analysis of the global copper system in the next 40 years

Delft University of Technology
Faculty Technology, Policy and Management
Master Systems Engineering, Policy Analysis and Management
SPM 5910 – SEPAM Thesis Project

Chairman graduation committee: Prof.dr.ir. W.A.H. Thissen
1st Supervisor TU Delft: Dr. E. Pruyt
2nd Supervisor TU Delft: Dr.ir. G.P.J. Dijkema
External supervisor TNO: Dr. A.G.T.M. Bastein

November 2011

W.L. Auping, 1014153
Preface

The rough scope of my graduation project was clear from an early moment before the real start of the project. Together with my supervisor Erik Pruyt, I decided that after my bachelor project about Lithium scarcity (Auping, 2009), the issues about mineral scarcity still existed and were very suitable to research with his newly developed method Exploratory System Dynamics Modelling and Analysis (ESDMA. Pruyt, 2010b), which allows exploring the future of a system, instead of trying to predict it.

The second step was meeting with my second supervisor, Ton Bastein of TNO, also in the period before my thesis project started. With him I talked about possibilities for a more precise scope of the project in preparation. After discussing practically all rare earths, the platinum group and “The metal wheel” (Verhoef, Dijkema & Reuter, 2004), he came with the thesis work of Rembrandt Koppelaar (2011) about mineral cost developments and told me that despite all the attention mineral scarcity receives the last years, copper seems to be neglected in this issue.

We decided to start a modelling project of the global copper system. The goal of this research should be to draw attention to the fact that also bulk metals like copper need consideration in the discussion of mineral scarcity. An extra advantage would be the fact that the copper market is well documented and relatively transparent when compared to for example, the relative dearth of information about the rare earth or lithium markets. Despite this, the omnipresent uncertainties give an excellent opportunity to explore their effects on the possible behaviour of the copper system.

Erik agreed with this subject because it combined three important subjects: energy transition, geopolitical issues and modelling uncertainty. In this way the project would fit very well in my master specialisations: Modelling, Simulation & Gaming combined with Energy & Industry. My other two supervisors were quickly found: Gerard Dijkema, the industry expert of my faculty and Professor Thissen of the department of Policy Analysis under which this research will be done.

This research study is thus written as a thesis report for the master degree course “Systems Engineering, Policy Analysis and Management” of the Faculty of Technology, Policy and Management at the Delft University of Technology. The thesis research was performed in cooperation with the division “Built Environment and Geosciences” of the Netherlands Organisation for Applied Scientific Research (TNO).

The target readership of this report embraces anyone who is interested in mineral (metal) scarcity issues. But, in addition, it is intended to be of specific interest for policy makers and researchers in the fields of sustainability, industry and recycling, both on a national and a European level. Finally, it aims at giving a clear example of the use and application of this new technique in the field of System Dynamics (SD).

This thesis has four parts. First is the introduction, in which the problem is introduced, the relevance and precise scope is discussed, the research question is explained together with the sub questions and the use of and choice for the ESDMA research methodology is explained. The second part is about the world copper system, it discusses the copper demand and energy needs for producing it, the current and potential structure of the copper market and uncertainties and risks in this market. The third part is an exploratory model analysis where possible scenarios and behaviour of the modelled copper market are given and the influence they might have on the future availability of copper is examined. In the last part, the evaluation, policy options are discussed which might counter unwanted effects of the system noticed in the study, conclusions are drawn on the subject and a reflection is made on the way the research was performed. To keep the report readable for non System Dynamics experts, all specifications of the used models are given in the appendices.
Some valuable information about the functioning of copper mining and the development of copper mining capacity was further provided by Piet Hein van der Klein, who owns my gratitude for his contribution to this research.

In conducting the Exploratory Modelling and Analysis (EMA) part of this research, I received much support from two postdoctoral researchers of the Policy Analysis group. The first is Jan Kwakkel, who helped me using the ESDMA interface, encouraged me to try to write Python scripts for transferring model variables to documents, helped me to write a script which enables using debugging data to develop debugging models and who helped me developing a 3D visualisation for the distribution of runs in the uncertainty space of a Key Performance Indicator. The second is Gönenç Yücel, who made it possible to classify runs by behaviour.

Final thanks are for my supervisors, professor Thissen, Erik Pruyl, Gerard Dijkema and Ton Bastein for their intensive supervision (especially Erik and Ton) and their valuable feedback. Last but not least, I thank Dieneke for her support and patience during my thesis work.

Delft, 28 October 2011, Willem Auping
Abstract

High copper prices have not led to a place for this metal in the debate about mineral scarcity, while copper is a base metal which has many uses and is vital for developments in the energy transition. In this research the global copper system is examined from the perspective of the development of supply and demand and the effects structural and parametric uncertainties in the system have on the development of behaviour in this system. The question immediately arises:

*What are the effects of parametric and structural uncertainties on the possible future behaviour of the copper system?*

The research approach is Exploratory System Dynamics Modelling and Analysis (ESDMA) and the period the copper system is examined is 2000 till 2050. For the analysis three different System Dynamics (SD) models were built, with regard to existing literature about the structure and functioning of the different elements in the copper system. These models were connected to a python shell to perform the Exploratory Model Analysis (EMA).

The effects of a specific ESDMA structure, a randomised economic feed, were first tested in this research. The conclusions were that, mainly due to the fact that this feed mainly influenced stocks in the system, the system behaviour was not significantly different due to this feed. Henceforth the other experiments were performed without the economic feed.

During the interpretation of these experiments it became clear that a mistake were made in the experimental setup. The lower bounds for the four coefficients relevant for the Recycling Input Rate (RIR) were taken too low, causing the RIR in effect to have an overly low modus, as well as a lower average value for the copper consumption. While this potentially could have changed the behaviour of the system, a new experiment with the corrected bounds has led to similar outcomes.

The behavioural conclusions of these experiments are that the copper consumption is likely to decline slowly in the coming 40 years. This reduction in consumption also leads to very high Reserve over Production (R/P) ratios. The system has further a high risk for volatile price movements, caused by a disbalance between copper supply and demand. This and the importance of copper for our economy make it a vulnerable resource, which needs to be monitored more closely.

Six different policy designs were tested in this research to try to counter potential unwanted effects in the copper system. These policies were designed from the perspective of European stakeholders. Performing experiments with these policies has lead to the conclusion that policies aiming at improving the collection rate of copper products at their end of life in combination with improving the Recycling Efficiency Rate (RER) leads on average to lower copper prices. The copper price volatility was lowered by a policy regarding the implementation of a strategic reserve.

Keywords: Copper, Mineral scarcity, Energy transition, System Dynamics, Exploratory Modelling and Analysis, Exploratory System Dynamics Modelling and Analysis
# Contents

Preface ........................................................................................................................................ iii
Abstract ........................................................................................................................................ v
Table of abbreviations ................................................................................................................ viii
Table of boxes ................................................................................................................................. ix
Table of figures ................................................................................................................................. x

1. Introduction ................................................................................................................................ 2
  1.1. The energy transition .............................................................................................................. 2
  1.2. Emerging economies .............................................................................................................. 2
  1.3. Uncertainties in the copper system ....................................................................................... 3
  1.4. Research introduction ........................................................................................................... 3

2. Problem exploration ..................................................................................................................... 4
  2.1. Problem exploration .............................................................................................................. 4
  2.2. Problem statement ................................................................................................................ 5
  2.3. Research objectives .............................................................................................................. 5
  2.4. Choice for research method and modelling software .......................................................... 5
  2.5. Scope of research ................................................................................................................. 6
  2.6. Research questions ............................................................................................................... 6

3. Research methodology ................................................................................................................. 8
  3.1. Exploratory Modelling and Analysis (EMA) ....................................................................... 8
  3.2. Exploratory System Dynamics Modelling and Analysis (ESDMA) ...................................... 9
  3.3. Research design .................................................................................................................... 9

4. Copper demand and substitution ................................................................................................. 12
  4.1. Main drivers for copper demand and model varieties ......................................................... 12
  4.2. Copper substitution .............................................................................................................. 16

5. Current and potential structure copper supply system ............................................................... 18
  5.1. Resources and reserves ........................................................................................................ 18
  5.2. Mining, smelting/SX-EW and refining ................................................................................ 20
  5.3. Deep sea mining .................................................................................................................. 22
  5.4. Copper recycling or secondary copper ................................................................................ 24

6. Uncertainties and risks in the copper system ............................................................................. 25
  6.1. Parametric uncertainties ...................................................................................................... 25
  6.2. Structural uncertainties ...................................................................................................... 25
  6.3. System risks ....................................................................................................................... 26

7. Behaviour and scenarios of the copper models ........................................................................ 30
  7.1. The effect of the ESDMA economic growth structure ......................................................... 30
  7.2. Behaviour observed in all model varieties .......................................................................... 32
  7.3. Behavioural differences between the models ...................................................................... 37
  7.4. Scenarios and risks displayed by the copper models ............................................................ 39
  7.5. Less valid outcomes .......................................................................................................... 39
  7.6. Observations from new data .............................................................................................. 41

8. Policy design for the copper system ........................................................................................ 42
# Table of abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asean-10</td>
<td>Association of Southeast Asian Nations, Indonesia, Malaysia, Philippines, Singapore, Thailand, Brunei, Burma (Myanmar), Cambodia, Laos and Vietnam</td>
</tr>
<tr>
<td>BEV</td>
<td>Battery (powered) Electric Vehicle</td>
</tr>
<tr>
<td>BGR</td>
<td>Bundesanstalt für Geowissenschaften und Rohstoffe</td>
</tr>
<tr>
<td>CIS</td>
<td>Commonwealth of Independent States, regional organisation of former Soviet Union republics</td>
</tr>
<tr>
<td>CLD</td>
<td>Causal Loop Diagram</td>
</tr>
<tr>
<td>CSP</td>
<td>Concentrated Solar Plant</td>
</tr>
<tr>
<td>Cu</td>
<td>Cuprum, the chemical element of Copper</td>
</tr>
<tr>
<td>Dmnl</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>EEZ</td>
<td>Exclusive Economic Zone</td>
</tr>
<tr>
<td>EMA</td>
<td>Exploratory Modelling and Analysis</td>
</tr>
<tr>
<td>EOL</td>
<td>End of Life</td>
</tr>
<tr>
<td>ESD</td>
<td>Exploratory System Dynamics</td>
</tr>
<tr>
<td>ESDMA</td>
<td>Exploratory System Dynamics Modelling and Analysis</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
</tr>
<tr>
<td>HEV</td>
<td>Hybrid Electric Vehicle</td>
</tr>
<tr>
<td>ICSG</td>
<td>International Copper Study Group</td>
</tr>
<tr>
<td>ISA</td>
<td>International Seabed Authority</td>
</tr>
<tr>
<td>ISI</td>
<td>Fraunhofer Institute for Systems and Innovation Research</td>
</tr>
<tr>
<td>JORC</td>
<td>Australasian Joint Ore Reserves Committee</td>
</tr>
<tr>
<td>KDE</td>
<td>Kernel Density Estimation</td>
</tr>
<tr>
<td>(K)PI</td>
<td>(Key) Performance Indicator</td>
</tr>
<tr>
<td>LME</td>
<td>London Metal Exchange</td>
</tr>
<tr>
<td>PHEV</td>
<td>Plug-in Hybrid Electric Vehicle</td>
</tr>
<tr>
<td>PRIM</td>
<td>Patient Rule Induction Method</td>
</tr>
<tr>
<td>R/P</td>
<td>Reserve/Production ratio (time left of production when no new reserves are discovered and the production remains constant)</td>
</tr>
<tr>
<td>RER</td>
<td>Recycling Efficiency Rate</td>
</tr>
<tr>
<td>RIR</td>
<td>Recycling Input Rate - The percentage of recycled copper in the total amount of refined copper at a given time</td>
</tr>
<tr>
<td>SD</td>
<td>System Dynamics</td>
</tr>
<tr>
<td>SDS</td>
<td>System Dynamics Society</td>
</tr>
<tr>
<td>SX-EW</td>
<td>Solvent Extraction - Electro Winning</td>
</tr>
<tr>
<td>t</td>
<td>Tonne or metric ton. Equal to 1000 kg or 1 Mg</td>
</tr>
<tr>
<td>TNO</td>
<td>The Netherlands Organisation of Applied Scientific Research (Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek)</td>
</tr>
<tr>
<td>UNPD</td>
<td>United Nations, Department of Economic and Social Affairs. Population Division, Population Estimates and Projections Section</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
</tbody>
</table>
**Table of boxes**

Box I: System Dynamics.................................................................................................................. 8
Box II: Modelling uncertainty: Economic growth ............................................................................. 13
Box III: Modelling uncertainty: Relations for demand ..................................................................... 15
Box IV: Modelling uncertainty: Substitution ...................................................................................... 17
Box V: Modelling uncertainty: Mining and refinery capacity ............................................................. 21
Box VI: Modelling uncertainty: Deep sea mining capacity ................................................................. 23
Box VII: Visualising ESDMA results ................................................................................................. 31
Box VIII: Modelling policies: Connection of policies to the model .................................................. 43
Table of figures

Figure 2.1: Copper System diagram ........................................................................................................6
Figure 3.1: Simple SD model .........................................................................................................................9
Figure 3.2: Traditional and two ESDMA research approaches compared ......................................................10
Figure 4.1: Top down intrinsic demand .......................................................................................................12
Figure 4.2: The economic growth structure ................................................................................................13
Figure 4.3: The effect of this uncertainty structure .......................................................................................13
Figure 4.4: Bottom up intrinsic demand .......................................................................................................13
Figure 4.5: The dominance scenario (Angerer et al., 2010: 18) ..................................................................14
Figure 4.6: The pluralism scenario (Angerer et al., 2010: 19) ....................................................................14
Figure 4.7: Regional approach. All variables with a green background are regional .................................14
Figure 4.8: SD structure for short and long term effects on demand ...........................................................15
Figure 4.9: Copper and aluminium price over the last 30 years (Index Mundi, 2011a, 2011b) .....................16
Figure 4.10: Relating copper price and the aluminium price .......................................................................17
Figure 4.11: SD structure for substitution in relation to demand .................................................................17
Figure 5.1: Extended stock-flow diagram of the copper supply system with some connections to the demand ...18
Figure 5.2: Relation between reserves and resources. Based on the Mckelvey Box (Mckelvey, 1973) ........18
Figure 5.3: Ore grade in relation to energy costs needed for processing copper (Skinner, 1976) ..............19
Figure 5.4: Typical distribution of reserve base and reserve of a mine. The split between them is the cut-off ore grade (Kleijn, P. H. v. d., 2011) ...........................................................20
Figure 5.5: SD structure for mining capacity ...............................................................................................22
Figure 5.6: Deep sea copper resource and reserve development .................................................................23
Figure 5.7: SD structure for new mining capacity .......................................................................................24
Figure 7.1: Global consumption of copper with economic feed, top down model ......................................30
Figure 7.2: Global consumption of copper without economic feed, top down model ................................30
Figure 7.3: Envelope. No distinction between policies ..............................................................................31
Figure 7.4: Envelope. There are two panes (colours are in the legend) super positioned over each other .....31
Figure 7.5: Lines graph ...............................................................................................................................31
Figure 7.6: Envelopes graph with KDE .......................................................................................................31
Figure 7.7: Lines graph with KDE ................................................................................................................31
Figure 7.8: 3D envelope with KDE values on the z-axis and the standard perspective .................................32
Figure 7.9: 3D envelope without the KDE values and a turned perspective ..............................................32
Figure 7.10: Multiplot with Part of original demand substituted and RIR ................................................32
Figure 7.11: Multiplot with Part of original demand substituted and RIR and different colour for the policies .....32
Figure 7.12: Lines graph for the Real price of copper, top down model ....................................................33
Figure 7.13: 3D envelopes of the Global consumption of refined copper [t/Year], top down model. The graph is truncated at 30 million tonne per Year ................................................................................34
Figure 7.14: Lines graph for Part of original demand substituted, top down model ..................................34
Figure 7.15: 3D envelopes of the Part of original demand substituted [Dmnl], top down model. The graph is not truncated, so the values for the substitution lie between 0 and 1 ................................................34
Figure 7.16: Lines graph for the Year left of copper mining, top down model ............................................35
Figure 7.17: 3D envelopes of the Year left of copper mining [Year], top down model. The graph is truncated at 500 year .......................................................... 36
Figure 7.18: Multiplot of Global consumption of refined copper [t/Year] and Year left of copper mining [Year], top down model .......................................................................................................................... 36
Figure 7.19: 3D envelopes of the Relative part of deep sea mining [Dmnl], top down model. The graph is not truncated, so the values for the substitution lie between 0 and 1, or 0% and 100% .................................................................................. 36
Figure 7.20: Lines graph for the Real price of copper, bottom up model.......................................................... 37
Figure 7.21: 3D envelopes of the Real price of copper [Dollar/t], bottom up model. The graph is truncated at 100000 Dollar/t .................................................................................................................. 37
Figure 7.22: Lines graph for the Real price of copper, regional model .................................................................. 37
Figure 7.23: 3D envelopes of the Real price of copper [Dollar/t], regional model. The graph is truncated at 100000 Dollar/t .................................................................................................................. 37
Figure 7.24: Lines graph for Global consumption of refined copper, bottom up model........................................ 38
Figure 7.25: 3D envelopes of the Global consumption of refined copper [t/Year], bottom up model. The graph is truncated at 30 million t/Year .................................................................................. 38
Figure 7.26: Lines graph for the Part of original demand substituted, bottom up model ........................................ 39
Figure 7.27: Low values for the Recycling Input Rate [Dmnl], top down model ...................................................... 40
Figure 7.28: The RIR [Dmnl] in the new runs, top down model ............................................................................. 41
Figure 7.29: The global consumption of copper [t/Year] in the new model ............................................................ 41
Figure 8.1: The recycling score (RER) policy connection ...................................................................................... 43
Figure 9.1: All policies for the real price of copper, global consumption of refined copper, the part of original demand substituted and the RIR in the top down model ............................................................... 48
Figure 9.2: All policies for the marginal costs of copper and deep sea copper, relative part of deep sea mining and the year left of copper mining in the top down model .................................................................. 49
Figure 9.3: Part of original demand substituted [Dmnl] with substitution policies .................................................. 49
Figure 9.4: RIR [Dmnl] with recycling policies ..................................................................................................... 49
Figure 9.5: All policies for the real price of copper, global consumption of refined copper, the part of original demand substituted and the RIR in the bottom up model ......................................................... 50
Figure 9.6: All policies for the marginal costs of copper and deep sea copper, relative part of deep sea mining and the year left of copper mining in the top down model .................................................................. 50
Figure 9.7: All policies for the real price of copper, global consumption of refined copper, the part of original demand substituted and the RIR in the regional model .................................................................. 51
Figure 9.9: All policies for the marginal costs of copper and deep sea copper and the year left of copper mining in the regional model ........................................................................................................ 51
Figure 9.8: Lines graph for year left of copper mining with all regional policies ...................................................... 51
Figure 9.10: All policies for the regional relative parts of deep sea mining .............................................................. 52
Figure 9.11: Real price of copper [Dollar/t], recycling policies ............................................................................. 52
Figure 9.12: Real price of copper [Dollar/t], all policies ....................................................................................... 52
Figure 9.13: Real price of copper, recycling policies ............................................................................................ 53
Figure 9.14: Real price of copper, strategic reserve policy .................................................................................... 53
Figure 9.15: Global consumption of refined copper [t/Year] with recycling policies ............................................. 53
Figure 9.16: Global consumption of refined copper [t/Year] with all policies .......................................................... 53
Figure 9.17: Real price of copper [Dollar/t], recycling policies .............................................................................. 53
Figure E.29: Lines graph for the Relative part of deep sea mining .............................................................. 107
Figure E.30: 3D envelopes of the Relative part of deep sea mining [Dmnl]. The graph is not truncated .......... 107
Figure E.31: Lines graph for the Year left of copper mining ........................................................................ 107
Figure E.32: Multiplot of Global consumption of refined copper [t/Year] and Year left of copper mining [Year]. 107
Figure E.33: Lines graph for the Real price of copper .................................................................................. 108
Figure E.34: 3D envelopes of the Real price of copper [Dollar/t]. The graph is truncated at 100000 Dollar/t...... 108
Figure E.35: Lines graph for the Global consumption of refined copper ...................................................... 109
Figure E.36: 3D envelopes of the Global consumption of refined copper [t/Year]. The graph is truncated at 30 million t/Year ............................................................................................................ 109
Figure E.37: Lines graph for the Part of original demand substituted ............................................................ 109
Figure E.38: Lines graph for the RIR .............................................................................................................. 110
Figure E.39: Lines graph for the Marginal costs of copper .......................................................................... 110
Figure E.40: Lines graph for the Marginal costs of deep sea copper ............................................................. 110
Figure E.41: Lines graphs for the regional relative parts of deep sea mining ................................................ 111
Figure E.42: Lines graph for the Year left of copper mining ........................................................................ 111
Figure E.43: 3D envelopes of the Year left of copper mining [Year]. The graph is truncated at 500 year ...... 111
Part One: Introduction
1. Introduction

Frequently the Dutch media report the theft of copper wire used by the Dutch railways (Klis, 2011; Volkskrant, 2011): The word "koperdief" (copper thief) was even added to the online version of the "Grote Van Dale" due to the enormous rise in the use of the word in newspapers (Sanders, 2011). It is also considered a growing problem, since the copper theft increased with 173% percent over the last year. The obvious reason for the rise in thefts is the high copper price of the last years (LME, 2011). There seem to be two causes for the high copper price: the energy transition towards a more sustainable mix of energy sources (Kleijn, R. & van der Voet, 2010) and the growing demand for minerals in fast developing economies like China and India (European Commission, 2011).

Next to this is the ongoing debate about mineral scarcity, which focuses on several "risky" metals, like lithium (Angerer, Marscheider-Weidemann, Wendl & Wietschel, 2009; Auping, 2009). There are signs that regulations to help industry obtain their scarce metals are being developed (Hekking, 2011). Despite the copper thefts not much attention is yet paid to copper, despite the fact that this bulk metal can be considered a scarce metal, in contrast with for example iron or aluminium (Gordon, Koopmans, Nordhaus & Skinner, 1987: 2).

1.1. The energy transition

The energy transition is the change from fossil fuels to renewable energy. It stems from the debate on climate change in combination with geopolitical issues related to the security of supply. These have brought the European Union (EU) to the idea that the dependence on fossil fuels should be reduced and the share of renewable energy, like hydro and wind power, solar energy, hydrogen production and bio fuels will have to increase (European Parliament & European Council, 2009). For this purpose, the often mentioned 20-20-20 goal was established (Council of the European Union, 2007), which means that countries in the EU will feel committed to decrease their greenhouse gas emissions by at least 20% in 2020 compared to 1990 and having a share of at least 20% renewable. For 2050 the goals are even more ambitious and the countries strive to collectively reduce the greenhouse gas emissions by 60 – 80 %. A similar policy exists in the United States, were the White House recently posted the goal to have 80% of the electricity production by clean sources (National Economic Council, Council of Economic Advisers & Office of Science and Technology Policy, 2011).

For the development of solar power for the European main land, several plans have been developed, like the Mediterranean Solar Plan. This plan aims at installing Concentrated Solar Plants (CSP) in the Southern Mediterranean Area and the Middle East (Presidencia Española de la Unión Europea, 2011; Viebahn, Lechon & Trieb, 2010). These solar plants will be connected to the European electricity network to provide solar power, as can be seen on the plans of the Desertec Foundation (Desertec Foundation, 2011).

For the electricity infrastructure large amounts of copper may be needed, but not much research has been done to create more insight in possible problems related to the availability of this metal on the long term, especially in relation with the energy transition (Kleijn, R. & van der Voet, 2010). The interest of this problem becomes clearer when falling ore grades are taken into consideration, which cause the energy demand of mining copper to increase. As a result of this, the price of the commodity will also have to rise (Koppelaar, 2011).

1.2. Emerging economies

The emerging economies have a great influence on the strong rising copper demand of the last years (ICSG, 2010b: 36, 50). One of the characteristics of these countries is the large population: larger than all the old developed countries combined (UNPD, 2011a). These people experienced a strong economic growth last years,
which in combination with the fact that people with a higher income on average have a higher need for resources (Gordon, Betram & Graedel, 2006: 1210), have resulted in the spectacular rise in copper demand from these areas.

1.3. Uncertainties in the copper system

Many things about the copper system are uncertain, while they may have a great influence on the development of the system. A first example is the development of the ore grade of copper in the future, which is one of the main drivers of the costs of copper mining (ICSG, 2010b: 12; Koppelaar, 2011). It is uncertain in what pace ore grades will decline. One theory which concerns this, the Skinner thesis (Skinner, 1976), has been neither adequately proven nor falsified.

The copper price is very sensitive to the grade of ore because of the large amount of energy that is needed to extract copper from the ore. This introduces considerable uncertainty into future scenario development. The future of energy prices is a second big uncertainty. Another big uncertainty is whether and how much substitutes of the metal can be used. This depends on the variety of substitutes available, the amount needed for substitution and the price of the substitutes (Gordon et al., 1987: 66-76). The future movement of the prices of these substitutes is unknown.

A final uncertainty is connected to the earlier mentioned relation between copper use, welfare and population size. Several scenarios exist for these developments (UNPD, 2011a), but the real development will remain unknown.

1.4. Research introduction

Despite the fact that the copper system is transparent and much information is available, it is interesting to relate the above mentioned trends to uncertainties in the copper system and to the future availability of this metal. A second matter is the development of potential policies to counter undesirable risks that might occur due to the energy transition. The question immediately arises:

*What are the effects of parametric and structural uncertainties on the possible future behaviour of the copper system?*

In the research performed here, an Exploratory System Dynamics Model and Analysis (ESDMA, see Pruyt, 2010b) is made for the period 2000 till 2050. For this purpose, three different models have been developed, representing different views regarding the demand and supply of copper. With these models it is attempted to find different types of behaviour for different system parameters and possible policy options to counter undesirable behaviour. The research is performed from the perspective of stakeholders in the European Union.
2. Problem exploration

The research problem is separated into two distinguished parts: the social and the scientific. The social relevance concerns the impact on society in general, while the scientific relevance emphasizes on the contribution of this research to the body of knowledge of System Dynamics (SD) modellers and researches. After this, the problem statement is given and the formulation of the research objectives. This is followed by a motivation for the choice of the research method. After this, the scope of the research is clarified. Finally, the research questions central in this research are presented.

2.1. Problem exploration

2.1.1. Societal relevance

The proposed energy transition discussed in the introduction can have as a consequence that due to the construction of transmission lines between Concentrated Solar Plants in the Southern Mediterranean area, copper will become scarcer and hence more expensive for the European Union. Interest is growing in the geopolitical aspects of the availability of many scarce metals and crucial metals, but copper is not mentioned in these lists (Hekking, 2011), since it is considered a base commodity and widely available.

Copper is however not only used in transmission lines, but also for construction, electronic products, industrial machinery and consumer products (Raw Materials Group, 17 March 2010). The present copper use is often given in kilogram per capita and compared to the Gross Domestic Product (GDP) per capita (Gordon et al., 2006; ICSG, 2010b: 37; Raw Materials Group, 17 March 2010: 11). An increasing GDP per capita in developing countries such as India and China has combined with a growing world population to put additional pressure on copper availability.

Due to ore grades falling, extracting copper from the ore will most likely become more expensive, since the energy costs are higher at a lower ore grade (ICSG, 2010b: 12). This makes it more interesting to investigate the effect of this increase in energy needed for copper ore mining and refining (Sun, Nie, Liu, Wang & Gong, 2010) and its effect on the marginal costs of copper. The copper price is related to these marginal costs. This price seems to have been more or less constant for the last 140 years (Svedberg & Tilton, 2006), with a great exception in the last 5 years, when prices surged upwards.

Geopolitically certain facts stand out about the concentration of power in this market: mining is concentrated in Chile (1/3rd of world production), while smelting is more and more concentrated in China (1/4th of world production) (ICSG, 2010b: 10,16) and the three largest mining companies produced 27.9% of all copper worldwide in 2005 (Bundesanstalt für Geowissenschaften und Rohstoffe, or BGR, 2007).

Finally, any modelling of future possibilities needs to embrace the uncertainties within the copper system relating to new product development, energy transition and geopolitical policies to counter uncertain scenarios in the next 40 years. At least the copper system has a considerable amount of reliable basic data, which is lacking in many other metal markets.

2.1.2. Scientific relevance

The scientific relevance lies in the fact that using ESDMA is a relatively new way of approaching uncertainty in systems. There is little experience in this type of modelling for metal scarcity, especially for a main metal like copper.

Despite the relatively well documented nature of the copper system, much uncertainty still exists, both structural and parametric. An example of a structural uncertainty is the debate whether metal scarcity should be
modelled with an open or closed stock for the reserve base, i.e. if the reserve base can grow from the resource base (Tilton & Lagos, 2007) or will remain constant in the next period (Gordon, Bertram & Graedel, 2007; Gordon et al., 2006). Also structurally uncertain is the growth of mine or smelting production capacity. It is unclear with what kind of delay this should be modelled. Since every type of structure can give a difference in system behaviour, it is important to explore this uncertainty. Parametric uncertainty is evident to the fact that this study tried to explore the future, at which time all kinds of parameters will become more uncertain.

Scarcity is in this research defined as the moment when copper availability cannot satisfy the demand, with as a result price (considerably) higher than the maximum marginal costs of copper.

2.2. Problem statement
In this project, an attempt was made to explore uncertainties in the copper system in the past 10 years and the next 40 years. For this purpose, three SD model varieties were made which were used in an exploratory way regarding structural and parametric uncertainty. The knowledge gap lies in a lack of insight in the dynamics of the copper system in the future and the uncertainties and risks associated with the present and future structure of this system, especially in relation to the rise in demand due to the energy transition from fossil to renewable energy. The perspective of the research is the European Union. The policy measures suggested and tested will thus be relevant for this problem owner and other actors active in the European part of the copper system.

2.3. Research objectives
This research is intended for everyone who is interested in the issue of mineral (metal) scarcity, but especially for policy makers and the SD community. The first group is relevant for this research, since they may have the opportunity to change the copper system in such a way that unwanted behaviour, like scarcity and price volatility, will occur in fewer instances. The other group is important, because this research makes use of a new development in the SD body of knowledge, being the use of System Dynamics models for Exploratory Modelling and Analysis.

The behaviour of the system is assessed by looking at Key Performance Indicators (KPIs) of the system. These are visible on the right side of Figure 2.1. These are the Real Copper price – which is the copper price corrected for inflation (Svedberg & Tilton, 2006), the Reserve over Production (R/P) ratio, the Global copper consumption, the Recycling Input Rate and the Part of original substituted. Further Performance Indicators (PIs) are the Marginal costs of copper, the Marginal costs of deep sea copper and the Relative part of deep sea mining.

2.4. Choice for research method and modelling software
The method Exploratory System Dynamics Modelling and Analysis is chosen, because exploration of the future of the copper system is very interesting from the perspective of different possible modes of behaviour of the above mentioned KPIs and PIs. The uncertainties which are present in the system (already partly discussed in section 1.3) span the uncertainty space of the systems future behaviour. Allowing these uncertainties to show their influence, gives also a better perspective on the effectiveness of possible policy options regarding the types of behaviour that are possible in this system.

The copper system is a well documented, complex system. It is characterised by the strong feedback loops present in the system (see for instance Appendix A). Another feature is the long time horizon of this research and the possible importance of stocks and flows in the system (see for example Figure 5.1) for the long term behaviour of the system. A very suitable research method for these characteristics is System Dynamics.
modelling, which emphasizes on the dynamic behaviour of the system in relation to stocks and flows in the system (Meadows, 1985).

Due to the open structure of the copper system, data is available in many different sources. The main sources used are the International Copper Study Group (ICSG), the United States Geological Survey (USGS), the World bank, UN Population division (UNPD), the German Fraunhofer institute, the "Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek" (TNO) and many scientific articles about this or similar subjects.

2.5. Scope of research

This research offers a global view on the copper system (Figure 2.1). This contains the subsystems for supply, demand and price mechanisms. A selection of policy options is visible on the left, while the (K)PIs are visible on the right.

The period examined in this research is the period 2000-2050. The reason for also trying to model behaviour already passed is that this gives an opportunity to validate the bounds of the behaviour generated by modelled system.

2.6. Research questions

The following main question is central in this research:

What are the effects of parametric and structural uncertainties on the possible future behaviour of the copper system?

Before answering the main question is possible, it is first of importance to look at the following sub questions:

• What are drivers for the copper demand?
• What is the current and potential future structure of the global copper supply system?
• What uncertainties and potential risks exist in the copper system?
• What is the behaviour of the modelled (K)PIs in the copper system and can this be related to the real world system?
• How can policies be designed for the copper system?
• What are the effects of the designed policies on the (K)PIs in the copper system?

Before these questions can be answered, the setup of this research and the research method are presented in chapter 3. These questions are discussed in respectively chapters 4 till 9.
3. Research methodology

The method used to explore the copper system is the aforementioned Exploratory System Dynamics Modelling and Analysis (Pruyt, 2010b: 3-7). This is the combination of System Dynamics (SD) modelling (Box I) with Exploratory Modelling and Analysis (EMA). It is a very new approach of using models for analysis. In this chapter, first the major concepts of Exploratory Modelling and Analysis are explained. In the next section, SD and EMA are combined to explain ESDMA. In the final section of this chapter, the new research design used in this study is clarified.

3.1. Exploratory Modelling and Analysis (EMA)

For most real world systems different opinions exist about how the system can be modelled. In traditional modelling, the analyst tries to converge these different perspectives into one single model definition, which is often supposed to give most valid results regarding the prediction of future behaviour. A totally different approach is not to try to unite all different opinions in one structure, but allow these structural uncertainties to exist and explore the different system futures possible by combining these possible structures with the uncertainties also existent in the parametric values relevant for the system. This is the essence of Exploratory Modelling and Analysis (EMA) (Bankes, 1993; Lempert, Popper & Bankes, 2003).

In this study, EMA is performed by changing all uncertainties in the SD copper models from a python shell (Python Software Foundation, 2011). This enables the modeller to perform a high number of runs: the only limitation is the amount of time available for the research combined with the clock speed of the computer and the amount of memory available for data storage.

The number of runs performed also depends on the type of analysis done. For exploring the uncertainty space, a Latin hypercube sampling (Iman, Campbell & Helton, 1981) is used. This allows a broad perspective on the modes of behaviour the model can develop. When testing policies, a Full factorial analysis (Fischer, 1952) can be used. The number of runs performed in this analysis is dependent on the level in which the space needs to be explored and the number of uncertainties. The number of runs is then:

\[ \text{#Runs} = \text{level}^{\#Uncertainties} \]  

To be able to explore the corners of the uncertainty space, the value for \text{level} in (3.1) is most often two. It is clear that with any run time not infinitely small, the number of uncertainties greatly limits the number of runs which can be performed. For example, with a model which can generate ten runs per second and twenty uncertainties, the experiment will already take more than a day to complete, while if this model has 62 uncertainties, it will require 14.6 billion years to complete. Therefore, in cases with many uncertainties, a selection needs to be made regarding the sensitivity of the model to the parameters.

---

**Box I: System Dynamics**

SD contains several elements, which combined form the models used for this study. These elements are levels, rates, auxiliaries and constants. The rates form flows to or from a level, like in Figure 3.1.

This is depicted by a double, straight arrow. The mathematical representation of a level is the first-order integral equation:

\[ Level = \text{Initial level} + \int_{t_0}^{t} (\text{Rate 1} - \text{Rate 2}) \, dt \]  

Where \( t_0 \) is the initial time and \( t \) is the time of the model. Auxiliaries (and rates, which are special auxiliaries)
can contain any mathematical equation containing other elements of the model. This is shown by the (curved) single arrows from for example Rate 1, the Level and Constant 1 to the Auxiliary in Figure 3.1.

A constant remains the same during the run of the model. An initial value of a level is also considered to be a constant. A level can also be seen as a first order delay. It is also possible to use higher order delays. These are shown in the model by a double dash through a curved arrow, like between Auxiliary and Rate 2 (Figure 3.1).

The model can contain loops between variables, which need to contain at least one delay order. These loops are called feedback loops. In the simple SD model there are three present, with different lengths: Auxiliary – Rate 2 – Level – Auxiliary with length two, Auxiliary – Rate 2 – Level – Rate 1 - Auxiliary with length three and Auxiliary – Rate 2 – Level – Rate 1 – Auxiliary of length 4. They can be either positive (reinforcing) or negative (balancing), depending on the relations between the elements. Positive loops in isolation cause exponential growth or decay, while negative loops in isolation have balancing or goal seeking behaviour (Pruyt, 2010b: 3, 4).

To give results of the SD model and solve the integral equations like (3.2), a numerical integration method is used to solve the equation. In the modelling package used for the models underlying this research, Vensim, this can be either the Euler method, difference equations or second and fourth order Runge-Kutta methods (Ventana Systems, 2010: 213). More insight in these methods can be found in Borelli & Coleman (2004: 122-129).

3.2. Exploratory System Dynamics Modelling and Analysis (ESDMA)

With ESDMA a SD model is used for performing EMA. This has certain consequences for the way the model is built, since it needs to fit the purpose of exploratory modelling, i.e. the mapping of the consequences of a very extensive uncertainty exploration. This means that the model is not developed with the purpose of being able to reproduce historic data in the base run or just similar modes, but should be able to produce many different types of behaviour, dependent on the set of uncertainties chosen for each run. Verification of the model happens in the traditional fashion, but validation takes place by examining the possibility and the plausibility of the outcomes the model generates.

To be able to explore the structural uncertainties mentioned above, an Exploratory SD model needs to contain separate structures for areas where structural uncertainties occur. An example of these structures used for the copper system, are structures which can generate different economic growth scenarios (Box II) and different scenarios for the development of the energy price and the prices of substitutes.

3.3. Research design

While System Dynamics modelling is a well documented and standardised research approach and fits very well the standard "model cycle" (SDS, 2011; Waveren, Groot, Scholten, Geer, Wöstien et al., 1999: 0-1), the combination of System Dynamics with Exploratory Modelling and Analysis is very new and does not have a well documented set of steps for performing the study. Therefore, both to give a framework for this research and to
give insight in how such a research could be performed, the research design is presented here (Figure 3.2). In this research design, two possible ESDMA approaches are compared with the traditional SD approach. The two new approaches were developed before and after performing the experiments. The difference can thus be explained by the change in perception of a good ESDMA approach that evolved during this research. The ex post ESDMA approach is the way the study was actually performed.

The differences between the traditional SD and the ex ante ESDMA approach are not very extensive, since the first ESDMA research design was largely based on the traditional SD model cycle. When, in an ESDMA effort, the researcher uses the ex ante framework, planning of the research will be practically impossible. After step 4 in this research cycle the researcher will have the feeling to be just past half way, while in the ex post framework he will turn out to have just begun.

A change which is present in both the ex ante and the ex post ESDMA approach, is the absence of an explicit dynamics hypothesis, since the inherently uncertain outcomes of EMA make it very difficult, or impossible, to define this. It is important however, to think in advance about potential undesirable behaviour the system can exhibit, both in discussion with the client and with experts. When specifying the model in the ESDMA approach, it is immediately important to think about elements in the model which values or build up are unknown or uncertain: the parametric and structural uncertainties.

Another big difference is the correct moment for verification and validation of the model. In the traditional SD model cycle, this is a separate step. In the ex post ESDMA cycle essentially validation is part of step two up to and including four. The ESDMA methodology is thus also used as a tool for validation of the research results.
Part Two: The World Copper System
4. Copper demand and substitution

There are different perspectives possible of looking at copper demand. Two major alternatives are a top down or a bottom up approach. Another way of looking at copper demand is from a regional point of view. These differences have let to different varieties of models which might demonstrate different behaviour of the copper system and the KPIs defined in section 2.3. In relation to this, substitutes for copper and their relation with the copper demand are discussed.

4.1. Main drivers for copper demand and model varieties

In this research, three model varieties have been made for the different perspectives for copper demand discussed above. These are discussed now, together with the main differences between the models.

4.1.1. Top down

When copper demand is determined top down, this means in this study that the Gross Domestic Product (GDP) per capita, with no inflation, is compared with the use of copper per capita and the size of the global population (Tilton, 2003: 70). In this respect, this is the least complex way of approaching the demand. A Causal Loop Diagram (CLD, see Lane, 2008; Sterman, 2000: 137-190) of this system view can be seen in Figure 4.1. This CLS is an expansion of the little CLD visible in the systems diagram (Figure 2.1).

![Figure 4.1: Top down intrinsic demand](image)

From a modelling perspective, this means that for the time period of the model values need to be found for the world population size, the GDP per capita and for the relation between the copper demand and the GDP per capita (Wouters & Bol, 2009: 18). For the world population, the low, middle, high and constant fertility scenarios are used which have been developed by the United Nations, Department of Economic and Social Affairs. Population Division, Population Estimates and Projections Section (UNPD, 2011a). The GDP per capita can be modelled by looking at the growth of the global GDP and dividing this by the world population. The main uncertainty here is the economic growth rate. How this is modelled here can be seen in Box II.

The economic paradigm behind this model is a perfect market, since all suppliers of copper are generalised in a global perspective and copper is being sold to the highest bidder. This leaves out the regional, geopolitical interference of regions. It is interesting to see whether this approach gives similar or different types of behaviour compared to the model with the regional approach (section 4.1.3).
In modelling economic growth, it is assumed that it consists of several cycles which are super positioned on each other. When there is a short, medium and long cycle, with each cycle being more or less dominant on different moments, this can be modelled as $3 \times 2$ sinus with 3 amplitudes, together with a base economic growth (Figure 4.2). This results in the following equation:

\[
\text{Yearly economic growth } \text{ESDMA} = \\
\text{Amplitude long sinus } \times \text{Economic sinus long period amplitudes } \times \text{Economic sinus long period} \\
+ \text{Amplitude medium sinus } \times \text{Economic sinus medium period amplitudes } \times \text{Economic sinus medium period} \\
+ \text{Amplitude short sinus } \times \text{Economic sinus short period amplitudes } \times \text{Economic short period} \\
+ \text{Base economic growth}
\]

All purple variables with a purple background are uncertainties which can be varied by the python shell. The effect is a behaviour which is chaotic, but which still has strong periodic aspects to it, as can be seen in Figure 4.3. Turning this behaviour on and off before runs, allows analysis of the influence of the economic growth on the copper system.

### 4.1.2. Bottom up

From the bottom up point of view, the copper demand is composed of a set of uses which all have a quasi independent growth. This allows testing of the effects of scenarios regarding energy transition developed by different authors. A selection of major uses of copper has been made by the Fraunhofer ISI (Angerer, Mohring, Marscheider-Weidemann & Wietschel, 2010: 16-20). Two of these uses, the automotive sector and infrastructure, are strongly linked to the development of a more sustainable way of using energy. Some different authors have thus hypothesised possible scenarios for these applications scenarios, which can form input for the bottom up model.

![Figure 4.4: Bottom up intrinsic demand](image-url)
In the model, the “dominance” and “pluralism” scenarios of electric vehicles for the automotive industry, developed by the Fraunhofer ISI, have been used (Figure 4.5 and Figure 4.6). These scenarios regard the relative part of new cars built which have (semi) electric propulsion. These types are, besides the conventional automobiles, the Hybrid Electric Vehicle (HEV), the Plug-in Hybrid Electric Vehicle (PHEV), the Battery Electric Vehicle (BEV) and the city BEV. These are relevant, since the amount of copper per vehicle depends heavily on the grade in which the vehicle has electric propulsion. For the development of the electricity infrastructure, which is related to the development of decentralised sustainable energy sources, another scenario is presented in an article of Kleijn & van der Voet (2010).

Figure 4.5: The dominance scenario (Angerer et al., 2010: 18)  
Figure 4.6: The pluralism scenario (Angerer et al., 2010: 19)

4.1.3. Regional

In the regional approach, visible in Figure 4.7, the global demand for and production of copper is divided in regions which are divided by the resources they have most. The supply side is extensively discussed in chapter 5. The copper price however remains global in this model. The big difference in economic perspective is the fact that this model variant does not assume a totally free market: a regional mine will first supply a smelter in its own region, and only when this demand is satisfied, other regions will be supplied. Since the highest bidder is most probable to receive the materials needed, the copper export over the regions is assumed to be divided regarding the GDPs per capita of the regions with a copper deficit.

Figure 4.7: Regional approach. All variables with a green background are regional

The regional model makes use of three distinct regions: the developed world (Europe, N-America, Oceania and Japan), the upcoming economies (Asia without the CIS and Asean-10) and the (resource abundant) developing countries (Africa, S-America, and Asean-10). These areas correspond with respectively the more developed countries, the Asian part of the less developed countries and the rest of the world (UNPD, 2011b). The idea is a
distinction between money (region 1), people (region 2) and the resources (region 3). The selection is thus not meant to be topographical. Together they might generate interesting geopolitical issues.

Deep sea mining is in this situation of course more difficult to regionalise, especially when deep sea mining takes place in international waters. The assumption made in the regional model to solve this issue is that a mining concession means that the copper mining is regionalised. Since the reserve base is part of a mining concession (see section 5.1.2), this is the moment to bring in the regional division. The regional "preference" to develop deep sea mining, is linked to the average GDP per capita in the region, since this can be considered an indicator for development as well. More details about deep sea mining are discussed in section 5.3.

Box III: Modelling uncertainty: Relations for demand

In the CLDs showing the different model varieties in this research, it is visible that the copper demand is influenced by three different elements: the intrinsic demand, substitution and the copper price. This is also visible in the model structure visible in Figure 4.8.

In this research it is assumed that each of these elements has both a short and a long term effect. To calculate these effects, each element is compared with its relevant counterpart to calculate their relation. For the three elements these are intrinsic demand (A) and availability (B) for the copper price, price of copper (A) with the price of aluminum (B, for more details about this, see Box V) for the substitution and finally the intrinsic demand with the demand (A) and substituted demand (B) for the effect of the intrinsic demand. This formula is of the form:

\[
\text{Relation} = \left( \frac{A}{B} \right) \cdot \text{Amplifier}
\]

Since the values for A and B are always positive, this relation will have a value between 0 and infinity as well, while the relation is equal to 1 when A and B balance. It is uncertain however how big the influence of the relation between A and B will be. Therefore, the relation can be amplified with a value around 1 (for example, between 0.25 and 4). This amplifying factor is an extra uncertainty in the relation.

![Figure 4.8: SD structure for short and long term effects on demand](image)

When calculating the effect of this relation, it is assumed that a balanced relation should have no effect. Further, the extreme values (i.e. 0 and infinity) should have the same effect. The following equation simulates this effect (with thanks to Bonthuis, 2011):

\[
\text{Effect} = 1 - 2 \cdot (1 - \text{Relation})
\]

The values for effect are between -1 for Relation = 0, 0 for Relation = 1 and 1 for Relation = \(\infty\). This effect can also be amplified similar to the Relation amplification. It is assumed that this effect can change the demand directly (short term) or by the accumulation of the effect of a longer period of time (long term). The sum of the short and long term effects define the maximum decrease or increase in demand, since the relation is as follows:
Loss in demand due to price elasticity =
( Short term copper price elasticity * Amplified effect of relative price on demand + Long term copper price elasticity * Average long term effect on demand ) * Total demand for copper

The total demand is subsequently calculated by solving the integral equation with the input regarding the intrinsic demand and the outputs regarding the price and the substitution.

4.2. Copper substitution

A significant change in the demand for copper can come from the substitution of this metal for another resource. This is a process that is of all times: a very early example may be the transition of the Bronze Age towards the Iron Age (Gordon et al., 1987: 60). In our times substitution and also resubstitution (a substitute is discarded for a renewed use of copper) of copper is also common practice, as the use of aluminium core steel reinforced cables for electricity transport, plastic pipes for water transport and glass fibre infrastructure for data traffic illustrate (Gordon et al., 1987: 74, 75; U.S. Geological Survey, 2011: 49). Substitution of electric wiring in homes has however caused serious fire hazards in the past (Gordon et al., 1987: 71).

The substitution of copper can be triggered by a crisis in availability, or sustained differences in price (Figure 4.9). It can however also in itself generate a crisis by a sudden collapse in demand and as such form a threat for copper production (Rademaker & Kooroshy, 2010: 3). It could therefore also pose a system risk.

The moment at which point substitution of a mineral becomes relevant, can be calculated by comparing the amount of substitute material needed to replace the original demand and the relation in price between both resources (Gordon et al., 1987: 66-69). The way in which this was implemented in the model, can be seen in Box IV. A major assumption here is the view that the substitution is compared with the excess demand which existed at the moment the model is initiated. The initial value for substitution is for this reason zero.
Substitution of copper demand takes place when the price of copper is at such an amount that it is cheaper to use the substitute than the original resource. This is modelled by using a threshold value, which models the fact that the weight of aluminium needed to replace copper is not equal to the weight of copper originally needed. This relation is then amplified, to increase (or decrease the effect) of the substitution relation Figure 4.10.

Relation between copper and aluminium price =

\[
( \text{Real price of copper} / ( \text{Substitution threshold} \times \text{Price of aluminium} ) ) ^ {\text{Substitution amplifying factor}}
\]

The method for modelling different uses in the bottom up model is by use of different threshold values for every use. This assumes a similar price development of the different substitutes, which is not necessarily true. However, it poses a significant simplification of the model, which adds to the intelligibility of the structure and reduces the amount of data needed as input for the model and the EMA.

The two-stock structure in Figure 4.11, which is based on the one-stock-structure from (Pruyt, 2010a: 5), allows the model to “store” the amount of demand which was substituted. This information is used for generating the new demand, since it is assumed that the part of demand substituted will again be substituted, ceteris paribus, in the new demand. The part of original demand substituted is calculated with the following equation:

Part of original demand substituted =

\[
\frac{\text{Total substitution of copper}}{\text{Total demand for copper} + \text{Total substitution of copper}}
\]

In reality this would mean for instance that if half the electricity transportation companies have decided to build new high voltage infrastructure with aluminium wires, they will make this choice again when they have to replace new bits of their network. Another effect which can be generated by this structure is oscillation between the substituted and the copper parts of demand. This could happen if the price oscillates around the threshold value for substitution already discussed above.
5. Current and potential structure copper supply system

In this chapter the structure of the physical copper supply system will be discussed. This consists of the resources and reserves, mining, smelting and refining and recycling. A schematic stock-flow diagram (Sterman, 2000: 191-229) of this system can be seen in Figure 5.1.

Figure 5.1: Extended stock-flow diagram of the copper supply system with some connections to the demand

5.1. Resources and reserves

The natural sources of copper which are theoretically minable are called mineral resources and ore reserves. Their classification is however bound to strict rules (JORC, 2004), in order to create an unambiguous image of the potentially copper availability underground. An easy way of depicting the relations between resources and reserves is the McKelvey box (Figure 5.2), which provides ordering on economic feasibility and geological assurance. In the copper EDSMA models some simplifications have been made in this perspective, which will be discussed in the next sections.

![Diagram of copper supply system]

Figure 5.2: Relation between reserves and resources. Based on the McKelvey Box (McKelvey, 1973)
5.1.1. Resource base and resources
The total amount of copper in the lithosphere can be calculated by taking the average elemental abundance of copper and multiplying it with the estimated weight of the earth’s crust. This is called the Resource base (Tilton, 2003: 22, 23). There is among scientists discussion on whether this is relevant for the – undiscovered – ever recoverable amount of copper (Gordon et al., 2007; Gordon et al., 2006; Tilton & Lagos, 2007). The resources are then the undiscovered, but potentially economic amount of copper available.

The exact distribution of the ore grade of undiscovered copper deposits is unknown, but it is often assumed that it is the high-end of a lognormal curve (Gordon et al., 1987: 38). Another option is the “Skinner thesis” (Skinner, 1976), which proposes a bimodal lognormal distribution. This consists of a lognormal distribution for copper ores and a similar, but at lower grades positioned distribution for deposits in common rock. Despite the fact that Skinner posed this theory in 1976 and it was considered probable, no proof can be found in the literature (Gordon et al., 1987: 39, 40). The most important consequence of accepting the Skinner thesis is the “mineralogical barrier” between the two lognormal modes of ore and rock deposits. This barrier means that the amount of energy needed to process copper ore dramatically increases around 0.1% Cu grade (Skinner, 1976).

![Figure 5.3: Ore grade in relation to energy costs needed for processing copper (Skinner, 1976)](image)

In the model some simplification is made for the resource and resource base. First, originally the lowest part of the sub-economic discovered copper is also considered to be part of the resources, and not of the reserve base. The distinction between reserve base and resources is thus strictly whether the deposits have been discovered or not. The distinction between resources and reserve base is now just an economic factor. When mining capacity is able to extend (due to profits), the resources extend due to the available resource base.

5.1.2. Reserve base and reserves
For resources to be turned into the reserve base, a proper assessment of the availability of the reserves and the economic feasibility to mine them needs to be made (JORC, 2004: 10-12). The difference between the actual reserve and the reserve base lies again in the economic value of the deposits: the reserves are economic, the reserve base is marginally economic (Gordon et al., 2007: 25). On mine level, the distinction is even easier to define. The reserves are the part of the deposits owned by the mine, which are above the cut-off ore grade. The reserve base is thus the rest, or the part which is below this ore grade (Kleijn, P. H. v. d., 2011, see also Appendix G). This can be seen in Figure 5.4. When the copper price rises or technology improves, the cut-off ore grade can become lower, which increase the reserves of the mine.
In the model the distinction is slightly aggregated: there is no distinction between reserves and reserve base, since both are physically minable. This is possible, since the average ore grade of the mining operations determine the marginal costs. When the price becomes too high compared to other options, the copper demand gets (partially) substituted, as was described above. The disadvantage of this approach is the fact that the KPI “Years left of mining” (R/P ratio), which can be calculated by dividing the reserves by the mining production, becomes several times higher when compared with the reserve base instead of the reserves.

5.2. Mining, smelting/SX-EW and refining

The transfer from copper reserves to copper in use happens through mining, smelting and refining. These processes will now be discussed, together with the way they are modelled.

5.2.1. Mining

After the classification of ore bodies at a certain spot, the mining operations can start. Dependent on the location of the deposits in the rock, this happens largely with two techniques: open-cast and underground mining. On average, the first technique is cheaper than the second. Other methods are in situ leaching and deep sea or ocean mining (Lossin, 2005: 9, 10). The latter will be discussed in section 5.3, due to its potential influence on the future of copper availability.

The biggest challenge of mining copper at this moment is the falling ore grade in developed copper mining areas, like Chile and the United States of America (ICSG, 2010b: 12). This, together with the increasing overhaul or overburden of rock due to deeper open-pit mines, increases the marginal costs of mining considerately (Gordon et al., 1987: 40-42; Kleijn, P. H. v. d., 2011).

A dynamic which is difficult to explain is happening in mine capacity utilisation over the last years (Table 5.1). The mine capacity is mostly defined by the size and capacity of the breaker (Kleijn, P. H. v. d., 2011), but can also be defined by looking at the relation between the size of the reserves and presumed lifetime (Wellmer, Dalheimer & Wagner, 2006). Mostly mining capacity utilisation rises in times of high prices and declines when prices are low. The last decade however, the copper price has risen to heights unknown before. Reasons why the mines did not fully use their capacity in this period are therefore important to obtain, but were not available at the time of this research.
Table 5.1: World Refined Copper Usage and Supply Trends, 2000-2010 (ICSG, 2010a, 2011). Production values are in thousand metric tons.

<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>World Mine Production</td>
<td>13203</td>
<td>13633</td>
<td>13577</td>
<td>13757</td>
<td>14594</td>
<td>14924</td>
<td>14991</td>
<td>15474</td>
<td>15528</td>
<td>15950</td>
<td>16097</td>
</tr>
<tr>
<td>World Mine Capacity</td>
<td>14277</td>
<td>14532</td>
<td>15193</td>
<td>15338</td>
<td>16072</td>
<td>16826</td>
<td>17141</td>
<td>18098</td>
<td>18739</td>
<td>19523</td>
<td>19898</td>
</tr>
<tr>
<td>Mine Capacity Utilisation (%)</td>
<td>92.5%</td>
<td>93.8%</td>
<td>89.4%</td>
<td>89.7%</td>
<td>90.8%</td>
<td>88.7%</td>
<td>87.5%</td>
<td>85.5%</td>
<td>82.9%</td>
<td>81.7%</td>
<td>80.9%</td>
</tr>
<tr>
<td>Primary Refined Production</td>
<td>12696</td>
<td>13746</td>
<td>13457</td>
<td>13485</td>
<td>13848</td>
<td>14411</td>
<td>14678</td>
<td>15191</td>
<td>15399</td>
<td>15414</td>
<td>15660</td>
</tr>
<tr>
<td>Secondary Refined Production</td>
<td>2100</td>
<td>1892</td>
<td>1898</td>
<td>1786</td>
<td>2069</td>
<td>2161</td>
<td>2613</td>
<td>2743</td>
<td>2823</td>
<td>2839</td>
<td>3401</td>
</tr>
<tr>
<td>World Refined Production (Secondary+ Primary)</td>
<td>14796</td>
<td>15638</td>
<td>15335</td>
<td>15271</td>
<td>15917</td>
<td>16572</td>
<td>17291</td>
<td>17934</td>
<td>18222</td>
<td>18523</td>
<td>19061</td>
</tr>
<tr>
<td>World Refinery Capacity</td>
<td>17145</td>
<td>17760</td>
<td>18320</td>
<td>18804</td>
<td>19179</td>
<td>20250</td>
<td>20664</td>
<td>21559</td>
<td>22462</td>
<td>23625</td>
<td>23908</td>
</tr>
<tr>
<td>Refinery Capacity Utilisation (%)</td>
<td>86.3%</td>
<td>88.1%</td>
<td>83.8%</td>
<td>81.2%</td>
<td>83.0%</td>
<td>81.8%</td>
<td>83.9%</td>
<td>83.2%</td>
<td>81.1%</td>
<td>77.3%</td>
<td>79.7%</td>
</tr>
<tr>
<td>World Refined Usage</td>
<td>15185</td>
<td>15014</td>
<td>15210</td>
<td>15717</td>
<td>16833</td>
<td>16683</td>
<td>17058</td>
<td>18239</td>
<td>18056</td>
<td>18900</td>
<td>19314</td>
</tr>
<tr>
<td>Refined Stocks End of Period</td>
<td>1291</td>
<td>1992</td>
<td>2048</td>
<td>1780</td>
<td>923</td>
<td>867</td>
<td>1131</td>
<td>1027</td>
<td>1159</td>
<td>1433</td>
<td>1289</td>
</tr>
<tr>
<td>Period Stock Change</td>
<td>-344</td>
<td>702</td>
<td>55</td>
<td>-267</td>
<td>-857</td>
<td>-56</td>
<td>264</td>
<td>-105</td>
<td>132</td>
<td>274</td>
<td>-144</td>
</tr>
<tr>
<td>Refined Balance</td>
<td>-389</td>
<td>624</td>
<td>144</td>
<td>-446</td>
<td>-915</td>
<td>-112</td>
<td>233</td>
<td>-305</td>
<td>162</td>
<td>163</td>
<td>-252</td>
</tr>
<tr>
<td>LME Copper Price (Dollar/t)</td>
<td>1814</td>
<td>1578</td>
<td>1558</td>
<td>1780</td>
<td>2868</td>
<td>3684</td>
<td>6727</td>
<td>7126</td>
<td>6952</td>
<td>5164</td>
<td>7539</td>
</tr>
</tbody>
</table>

Modelling of mining capacity has been done by looking at the profits that are and were made and comparing these with the – uncertain – capital investment costs. The model further assumes three different states the mining capacity can have, the mining capacity in preparation, mining capacity and the parked mining capacity. In the models, mines close when they have reached the average mine lifetime or when continued losses occur and largely ignores the difficult processes that happen at mine closures (Cochilco, 2002). A more detailed description can be found in Box V. Artisanal or illegal mining is not separately incorporated in the model.

---

Box V: Modelling uncertainty: Mining and refinery capacity

As mentioned above, the mining capacity is modelled in three states (Figure 5.5). This structure resembles the two-state structure used by Pruyt (2010a: 6), but differs in the way that here a bad economic situation will lead to first parking of the mining capacity and then, after continued losses, decommissioning. A second difference is the lack of a learning effect due to the cumulatively mined metal. The assumption here is that in a mature market these effects are comparatively small in relation to the increasing costs due to the declining ore grade. The growth of the mining capacity, from the state Mining capacity in preparation to the World copper mining capacity, uses the following delay structure (Pruyt, 2010a):

\[
\text{Growth mining capacity} = \text{DELAY N (Preparation of capacity increase, Average mine permit term, Initial mining capacity in preparation / Average mine permit term, Delay order mining capacity)}
\]

This is a way of modelling the structural uncertainty in the distribution of permit terms. The delay order (green background) can now be changed using the EMA method.
The preparation of capacity increase is relative to the already existing (used) and prepared mining capacity. First a comparison is made however between the marginal costs of conventional mining and deep sea mining. The cheapest method will receive most of the new capacity. A similar structure also exists for the development of deep sea mining capacity and the capacity of smelters and refiners.

5.2.2. Smelting and refining

After mining, the copper ore needs to be processed before it can be incorporated in products. How this happens, depends on the type of ore. Sulphide ores are processed by traditional smelting, while oxide ores and some sulphide ores use solvent extraction-electro winning (SX-EW) (Lossin, 2005: 43). The latter is a relatively new technique, developed in the sixties, which was in 2009 responsible for 18% of the copper production (ICSG, 2010b: 7). The products of copper smelters are blister and anode copper. In the refineries the copper is further concentrated till it can be melted and cast (Lossin, 2005: 12, 13). The final product before “consumption” of the copper is cathode copper and ingots.

In the model, smelting and refining processes are taken together, since the smelting and refinery concentrations are comparable per country (ICSG, 2010b: 15-22). A second reason is the relatively low export and import of blister and anode copper, compared to the export and import of other copper product categories. This also indicates that smelting and refining are often in proximity of each other (ICSG, 2010b: 27).

Another simplification is the fact that copper semis and alloys are not separately considered in the model. The reason for this is the fact that this will further complicate the model, but since the mass balances over the stocks of copper do not change with these products, will not generate new insights with regard to the sustainable use of copper.

5.3. Deep sea mining

The discovery of manganese nodules in the Pacific brought forward the interest about deep sea mining. These nodules contain apart from manganese also cobalt, nickel and copper (Glasby, 2000). Until now, mining this enormous resource has proved to be too expensive, but due to the high copper prices of the last years (Figure 4.9), there is at present at least one tangible project near Papua New Guinea for mining gold and copper in deep sea (Hobson, 2011).

There are several concerns regarding deep sea mining operations. The first is the environmental concern that mining in the ocean poses a serious threat to marine ecosystems (Halfar & Fujita, 2007). Especially the sediment plumes and toxic effects in the ocean water could have a devastating effect. Other concerns are about the legal aspects of deep sea mining outside Exclusive Economic Zones (EEZ) of countries. For this purpose, the United Nations Convention on the Law of the Sea (UNCLOS, McKelvey, 1980; United Nations, 1982) was
undertaken and the International Seabed Authority (ISA) was set up (Glasby, 2000). These last developments and the lower price of metals in the 1980’s and 1990’s stopped many initiatives on this subject.

Considering the legal status of the oceanic area outside the EEZ, especially articles 137 and 138 of UNCLOS are important. They state that the area is common heritage of mankind and that no state or person can claim any area or the resources in this area exclusively. Also articles 150 and 164 are particularly relevant, since they discuss the development of deep sea mining in relation to the world economy and a balanced growth of international trade. Annex III further describes conditions for prospecting, exploration and exploitation of mineral resources outside the EEZ (United Nations, 1982).

Despite these limitations, it is considered very feasible that significant deep sea mining will be happening in the future to come (Hobson, 2011). For this reason, it has been made an endogenous development of the copper system modelled. Initially, it is assumed to be of negligible size. The marginal costs of deep sea mining and conventional mining are compared to divide new mining capacity over both deep sea and conventional mining. These two forms are in this way assumed to be competitive. In this way, it limits the growth of the marginal costs of copper and potentially increases the supply and consumption of copper. In the regional model, the development of deep sea copper happens only in those regions which have an average GDP per capita above a certain threshold value. This resembles the need for sophisticated technology for deep sea mining, but this approach is conflicting with the idea of the UNCLOS agreement. It is still considered to be realistic, since even when profits of deep sea mining are shared via the ISA, the actual resources will most probably find their way to the region where the technology existed.

Box VI: Modelling uncertainty: Deep sea mining capacity

While the structure and development of conventional (onshore) copper mining operations are well documented, the development of deep sea mining is not, apart from UNCLOS (United Nations, 1982) and the few developments that are currently taking place (Hobson, 2011). This makes it more difficult to model this potential new source copper, while it has the potential to make a difference in the long term availability of this metal.

The first uncertain issue is the development of the deep sea resources and reserve base (Figure 5.6). This is considered to be comparable with the development of conventional resources and reserves. There is however one big difference: presently no deep sea copper reserves are classified (U.S. Geological Survey, 2011: 49). The model therefore uses a “normal resource reserve relation” to kick start the deep sea reserve development.

Figure 5.6: Deep sea copper resource and reserve development

The development of deep sea mining capacity has a similar problem: even though some deep sea mining capacity is already under development (Hobson, 2011), it is perceivable that the growth of deep sea mining will exceed normal growth percentages for the conventional mining capacity by far. The assumption in the copper models is consequently that all new mining capacity is related to all existing mining capacity and mining capacity in preparation. This can be seen in Figure 5.7. This is divided over the conventional and deep sea preparation of new mining capacity by comparing the marginal costs of both distinct types of mining. Roughly put is the preparation of new deep sea capacity equal to the new conventional capacity, when the marginal costs of both
copper sources are equal.

Figure 5.7: SD structure for new mining capacity

A consequence of this type of modelling, where the deep sea reserve base and mining capacity are not coupled, is that a situation is perceivable where the mining capacity exceeds the remaining copper reserve base, resulting in a sudden drop in production. This seems possible however, since the production capacity of deep sea copper mining will probably be mobile and not linked to production locations.

For the regional model, an assumption was made that the possibility for deep sea mining is dependent on the regional GDP per capita. This resembles the thought that the higher technological demands necessary for this kind of mining is probably not available in lower income countries. A threshold was thus built in, only enabling the possibility for deep sea mining development when the GDP per capita in a certain region is higher than this value.

5.4. Copper recycling or secondary copper

A considerable proportion of all used copper is recycled, resulting in a Recycling Input Rate (RIR) of approximately 35% in 2008 (ICSG, 2010b: 47). Copper does not lose its chemical or physical properties when recycling, even when it is recycled over and over again (Lossin, 2005: 38). Reasons this percentage is not higher are the long average lifetime of copper products (Angerer et al., 2010: 26) and the still growing consumption of the metal. This is also illustrated by the higher input rate of 37% for secondary copper in 1997 (Lossin, 2005: 38).

In copper recycling two important input streams are distinguished. Primary or new scrap is copper which is lost during production of copper products, while secondary or old scrap comes from products at the end of their lifetime. (Lossin, 2005: 38). Dependent on the grade of the scrap, it needs smelting or refining before reuse is possible.

Especially for the secondary copper, several factors limit the amount which is produced. These are first the collection rate, the percentage of products recycled. This is an important factor which can be increased with policies from local government. Other factors are the coefficients which influence the RER copper score during treatment, the copper score during dismembering and the percentage of copper recovered from scrap (Angerer et al., 2010: 26), which combined give the total recycling score or recycling efficiency rate.

The modelling of the recycling happens in a similar way. The different factors mentioned above are uncertain parameters in the model. The smelting and refinery capacity is used for the recycling process, which uses in this way a part of the capacity otherwise used for primary copper production.
6. Uncertainties and risks in the copper system

Despite the fact that the copper system is well documented and the copper price is formed in an open way, much information about the system’s parameters and structure remains uncertain. In combination with these unknowns, also risks exist for the system. In the next sections, which are the last chapter concerning the conceptual phase of this research, these uncertainties and risks are discussed.

6.1. Parametric uncertainties

Simply put, the parametric uncertainties are all external variables, which can be “caught” using a single value, initialised during the setup of the model. These can be divided into parameter values, initial values, delay orders, delay times and switches. The first category is the simplest. Good examples are the “Average lifetime of copper in use” (see the model structure in B.1.1, this variable in on the right of the figure) and the “Substitution threshold”, which is used by comparing the aluminium price with the copper price. Despite the fact that these values are constant throughout the run, this is of course a simplification of reality. All sorts of variables, both endogenous and exogenous of the copper system, can change these values during the period. For experimental purposes however, it is important to be able to alter these variables and keep considering them as constants. When an uncertainty can impossibly be considered constant throughout the run time, it may be built as a lookup function (Sterman, 2000: 552-563) dependent on time.

The second type is the initial value. An initial value sets a stock at the beginning of a run. The only moment they influence the system is thus at the moment of initialisation. Therefore, they do not give us the same problem as the constants described above. Good examples are the initial values for the Reserve base and the Mining capacity.

Delays have two different kinds of parametric uncertainties: the delay order and the delay time. The latter is largely comparable with the earlier mentioned constants and requires the same assumption for them to be constant during the entire run, but they may also be modelled dynamically and change over time. The delay order can be any integer value of at least 1. A good example of the delay was the mining capacity discussed in Box IV. The delay order in this case can be seen as the number of procedures the mine developer needs to work through before the mine is constructed. The sum of the average delay times per procedure is the total delay time.

The last type is the switch. This is used for alternating between different model structures and structural uncertainties. It can also be used for changing between certain scenarios, like the world population scenarios which form input for the model (UNPD, 2011a). The switch can be considered a true ESDMA uncertainty, since it is not used in normal System Dynamics practice, but is essential for being able to explore the structural uncertainty space of the system.

All parametric uncertainties belonging to the different copper models can be found in the Excel document attached to this report. To be able to generate these Excel worksheets a Python script was used which was developed especially for this research in cooperation with Jan Kwakkel (appendix D.3).

6.2. Structural uncertainties

The structural uncertainties cannot be caught using parameters. They pose a true difficulty for the modeller. In the copper system, despite the fact that it is well documented, these uncertainties also exist. The first of them was already discussed in section 5.1.1. It is the fixed stock verses the opportunity cost paradigm (Tilton & Lagos,
2007: 20). The models used in this study choose side in this discussion, by using a Resource base and letting the Resources develop on behalf of it.

Another structural uncertainty is the Copper use per dollar, or per GDP/capita. Despite some research and information on the type of relation to be expected, the exact form of the relation between GDP/capita and the copper use remains unclear and is probably subject to changes over time (Wouters & Bol, 2009). This is modelled by using different types of relations, which are normalised on a dimensionless scale. By comparing the calculated GDP/capita with a normalisation value (which is a parametric uncertainty) and switching between the different relations per run, it is possible to place this structural uncertainty in the uncertainty space of the model.

Further examples are the ore grade, economic growth (Box II) and the formation of energy and aluminium prices. For more information about how these are modelled, please look at the model structure in Appendix A and the model equations in the linked Excel file.

6.3. System risks

The copper system could be subject to system risks which can cause unwanted behaviour for system stakeholders, but no risks were defined at the beginning of this study. The research primarily aims at generating insight in the systems behaviour and not at assessing the value of the behaviour characteristics. Further, the commissioning actors were and are not active in the copper system. The great advantage of this point of origin is that it leaves space for the researcher and the reader to think independently about possible system risks.

For possible policy design in the copper system, further discussed in chapter 8, and when thinking about ways of influencing the system by actors participating in it, it is important to think about types of behaviour which need to or can be countered. The risks stated here are therefore assumptions and suggestions by the researcher, and no universal truths. They are intended to illustrate potential unwanted behaviour, from perceived different perspectives (actors or stakeholders) in the system. This process was however supported by literature and experts suggesting certain characteristics of unwanted behaviour, for example Rademaker & Kooroshy (2010), Van der Kleijn (2011) and Gordon et al. (1987). This behaviour will now be discussed with regard for the actors for which the risk exists. All risks are summarised in Table 6.1.

The first risk discussed here are extremely high prices, where especially consumers are at risk. The relevant question now is: what is high, or what is the threshold above which the copper price can be considered high? In this research this is assumed to be at 100000 Dollar/t of copper, a price level approximately 10 times as high as presently. Copper will at that moment not yet be as expensive as precious metals like gold, but price level will make many present-day applications significantly more difficult.

Another risk could be high price volatility. Here both consumers and producers can be at risk, since the price alternates between high and low values. In this research the price is considered excessively volatile if the change in price is more than a factor two positive or negative in a period of a 1/8th (0.125 yr) of a year. This will be called a copper crisis in this report.

High substitution can also be a risk for the copper system, since high substitution can cause a rapid decline in demand. This is mainly disadvantageous for producers and investors on the copper supply side. Substitution is considered high when more than 80% of the intrinsic copper demand is substituted at any given time.

One of the risks that is often mentioned in discussions about mineral scarcity, is the low number of years left of production, which is calculated by dividing the reserves by the production (the R/P ratio). This would be disadvantageous for the copper consumers, since it would indicate that the copper reserves will soon be finished. The extreme low value is defined here as a value under 10 years. This would mean that the copper reserves are
not being further developed, or that the reserve development cannot keep pace with the mine production. Please note: the R in the ratio is in this case the reserve base, as was already mentioned before. The value is thus higher than the R/P ratios normally found in literature.

The final risk assumed to exist in the copper system is the opposite of the former. The year left of copper mining can also become very high. This is would be a risk for producers, more specifically the mining companies, and the investors in those companies. The value taken here is an R/P ratio larger than 500 years. It could be an indicator that the copper production has collapsed, since the reserves are linked to mining operations and developing reserves is also an investment.

After the review of the results generated by the different copper models in sections 7.2 and 7.3 it was considered whether these risks occur. For those risks that form a potential threat to the system, policy options have been designed.

Table 6.1: Potential risks

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Name</th>
<th>Criterion</th>
<th>Stakeholder</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High price</td>
<td>Real copper price &gt; 100000 Dollar/t</td>
<td>Consumers</td>
</tr>
<tr>
<td>2</td>
<td>Copper crisis</td>
<td>Change in price &gt; factor 2 in 1/8th of a year</td>
<td>Consumers, producers</td>
</tr>
<tr>
<td>3</td>
<td>High substitution</td>
<td>Part of original demand substituted &gt; 0.8</td>
<td>Producers, investors</td>
</tr>
<tr>
<td>4</td>
<td>Low R/P ratio</td>
<td>Year left of copper mining &lt; 10 Year</td>
<td>Consumers</td>
</tr>
<tr>
<td>5</td>
<td>High R/P ratio</td>
<td>Year left of copper mining &gt; 500 Year</td>
<td>Producers, investors</td>
</tr>
</tbody>
</table>
Part Three: Exploratory Model Analysis
7. Behaviour and scenarios of the copper models

In this chapter, the behaviour and scenarios displayed by the three copper models is explained and related to the reality of the copper system. Firstly, it will be explained why the economic feed structure had little effect on the behaviour of the models. Secondly, the most distinct types of behaviour of the (K)PIs, the price volatility, gradually declining demand, potentially strong substitution and high values for the years left of copper mining, will be explained that were observed in all model varieties. This is followed by differences in behaviour visible in the different model varieties, like the higher consumption of copper displayed in the bottom up model and in the same model, the lower speed of substitution. Thirdly, some remarks will be made regarding the validity of the outcomes. Especially the recycling input rate and the global consumption of copper showed too low values due to wrong assumptions. It is demonstrated however that changing these assumptions does not change the overall behaviour of the system. Finally, the scenarios visible in the copper system will be explained. This chapter draws much information from 0, which is the experimental report for the main ESDMA experiments.

7.1. The effect of the ESDMA economic growth structure

The economic growth does not seem to make a large difference in behaviour. This can be seen by comparing the runs lines of the different (K)PIs or the Kernel density estimations (KDE, see Parzen, 1962; Rosenblatt, 1956) of the distribution of the run lines at the end state. An example of the behavioural patterns for the case with and without can be seen in Figure 7.1 and Figure 7.2, where the global consumption of refined copper can be compared. The only (K)PI that did show a difference was the real price of copper. The outcomes of all performance indicators are visible in E.2.

![Figure 7.1: Global consumption of copper with economic feed, top down model](image1)

![Figure 7.2: Global consumption of copper without economic feed, top down model](image2)

Whether indeed the economic feed has little effect, can be proven with a regret analysis, but this has not been performed due to the scope of the research. There is however some logic behind the little difference: the economic growth drives stocks: the GDP, the aluminium price and the energy price. These stocks smooth the capricious behaviour of the economic growth. Some difference could have been expected due to the substitution threshold, where a small difference can already cause substitution or resubstitution. Long term effects are however, as well with substitution, more important than the fluctuations generated by the economic growth.

When thinking about the real world copper system, it also seems plausible that fluctuations in the economic growth will not have a considerable effect on the development of capacity for mining and refining of copper, but only long term economic trends. The current high level copper price is therefore probably caused by a disbalance between supply and demand, which will be discussed in next section, and not by the current economic growth, as was postulated recently in Dutch media (Depuydt, 2011).
Taking all these issues regarding the little effect of the economic feed structure in consideration, the further experiments in this research have been performed without the economic feed active. This allows a clearer view on the different types of behaviour displayed by the copper models and will make it consequently easier to interpret the outcomes, without changing the underlying dynamics of the system, as this test demonstrated.

Box VII: Visualising ESDMA results

There are different methods for showing data generated by the runs performed for ESDMA (EMA Group, 2011). This research method generates a considerably larger amount of data than traditional SD modelling does. The trick is therefore to leave certain information out, in order to create a clearer image. In this box the different visualisation techniques used will be discussed. For clarity, the same input is used for every figure in this box, the RIR.

The first visualisation is the envelopes graph (Figure 7.3). The envelope is created by using the highest and lowest explored value of a (K)PI on any saved time step. The behaviour of specific runs is thus not visible. The advantage of this visualisation is the quick overview it gives of the perceived bounds. Differences in policies or other characteristics can be shown by using different coloured envelopes for each policy (Figure 7.4). In the envelopes used here, the horizontal or x-axis shows the time (unit Year), the vertical or y-axis the (K)PI, while the unit is displayed next to it.

The lines graph (Figure 7.5) shows the behavioural patterns of the (K)PI, in this case of a set of 100 runs. Every line represents a different run of the model. A set of colours makes it possible to distinguish them.

It is also possible to give a kernel density estimation or KDE (Parzen, 1962; Rosenblatt, 1956) next to envelopes and lines graph (Figure 7.6 and Figure 7.7). These estimate the distribution of runs at the final run time, i.e. 2050 in this research and are displayed to the right of the envelopes or lines graphs. A histogram (Pearson, 1895) can be used for the same purpose.

A disadvantage of the two dimensional envelopes graph with the KDE for the end state is the fact that may be interested in the distribution of the behaviour patterns on other moments in the run time as well. A solution for this problem is offered by 3D envelopes graph (Figure 7.8). The KDE is now calculated for every time step saved and projected on the y-z-plane for the given time. Over the different KDE values the surface is drawn which is visible in the graph. The easiest way of imagining it is printing an Envelope (Figure 7.6) with a KDE and folding the paper between the envelopes and the KDE in such a way that the KDE stands upright. The distribution of runs is then depicted on the Z-axis, but this axis is often left away, since the exact value for the KDE often does not add any information. Red indicates a very high concentration of runs, red a high concentration, and via green and cyan to dark blue, which indicates zero likelihood. The time and the (K)PI are given on the x and y axis and lie in the horizontal plane. For interpretation purposes, the envelope can be turned in all three dimensions, to
reveal the side which gives the best view on the data.

Figure 7.8: 3D envelope with KDE values on the z-axis and the standard perspective

Figure 7.9: 3D envelope without the KDE values and a turned perspective

In this research, mostly the lines and the 3D envelopes graphs will be used for interpretation. This is, because in addition to these, the normal envelopes graph does not add any more information. Since the normal envelopes are easier to overview than the 3D envelopes, they can be found in the annexes for comparison.

A totally different way of visualising the information generated by the models, is the multiplot (EMA Group, 2011). In this graph different (K)PIs are plotted against each other on the end state of the time period. The names of the outcomes are plotted on the diagonal axis, from top left to bottom right. On the intersecting panes, the correlation between the horizontal and vertical outcome is visible (Figure 7.10). In this case, there is clearly no correlation visible. The same plot can also be made with distinction in colours for the different policies (Figure 7.11).

7.2. Behaviour observed in all model varieties

The different copper models showed similar behavioural patterns regarding five (K)PIs in the system. These types of regularly occurring behaviour in the runs were periodic price volatility and very high copper prices, a declining copper demand, a potentially strong substitution and oscillation in the substitution, high values for years left of copper mining and low values for the relative part deep sea mining. Four of these issues were also identified as potential system risks in section 6.3. In the next sub sections, the causes for this behaviour in the modelled system will be discussed and linked to the real world copper system.

7.2.1. Price volatility and high copper prices

In lines graph (Figure 7.12) it is visible that the copper price shows diverse and extreme behaviour. The highest prices found in this case are well over 1 million Dollars per tonne, but most typical is the volatile behaviour the
In many runs, sharp increases and decreases are visible, or copper crises as defined in section 6.3. These crises seem to occur multiple times in a run, alternating between a strong drop and strong rise in price. These indicate a strong disbalance between the availability and the demand of copper over a prolonged period of time. In the line graph it is unclear whether these crises tend to increase in severity during the run time, stay rather stable or are dampened and what the chances are for either of these options. The lines graph cannot help in this case, but clustering of the behaviour could. This analysis has however not been performed here.

This cyclical behaviour with alternating prices below and above the marginal costs of copper seemed to be present in the real world copper system as well, as the copper price developments of the last thirty years in Figure 4.9 demonstrate. When observing copper price data before 1981 however, price oscillations occur, but not in the same manner. This can be due to system changes, which also caused the since 1914 traded electrolytic wire bars to be changed to cathode copper in 1981 (Svedberg & Tilton, 2006: 510, 517).

Another reason for a change in the copper price behaviour may be changes in the delay times, like the permit term for developing new mining capacity, causing the periodic behaviour. While they have been kept constant during each run in the models, it is very likely that in reality these may change over time due to changing institutions and investor demands.

7.2.2. Declining demand

Another important finding from the ESDMA study is the general behaviour of the global consumption of refined copper (Figure 7.13). The copper consumption seems to be slowly decreasing after 2010. This is probably due to the increasing marginal costs of copper compared to the costs of substitutes. The rising costs are caused by the falling ore grade, making the demand for energy to process the ore higher. It is likely that substitutes are not subject to these increasing energy needs.

In the case of aluminium, already mentioned before as one of the main substitutes of copper, this is probably true (Gordon et al., 1987), since this metal is significantly more abundant than copper (U.S. Geological Survey, 2011: 17, 27, 49). It is therefore well perceivable that even with fluctuating copper prices the overall trend of copper use in the coming 40 years will be declining.

The overall global copper consumption explored by the ESDMA effort seems rather low however, since the present consumption (see Table 5.1) was considerably higher than the values displayed in Figure 7.13. This validity issue will be further discussed in section 7.5.
Figure 7.13: 3D envelopes of the Global consumption of refined copper [t/Year], top down model. The graph is truncated at 30 million tonne per Year

7.2.3. Strong substitution and oscillation

The substitution of the copper demand tends to be increasing during the run time for many cases, but it is also visible that this happens with oscillatory behaviour. This behaviour can be explained with the modelling assumptions for substitution (Box IV). For example, when at a certain moment in time 20% of the demand is substituted and new demand arises due to the economic situation, this percentage will remain the same only when the copper price is equal to the substitution threshold on short term and when the average copper price over a longer period is also comparable to this value. Especially the long term effect is important here, since a copper consumer will first take his loss when first confronted with a high price. A prolonged period of time with a higher price for copper than the substitution threshold will however cause a rapid increase in the part of the demand that is substituted, since this longer period allows more opportunity for the choice for a substitute. The subsequent strong decrease in demand for copper will result in a sharp decrease of the copper price, which can in turn become lower than the substitution threshold for a longer period of time, which reverses the process.

Figure 7.14: Lines graph for Part of original demand substituted, top down model

Figure 7.15: 3D envelopes of the Part of original demand substituted [Dmnl], top down model. The graph is not truncated, so the values for the substitution lie between 0 and 1
The trends of substitution show some bifurcation, as can be seen both in Figure 7.15 and the KDE of Figure 7.14. This means that two trends seem plausible, one with relatively little substitution (up to 30%) and one with relatively much substitution (over 30%, with a peek around 90%). The high copper substitution is the primary cause for the above discussed declining consumption of refined copper, while the situation with little substitution is more comparable to the present use of copper. In many cases the oscillatory behaviour for the substitution moves between these two states of low and high substitution and vice versa.

This situation is well perceivable in the coming years, even when it was not observed in the period before. Till 2005 copper was indeed more expensive than aluminium for most of the time (see Figure 4.9), but given the better electrical conductivity of copper (Lossin, 2005: 4, 5) the price difference could not be considered a prime reason for substitution. The current high copper price will, if it continues to remain on this level, probably instigate a considerable demand substitution. When this occurs, this will immediately result in a lower copper price which might even become lower than the values of before 2005. With rising marginal costs for copper mining this forms a motivation for the classification of a system risk for copper producers and investors in mining and refining capacity, as was given in section 6.3.

7.2.4. Many years left of copper mining

The lines graph for year left of copper mining shows a remarkable empty view. This has to do with the extraordinary high values for this KPI that some runs show. Its variable is calculated by dividing the reserve base (contrary what was done for example by Koppelaar (2011), who looked at the reserves) by the global mine production. The reserve base can only decrease by mining, while it grows semi-autonomous by findings of the junior companies, the semi independent exploration companies. The drastic growth of the year left of mining can thus only be explained by cases in which the production declines heavily compared to the reserve base present. This is probably caused by the strong substitution, of which cases were visible in Figure 7.14 and which was discussed above.

![Figure 7.16: Lines graph for the Year left of copper mining, top down model](image)

Figure 7.16 shows a similar view as the copper price development in Figure 7.16. After some time the year left of copper mining has diverged so much, that not many trends can be seen, other than the divergence itself. This view corresponds with the idea that the copper production is likely to decrease in the coming period of forty years. This is also clearly visible when the year left of copper mining is plotted against the copper consumption (Figure 7.18). A high value for the year left of copper mining only exists with a low value for the global consumption of refined copper.

Whether the values for this KPI will actually rise so dramatically in the coming years, is unclear. These results do demonstrate what the true value of this outcome is. By some authors a small value for the R/P ratio indicates a possible risk for depletion (see for example Diederen, 2009). In the dynamic perspective of this research a short period "left of mining" indicates that most reserves discovered and classified are minable to a large extent, indicating a good price for the mineral and little risks for producers and investors. Another reason for a low lifetime of copper mining may be the size of the different mines and the time needed to pay back the
loans taken for development of the production facility (Wellmer et al., 2006). In both cases, low values for year left of copper mining do not pose to be a system risk, while high values indicate either a decline in the mine production or high investment costs for development of the facilities.

Figure 7.17: 3D envelopes of the Year left of copper mining [Year], top down model. The graph is truncated at 500 year

Figure 7.18: Multiplot of Global consumption of refined copper [t/Year] and Year left of copper mining [Year], top down model

7.2.5. Low relative part deep sea mining

A final important outcome is the perspective on the future of deep sea mining in the coming years (Figure 7.19). In some cases the deep sea mining seems to form a substantial part of the total amount of mined copper, but given these outcomes it seems most likely that deep sea mining is not going to form more than a few percent of total mining. Please note however that, considering the size of the yearly copper production, that this will be very large operations.

This result is comprehensible when indeed the current size of all copper mining operations is considered. Even when a considerable part of new mining capacity is deep sea mining capacity, the share of the active deep sea mining capacity will remain rather low. Only when practically no new conventional mining capacity is being development, high proportions of ocean mining can be expected, which seems highly unlikely. Deep sea mining will therefore probably not form an important solution for potential future copper scarcity issues.

Figure 7.19: 3D envelopes of the Relative part of deep sea mining [Dmnl], top down model. The graph is not truncated, so the values for the substitution lie between 0 and 1, or 0% and 100%
7.3. Behavioural differences between the models

Despite the fact that the above mentioned behavioural patterns were observed in all three copper models, some differences were also found in the results of the experiments. The first difference found was the strong cyclical behaviour for the copper price in the bottom up model, while the regional model showed higher prices for copper than the other models. Another difference was the global consumption of refined copper, for which the bottom up model showed a wider spread in values. Finally, the bottom up model showed slightly slower maximum rates of substitution. Now these types behaviour will be discussed and explained.

7.3.1. Different types of price volatility

The Real price of copper in the bottom up model seemed to have a strong tendency for cyclical, oscillatory behaviour, which seemed to have a far more constant period than the behaviour of the top down model. This is visible in both Figure 7.20 and Figure 7.21. It is unclear what causes this very distinct behaviour, since all parameters of the model were varied in the ESDMA experimental setup. Further analysis by means of the Patient Rule Induction Method (PRIM) (Friedman & Fisher, 1999), Random Forests (Breiman, 2001), clustering the behaviour or other machine learning methods might help in this case. It is interesting to see however that the prices are on average less high than the prices in the top down model. This is also indicated by the highest value of the KDE, which is almost $1.8 \times 10^{-5}$, which is significantly higher than the value just under $1.0 \times 10^{-5}$ in Figure 7.12.
The real price of copper for the regional model shows the most extreme view for possible price developments in
the coming forty years. While clustering could shed more light on the exact behavioural modes of the runs, the
behaviour of the copper price seems to be characterised by strong surges followed by a gradual decreases
(Figure 7.22). The strong increases can be caused by the same disbalance noticed in section 7.2.1. Figure 7.23
shows no distribution of data after approximately 2020. This is due to the fact that the differences between the
runs are so great, that no concentration of values can be seen. Between 2010 and 2020 this already happens, but
to a lesser extent. It is also unclear why specifically in this model variety the prices show this wide distribution of
possible values. Further analysis could help in this case by distinguishing which uncertainties play a major role in
causing the price volatility and distribution.

Since it is unclear what causes these types of behaviour, it is difficult to relate it to reality and explain
whether this is indeed likely to happen.

7.3.2. Different calculations for global consumption of copper

The first big difference of the global consumption of refined copper generated by the Bottom up model is higher
than the consumption displayed in Figure 7.13, but in the period 2000 – 2010 on average still lower than the
historical data found in Table 5.1. A second feature of the top down consumption behaviour, the serration in the
different run lines, seems to be less distinguished, although it is still visible.

The overall higher consumption copper, which was just noticed, is probably caused by a higher average
value for the RIR, which will be discussed in 7.5.1. The same assumption was made however for the relation
between primary scrap and copper consumption, causing the values to be too low again and perhaps also the
initial value error visible in Figure 7.25 at time is 2000.

7.3.3. Differences in substitution

The sometimes oscillating behaviour of the demand substitution in the bottom up model is largely the same as
the substitution displayed in Figure 7.14, but the slopes of the runs seem to be less steep. This is well
understandable with some knowledge of the structural differences between both models. The top down model
used only one substitution threshold, while the bottom up model used six, one for each major use of copper (the
different uses were visible in Figure 4.4). When the copper reaches the threshold of one of the uses, this
particular use will be more substituted, while other uses, with higher thresholds, may even experience
resubstitution. Since the speed of substitution seems to have a great influence on price volatility in the copper
system due to sudden drops and increases of the demand, this would explain fewer occurrences of copper crises, as defined in section 6.3, in the bottom up model.

Also in reality the slower substitution due to the availability of different kinds of substitutes for copper, each with an own price and price development, seems plausible. This reduces the effects of the system risk of high substitution. This was also noticeable by the shorter time needed to run the experiments for the bottom up model, compared to the top down model, since crises in the price caused Vensim to take a very long time needed to perform a run containing these heavy crises. The less severe nature of copper crises occurring in reality does not mean however that they will not occur. Even with substitution rates comparable to the rates observed in the bottom up model, the copper price fluctuations due to substitution may be very strong.

Figure 7.26: Lines graph for the Part of original demand substituted, bottom up model

7.4. Scenarios and risks displayed by the copper models

As a short summary of the behaviour discussed above, in this section some scenarios displayed by the copper models will be identified. First, the models show a declining copper consumption. Probably this causes a decline in copper mine production, which can be related to increasing years left of copper mining. Regarding the copper price it became clear that the price may rise, but that high price volatility with alternating periods of low and high prices are more probable. The high copper prices cause the substitution of demand to increase, sometimes dramatically, causing more price volatility. Finally, deep sea mining will probably become part of the copper "mixture", but will probably not be the solution for copper shortages in the coming forty years.

Regarding the five risks stated in section 6.3, it seems that high prices over 100000 Dollar/t are visible in a considerable amount of runs. Heavy price volatility, or copper crises, seems to have an even higher prevalence. Exact numbers regarding these issues cannot be given however, but respectively PRIM and clustering analyses could elucidate the matter. High substitution, with values for the part of original demand substituted of over 0.8, is also seen in many runs, for all models. This could be the cause of the high values for the years left of copper mining. Many runs show values over 500 years, some even substantially larger numbers. The potential risk of having only a few years left of copper mining did not seem to be a problem.

One final remark needs to be made about the substitution of copper. The real problem concerning the substitution of copper did not seem to be a high substitution, but a rapid change in the substituted part of the intrinsic demand, probably causing many copper crises. This risk was not considered in section 6.3, but seems to be, in addition to disbalance in the supply structure, a major source of heavy price fluctuations.

7.5. Less valid outcomes

Despite the well perceivable nature of different types of behaviour observed from most (K)PIs, some outcomes are less plausible. First of all, the values shown by the RIR and the consumption of copper were too low. Another issue is the initial value error displayed by the global consumption of refined copper. Finally, it is explained why these less valid outcomes do not have a considerable effect on the other outcomes of this research.
7.5.1. Low RIR and consumption
In a stable system, the amount of End of Life (EOL) copper is equal to the copper consumption. The output of secondary copper is then equal to the collection rate times the Recycling Efficiency Rate (RER), while when we assume that all recycled copper is reused, this is exactly the RIR. Since in this research both the collection rate and the RER are modelled statically, changes in the RIR during runs are only dependent on changes in the copper consumption. A growing copper consumption will thus result in a lower RIR and vice versa. The increasing values for the RIR (Figure 7.27) are consequently caused by the gradually declining copper consumption visible in Figure 7.13.

![Figure 7.27: Low values for the Recycling Input Rate [Dmnl], top down model](image)

It is however typical to notice that the RIR generated by the ESDMA research is lower than the RIR of around 1/3 mentioned by the ICSG (2010b). The easiest way of explaining this is by an exaggeration of the uncertainties regarding the collection rate and the RER. The four uncertainties relevant in this case (collection rate, copper score during treatment, copper score during dismembering, and the percentage of copper recovered from scrap) (Angerer et al., 2010) need however to have an average value of almost 76% to create an RIR of 33.3%, while an average value of 50% gives an RIR of no greater than 6.25%, both in a system in equilibrium. This indicates the importance of both high collection rates and RER, despite the fact that the values presented in Figure 7.27 might be an underestimation of reality. When thinking about the possible RIR however, these values indicate clear the fact that with growing marginal costs for copper mining it is of utmost importance to increase both collection rate of EOL copper and the RER. In chapter 8 and 9 will be more focus on the RIR and the effect of a higher RER.

7.5.2. Low consumption of copper
Overall the global copper consumption explored by the ESDMA effort seems too low, since the present consumption (see Table 5.1) was considerably higher than the values displayed in Figure 7.13. The bottom up consumption (Figure 7.25) showed also higher values, but is on average still too low. There are two possible explanations for these low values. First, the RIR is probably an underestimation of the true RIR, as was discussed in the previous section.

Second, the bounds of the value of the yearly copper use related to GDP are probably taken too narrow. Another reason could have been a wrong assumption about which flow the global consumption of copper and the copper demand actually represent. Further investigation of the values of the ICSG however proved that the initial assumption was right, but that the definitions of the relevant variables in the model could be improved. This did not have an effect however in increasing the copper consumption.
7.5.3. Initial value error consumption of copper

The initial value problem visible in Figure 7.13 and Figure 7.24 is caused by the way the availability of copper, crucial for the amount of copper which can be consumed, is calculated. This happens by dividing the global inventories of copper by the production time. The first variable is a stock, while the second is modelled as a constant. Both values are in essence uncertain, but the range of the first is considerably smaller due to the latter given its well documented nature. Since the consumption is defined as the smallest value of either the availability of refined copper, or the copper demand combined with the postponed demand, a relatively high availability in the initial state may cause a very short termed higher consumption of copper.

7.5.4. Effects on the validity of the other outcomes

The question now remains how valid the outcomes of the research are, without the above mentioned correct assumptions and values. First, this research was not only performed to explore the bounds of (K)PIs in the copper system, but also to explore the behavioural modes and, by doing so, discover what structures and mechanisms in the system causes them. It is not likely that with higher average values for the RIR and the different assumption for the consumption of refined copper, the modes of conduct of the (K)PIs will change considerable, since these changes are mostly parametric in nature and do not contain extensive structural alterations in the model. Therefore, despite the problems noticed, the types of behavioural modes probably will not change much with higher values for the RIR, as does the evaluation of the policy options will show in chapter 9.

To test this thought, a new set of runs has been performed in which the wrong bounds for the recycling coefficients have been corrected and the definition for the global consumption of refined copper has been remodelled. The results of this experiment are discussed in next section.

7.6. Observations from new data

The new runs indeed displayed higher values for the RIR and the global consumption of copper, as can be seen in Figure 7.28 and Figure 7.29. The global consumption is however still relatively low compared to the data provided by the ICSG (ICSG, 2010a, 2011). This is probably due to the already mentioned small bound for the constant yearly copper use related to GDP. The advantage of the small bound is however that the outcomes are easier interpretable, since the directions of behaviour are clearer visible in the figures. The overall behaviour of the outcomes remained however the same in new runs. This was expected and validates the outcomes discussed above.
8. Policy design for the copper system

This chapter regards the designing of policies able to limit the potential unwanted behaviour that was discussed before in section 6.3. First the different approaches for policy design and testing are discussed. This is followed by the basic setup which all policy options share. In the third section, the different characteristics of all designed policies are discussed, while the differences in design regarding the model varieties are discussed in the final section. An overview of all policies and their characteristics is given in Table 8.1.

8.1. Development and testing of policy options

For the design of policy options in an ESDMA context, roughly two approaches can be chosen:

- Closing the circle: select problematic behaviour patterns, try to find which selection of input parameters cause these behaviour (for example with the random forest method), select those that can be influenced by policy makers, companies or investors and try to develop policies that (combined) have the biggest impact.

- Understanding of the system: the modeller needs to know which stakeholders can have an influence on the system and at which points this influence "connects" (Box VIII). This influence needs to be developed into possible policy options.

In this research, the second option is chosen, since the development of policy options is not in the primary scope of this research. These options have been developed in different forms to acknowledge the different paradigms the model varieties stand for. These differences will be discussed in section 8.4.

Testing of the effects of the policies happened by running each model variety with the different options with one set of input parameters. This allowed assessing the effects of each policy by comparing its behaviour with the base run of the model. Another test, which was not performed, could be a full factorial analysis on a selected set of runs, which behaviour for certain (K)PIs is representative for the different behavioural modes the model generates. The results of this approach can make clear which selection of combined policy options has most effect in reducing the systems unwanted behaviour, which was defined in section 6.3. These selected runs can be selected by picking them from clusters of behaviour.

8.2. Basic setup for the policy options

With the approach mentioned in last section, six different policy options have been developed. These policies are rather classical: they do not react to system behaviour and cannot be considered proper adaptive policies (Walker, Rahman & Cave, 2001). To improve the realism regarding the implementation, they are not considered to be instant improvements: they follow a continuous implementation path between the start date and the end date. The start date of the policies is 2015. At this time, nothing has changed yet. The end date is 2025. At this moment, the policy is completely functional and the effects remain till the end of the run time (2050).

The stakeholders relevant for these policy designs are all actors with interests in the copper system and localised in the European or more specifically, the Dutch perspective. First of all, these are governments on national or supranational scale which have power to enforce rules and regulations regarding copper, or who can issue incentive measures. The second group is formed by developers of technologies relevant for the copper system. Since technology development can be a cost intensive process, investors in technology or the copper system form the final category.
Box VIII: Modelling policies: Connection of policies to the model

All policies are connected to a specific point in the model. This can be seen in Figure 8.1. All policy variables have a green background colour.

Figure 8.1: The recycling score (RER) policy connection

The new copper score is calculated by interpolating between the original value (fed by the purple uncertainties) and the policy goal. This new value is always calculated, but a switch is used for turning the effects of the policy on and off.

8.3. The different policy options

In this section all different policy options will be discussed regarding their connection to the model, the goal of each policy and which type of actor is able to implement it. An overview of all policies and their most important characteristics is given in Table 8.1.

Table 8.1: Policy options for the copper models. All policies start in 2015, policies 1, 2, 4, 5 and 6 have full effect in 2025: 1, 2, 4 and 5 with linear interpolation, 6 with an S-curve

<table>
<thead>
<tr>
<th>Nr</th>
<th>Name</th>
<th>Connection</th>
<th>Goal</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Recycling 1</td>
<td>Recycling score</td>
<td>0.95</td>
<td>Technical</td>
</tr>
<tr>
<td>2</td>
<td>Recycling 2</td>
<td>Collection rate copper products</td>
<td>0.95</td>
<td>Political</td>
</tr>
<tr>
<td>3</td>
<td>Strategic reserve</td>
<td>Global inventories of refined copper</td>
<td>0.5 * Global consumption of refined copper; Selling at over 1.3 * MAX(Marginal costs)</td>
<td>Political</td>
</tr>
<tr>
<td>4</td>
<td>Substitution 1</td>
<td>Substitution threshold</td>
<td>0.7 * original Substitution threshold</td>
<td>Technical</td>
</tr>
<tr>
<td>5</td>
<td>Substitution 2</td>
<td>Growth of effect of substitution</td>
<td>Minimum 0.7</td>
<td>Political</td>
</tr>
<tr>
<td>6</td>
<td>Deep sea</td>
<td>Marginal costs deep sea mining</td>
<td>0.5 * original Production costs deep sea copper</td>
<td>Technical</td>
</tr>
</tbody>
</table>

The first two policy options regard recycling. The first recycling policy influences the RER, which is modelled as the recycling score. Again, regardless of the initial value of the coefficients relevant for the recycling percentage of copper, this rate is improved till 95%. This policy is more technological in nature, since it influences the recycling technologies, which in their turn seem to define the efficiencies reached in the recycling process. It is however interesting for investors as well, since they may want to invest in copper recycling, which has, as was discussed in section 7.5.1, the potential of forming the major supplier of refined copper.

The second recycling policy connects to the collection rate of copper products in the model. This policy has the effect that, regardless of the initial collection rate, the collection rate in 2025 will be 95%, which means...
that only five percent of all used copper will be discarded at the end of the lifetime. This is mainly a political policy option, since a law obliging, or an incentive measure encouraging, citizens to recycle their disbanded products could have this effect.

The third policy option in this research is the construction of a strategic reserve for refined copper. It thus connects to the global inventories of copper. The goal for this strategic reserve is defined with respect to a certain amount of time of copper consumption, in this case, this line is put at a half year consumption. The copper for the reserve is only bought when the copper price is below the highest marginal costs for copper production (either for conventional or deep sea copper). It thus uses only the market surplus: the positive difference between the total production of refined copper and the total copper demand. This copper is sold (the reserve is used) when the copper price is above a certain threshold for the copper price relative to the marginal costs. This threshold is taken at 1.3 times the marginal costs. The rate at which the strategic reserves can be emptied is defined as two years, which means that the volume of strategic reserve divided by the outflow of copper in times of need is equal to two years. This means that the outflow will gradually decrease as the strategic reserve empties. This, again, is a political policy option, but it can also be performed by investors with a long term perspective, since buying refined copper when the price is low and selling it when the price is high, is potentially profitable.

The fourth policy, or the first substitution policy, comes down to lowering the substitution threshold for copper. Practically this means that either the price of the substitutes becomes lower, or that less of the substitute is needed. This is thus mainly a technological policy, but it can also be seen as an investment strategy.

The second substitution policy, or the fifth in Table 8.1, regards the growth of the effect of substitution. This can be seen as an incentive measure and thus a political policy. The copper system thus, regardless the then-present costs of copper and substitutes, looses part of the copper demand.

The final or sixth policy regards the reduction of the production costs of deep sea copper. Example of such a development would be investing in improving the efficiency of deep sea mining equipment. This is also a technological policy, but again with an investment side.

Four combinations of policies will also be tested. These are the combination of both recycling policies, the combination of both substitution policies, the combination of both recycling policies with the strategic reserves policy and finally all policies combined. The goal of this additional analysis is to start with the exploration of the effects of combined policy measures.

8.4. Differences in policy design between model varieties
Since the policy designs also consider variables that are subject to different uses or regionalised, there are differences in the policy options between the different model varieties. In this chapter these changes will be related to the policy approach taken in the top down model.

The policies in the bottom up model differ in the following ways. First, the collection rate of copper is dependent on the copper use category. The policy brings all collection rates, regardless of the initial value, up to 95%. The same counts for the second recycling policy. Some coefficients of the RER were split up for the different uses of copper. The second recycling policy too ignores this and pulls the overall recycling score or RER to 95%. A next variable divided by copper use is the substitution threshold. The first substitution policy changes these different values by lowering them with 30%. The use dependence therefore remains present in this policy. The second substitution policy connects to the growth of effect of substitution, which is the only influence for long term substitution. It minimizes, again without regard for initial values, this growth to 0.7 (on a scale
between -1 and 1, as was explained in Box III). The remaining two policies, the strategic reserves policy and the deep sea policy, are identical in implementation to the top down model.

For the regional model, the policy design differences can be explained more easily. Simply put are all political policies only regional, while the technological policies are globalised. This means that the first recycling policy, the strategic reserves policy and the second substitution policy are only implemented in region 1. The second recycling policy, the first substitution policy and the deep sea policy have an identical effect in all three regions, since they all have a major technological component.
Part Four: Evaluation
9. Policy evaluation for the copper system

The policy evaluation will be done per model, in which the different policies were implemented. The first model discussed is again the top down model, after which the differences between the outcomes from this model and respectively the bottom up and regional model will be assessed. This is done by first looking at the behavioural bounds of all (K)PIs, followed by a more detailed view on the effects of the policies for the behaviour of the copper price and consumption of refined copper. Finally, some conclusions are drawn about the successful recycling policies and the strategic reserve policy, as well as the combination of all policies.

9.1. Overall effects of policies

The six policies and the three combinations of policies will be first assessed by looking at their effects on the (K)PIs, especially the envelopes of these values. Behavioural analysis is very difficult without clustering or PRIM analyses, and will thus only be done in very clear cases.

9.1.1. Top down model

A first look to the envelopes of the first four (K)PIs in Figure 9.1 immediately shows differences in effect of the different policies and policy combinations. A good reference is the base model, which is visible on the left side of the figure with the dark blue line. The real price of copper seems to be limited in its extreme values by the recycling policy 1 and even more by the combination of recycling policies, while the single effect of recycling policy 2 is not impressive. The combination of all policies has the lowest maximum value for the price. The different substitution policies and their combination also seem to have lowered the price slightly. The strategic reserves policy gives the smallest effect. The consumption seems likewise to have increased due to the recycling policies, especially the first one and the combination. All other policies had virtually no (visual) effect, except the combination of all policies. It is further visible that the recycling policies lower the average part of original demand substituted, while the substitution policies had, as could be expected, an effect which increased the substitution. The effect of all policies was that very high substitution was limited (probably due to the effects which lower the price), while the medium substitution was more dominant. The RIR reacted heavily on the first recycling policy and even more on the combined recycling policies, while all other policies did not seem to have much effect. The combination of all policies produced a similar shift in behaviour as the recycling policies. This is logical, since the recycling policies also form part of all policies.

Figure 9.1: All policies for the real price of copper, global consumption of refined copper, the part of original demand substituted and the RIR in the top down model
The next four (K)PIs are visible in Figure 9.2. Both marginal costs did not seem heavily affected by the policies. The relative part of deep sea mining is very little expanded by its almost direct policy, the deep sea policy. The second recycling policy did have an effect as well, but only in limiting the deep sea mining. Finally, the year left of copper mining was in the end state limited by the first recycling policy and the combination of the two recycling policies. The second recycling policy however seems to have increased the year left of copper mining, probably by reducing the mining due to a higher inflow of secondary copper.

Finally, it is interesting to see what the effect was of the substitution policies on the part of original demand substituted and the recycling policies on the RIR. These are visible in respectively Figure 9.3 and Figure 9.4. The substitution effect is clearly visible by a "wave" of extra substitution which departs from the lower substituted state to the higher substituted state between 2015 and 2025.

The RIR showed an even clearer image of the effects of more collection of copper scrap and a higher RER. This is also clearly visible between the start and end date of the policies. The rise in RIR after 2025 is probably due to a declining consumption of refined copper.

9.1.2. Bottom up model

The oscillating behaviour which was so visible in the real price of copper, tended to decrease due to the recycling policies and the strategic reserve policy, but most dramatic by the combination of all policies. For the global consumption the same effects as observed for the top down model were visible, just like the part of original...
demand substituted and the recycling input rate. Further, the effect on the RIR seems to be even bigger with the bottom up recycling policies, compared to the top down model. This is typical, since the bottom up model originally had an already bigger average for the RIR.

The two marginal costs and the relative part of deep sea mining show the same picture as with the top down model, although the combination of the two recycling policies seems to have increased the relative part of deep sea mining around to 2030. This was due to one single run. In the year left of copper mining virtually no visible change can be detected due to the policy measures.

In the regional model, the real price of copper was substantially limited by recycling policy one and the recycling policies. An even stronger effect was reached by the strategic reserve policy. The combination of all policies had the biggest effect. This is clearly visible in Figure 9.7. The global consumption had an envelope with higher possible values due to the first recycling policy and the recycling policies combination. This was just one run, but still it would be interesting to analyse which input parameters caused this gradual rising high value for the copper consumption. There was no significant difference in demand substitution due to the policies. This was probably due to the regional effect of the second substitution policy. The RIR showed the same behaviour due to the policies as was already noticed with the other models.
Now it is interesting to look at Figure 9.9. This shows that the policies had little effect on the envelope of behaviour of the marginal costs for conventional and deep sea copper. The change in the year left of copper mining is however very dramatic, which were due to the recycling policies again (Figure 9.8). Originally the values for this outcome after 2040 were extraordinarily high, as can be seen in Figure E.42. The relevant policies lower these values with approximately a factor 100 in 2050. While this does not indicate anything about the validity of these high values for this outcome, it is clear that in reducing this extreme behaviour, these policies perform very well.

Apart from the differences which were visible for the relative part of deep sea mining in region 3, it seems that the policies did not have a significant effect on these outcomes, which can be seen in Figure 9.10. This corresponds with the findings of the other models, where the effects on deep sea mining were not impressive as well.
9.2. Effect of policies on copper price and consumption

The effects of the policies can be assessed in more detail with emphasis on two KPIs, the copper price and the consumption of refined copper.

9.2.1. Top down model

When comparing Figure E.3 with Figure 9.11 and Figure 9.12 the reduction of extreme behaviour due to the combination of recycling policies and all policies is very clear, although the policies do not eliminate the spread in the real price of copper altogether.

Now it is interesting to look at the behaviour of the different runs in the model regarding this outcome. Figure 9.13 shows that the higher RIR does not change the volatile behaviour of the price. It is therefore interesting to look at the effect of the strategic reserve policy (Figure 9.14). The lines which were still quite serrated with the recycling policies seem to have smoothed due to strategic reserves. This is understandable behaviour, since the strategic reserves are intended to relieve the copper market in case of an extreme high difference between supply and demand. This same smoothed behaviour is also visible when all policies are combined. Apparently, the combination of a higher RIR and a strategic reserve has an effect on the copper system which reduces extreme high prices and also slightly reduces some volatility in the system.
The global consumption of copper also displays a more positive view, as some more consumption seems possible due to the recycling policies and the combination of all policies. However, after the policy has reached its full effect, the average global consumption seems to decrease again, so this tendency is quite strong. It is therefore not likely that recycling will stop the decrease of the copper mining production.

9.2.2. Bottom up model

In Figure 7.21 it was visible that the behaviour of the real price of copper was subject to periodic oscillatory behaviour. The recycling policies seemed to limit this behaviour slight (Figure 9.17), as did the combination of all policies (Figure 9.18). The extreme values were reduced as well by these policy combinations, but this was already demonstrated in section 9.1.2. It is also visible that, just like in the top down model, the price trend is confined a little more to the lower regions. The type of behaviour does not seem to be changed however, or at
least not as clear as in the top down model. More specific analyses regarding the model behaviour could clarify this issue further.

For the global consumption (Figure 9.19 and Figure 9.20) it could be noticed that again the values slightly increase due to the implementation of the combination of the recycling policies and the combination of all policies. This KPI in showed in the base case ESDMA results already a broader spread in behaviour than the top down equivalent, making it harder to observe these differences. The strategic reserves policy finally does have an positive effect in limiting the amplitudes of oscillations in the bottom up model, but does not change more gradual behaviour with high prices. The overall conclusion for the bottom up model is that strategic reserve policy and the combinations of recycling policies and all policies show an overall improvement of the behaviour, especially with regard to the risks defined in section 6.3.

9.2.3. Regional model

The real price of copper in the base run showed such a wide distribution of possible values, that effectively nothing could be seen after 2020. It is interesting to see which policies were able to improve this behaviour. In Figure 9.21 it is visible that the recycling policies already sorted some effect in reducing the average price. The combination of all policies did an even better job (Figure 9.22). This is probably due to the combination of strategic reserves policy and the recycling policies, which could reinforce each other in limiting extreme price behaviour.

The policy effects on the global consumption of copper in the regional model seem less clear than the results in the other two model varieties. This was to be expected, since the most effective single policy in increasing the RIR and via the recycling also the consumption of copper, is the collection rate of discarded copper products. This
policy, being political in nature, was regionalised in the regional model and was only implemented in region 1. The effect of this policy would thus only work on the discarded copper in this region, which was a considerable amount, but not as much as the amounts in the top down and bottom up models.

The conclusion of the policy analysis in the regional model is that the same policies as mentioned before seem effective, i.e. the strategic reserves policy, the combination of the recycling policies and also the combination of all policies.

Figure F.9.23: Global consumption of refined copper [t/Year], recycling policies
Figure F.9.24: Global consumption of refined copper [t/Year], all policies

9.3. Policy design conclusions

Despite the problems already noticed in chapter 7 regarding the wrong input values for the collection rate and RER coefficients and the wrong assumption for the consumption of copper, a policy analysis was performed to see what differences in behaviour they could cause.

The results of these tests were that the two recycling policies were able to limit extreme behaviour of several (K)PIs, especially the year left of copper mining and the real price of copper. It should be noted though that this effect is exaggerated, since the original RIR was far too low. This indication of the importance of a good recycling structure for the stability of the copper system is however unambiguous.

Slightly less influential, but still of some use, especially in limiting the amplitude of oscillatory or crisis behaviour is the strategic reserves policy. This can be explained by the smoothing or balancing effect such a policy can have when implemented and used correctly. The two substitution policies and the deep sea policy did not show a clear use in reducing the risks considered in this research. It could even be argued that the substitution policies could have potentially a negative effect on the price volatility, since the models earlier showed that fast substitution could be linked to a rapid decline in demand, causing the copper price to fall.

Probably the recycling policies combined with the strategic reserves policy will have a balancing effect on volatile behaviour of the model, and, by keeping more copper in the system, they may also allow for more copper consumption. It is interesting to test this hypothesis in further research, for example the earlier proposed full factorial analysis on a small but representative set of model input variables.

Further analysis of the system and the search for early warning indicators of undesirable behaviour may lead to additional insights regarding a more adaptive policy design for the copper system. This will be more in line with the first policy design option which was presented in section 8.1.
10. Conclusions

In this research an attempt was made to model the global copper system with its uncertainties and by doing so, explore possible types of behaviour that the system can generate. In this chapter, first the possible future behaviour of the copper system is discussed. This is followed by policies which could counter potential undesirable effects.

10.1. Possible future behaviour of the copper system

The most important findings about the possible future behaviour of the copper system are that the economic feed does not make a big difference in the behaviour, often high price volatility and copper price crises occur (these were defined as fast and big changes in the price), the copper demand tends to decline as a result of substitution of the metal and finally that the relative part of deep sea mining is not likely to be very high compared to conventional mining. Further, the (K)PI year left of copper mining did not signify to be an important feature of scarcity in the copper system. Finally, the wrong bounds for the recycling coefficients, which resulted in too low values for the RIR, did not significantly change the behaviour of the (K)PIs observed in the experiments.

The reason the economic feed did not make a big difference can be explained both from a modelling perspective and from reality. In the model, the economic growth only influenced stocks, which tend to smooth the capricious behaviour displayed by the economic feed structure. In reality, the demand will probably also only change a little due to economic growth, while the supply will not be able to react on yearly changes, but only to long term trends.

The potential high price volatility is caused by a disbalance between supply and demand of copper. The underlying dynamics causing this are long delays in the building of capacities and development of the demand. This effect is started by the demand which is influenced by price mechanisms combined with influences from substitution, the intrinsic demand and postponed demand in the case of scarcity. The price volatility mechanisms observed in this study could explain the price fluctuations in the past thirty years. A slight unbalance between supply and demand is well perceivable, especially since the exact growth of demand is difficult to predict, as the differences between the top down and bottom up approach demonstrated.

The coming forty years may well experience a declining copper consumption. This is caused by the rising energy costs related to the falling grades of copper ore. The available substitutes for copper, like aluminium for electricity transmission, do not encounter this problem. It is therefore well perceivable that the price for copper will rise compared to the alternatives. Strong substitution after a longer period of high copper prices may however very well result in a drastic drop in the copper price. This may (temporarily) reverse the effects just described, resulting in renewed use of copper. This oscillation is also a major reason for price volatility and unbalance in the copper system.

Deep sea mining will probably not form a substantial part of the input of primary copper. This has to do with the sheer size of the current copper mining operations. Only in very exceptional cases, for instance when the marginal costs of conventional mining become considerably larger than the marginal costs of deep sea copper. Limitations may also come from the international regulations regarding deep sea mining and the potentially high environmental impact of deep sea mining. In this research however, these issues have not been taken into explicit consideration.

The often mentioned R/P ratio, in this research represented by the (K)PI year left of copper mining, did not signify to be an important indicator of scarcity. It was found out that high values for this indicator were most likely caused by a declining mining production and not of an increased finding of new reserves. The lifetime of
copper mines is also principally determined by the size of the reserve present at a particular operation site. Many small mining operations might therefore result in a short mining lifetime, but in a high overall production, while the discovery of new deposits may not let it result in scarcity of the mineral mined.

Finally, for the RIR and the global consumption of refined copper, too low values were witnessed as results of the ESDMA experiments. Changing the bounds of the uncertainties for the different recycling coefficients could theoretically have changed part of the behaviour of outcomes displayed in the experiments. Performing new runs with improved bounds and higher RIR and consumption of copper as a result has let however to the conclusion that changing these bounds did not change the modes of behaviour.

10.2. Policy designs for the copper system

The results of the policy designs made to counter potentially undesirable effects in the system were that improving recycling and developing a strategic reserve may counter high prices and copper crises, as well as allowing more copper to be consumed.

The recycling policies comprehended improving of the collection rates of EOL copper products, as well as improving all RER coefficients in order to create a higher recycling efficiency. These two policies are most effective when combined. This can be easily understood, since the effectiveness of recycling depends on the product of both policies. When the recycling efficiency is improved by investments in the technology and equipment used for recycling, this will not have much effect, when the rate of EOL copper collection is low. The same counts for the improvement of the collection rate. When both policies are in place however, the make it possible to receive a very high RIR, making European countries less dependent on resources from other regions. Since recycling is not subject to falling ore grades, it will not have a negative effect on copper mining either, since more copper will remain used and less copper will be substituted.

Developing a strategic reserve of copper can happen in different ways, but in this research it was proposed to by the reserve when the copper price is under the marginal costs of copper and to utilize the reserve when the price is well above the marginal costs. In this way the strategic reserve, which serves intrinsically a geopolitical security goal, can be used to counter volatility in the copper price. A requisite for the strategic reserve will however be that the size is sufficient to have an effect. It is however unclear whether governments presently developing strategic copper reserves follow the same strategy.
11. Reflections

After performing a research, it is wise to reflect on the way it has been performed, limitations of the chosen method and recommendations for further research.

11.1. Pitfalls in using a “traditional” SD model for ESDMA

In this research, an extensive, traditional SD model was built. For the construction, extensive use of literature was made. This “traditional” SD model was subsequently adjusted and transformed for ESDMA use. The results of this study were interesting, but this approach had a few drawbacks.

The biggest problem was the wrong perception of the researcher of the actual research design framework chosen in this study. The original perceived framework was closely related to the traditional SD approach and model cycle, while the actually used framework closer resembled a scientific experiment, where the SD model was only part of the experimental setup. The result of this difference was while in the traditional, ex ante ESDMA framework the research should have been more than half completed after finishing the SD models used in the research, the ex post ESDMA framework showed that the analyst was actually more around 25% of his study. This caused a wrong distribution of time for the different research elements, which could have been avoided with more knowledge beforehand of the scientific process characterising an ESDMA effort.

Another pitfall is the way in which the research is documented. The enormous amounts of data and the often difficult to interpret visualisations of this data make it hard for a non insider in this research methodology to understand and value the results presented in an ESDMA research. When a study is intended to be interesting however for those actually interested in the case research with the methodology, a translation needs to be made.

Finally, the approach used is a very innovative and interesting research method. It still needs however much time and effort to make new features and visualisation techniques available. A great risk for the researcher is thus to lose himself in trying to improve the method, and not his subject...

11.2. Limitations of the chosen research methodology

The chosen research method, i.e. SD modelling combined with EMA, has of course its limitations. A few of them will now be unravelled. First of all, this approach allowed little or no focus on single actors in the copper system: this can be interesting for dynamics of single copper mines, with different parameters (ore grade, political situation, remoteness, etc.). Presently the five biggest producers of copper supply almost 40% of the mined copper available (BGR, 2007: 12). This makes an Agent Based Modelling view especially relevant, since the risk of actors exercising their market power is well thinkable.

A second limitation lies in the already mentioned calculation power, which is not enough for full factorial analysis in large models. This problem can be solved by making more different models, since these will only result in a linear growth of calculation time, compared to an exponential growth of run time necessary for less models with more variables.

Another limitation of the approach chosen is the fact that not much contact with the copper industry existed. It would be interesting to see what points of the copper system they regard as vulnerable and explore these parts. This will increase the value of this research on two sides: the model development can be better supported, while the interpretation of the outcomes improves as well.
11.3. Possibilities for further research

The ESDMA method is very powerful and has not been used to the full extend yet. This is especially the case for this study, also due to the pitfalls already mentioned above. Many tools have now not yet been used, while they may have a profound impact on the quality of the policy options developed.

One improvement might be the engineering of adaptive policy options. This kind of policy will react to the systems behaviour, in contrast with the more traditional policies presented in this research, which are static decisions. For these adaptive policies it is necessary to find “early warning indicators” for copper crises. This happens by looking at parameters that cause this behaviour with the newly developed methods for mode selection and interpretation. The uncertainties can then be further explored by making different models for the new policy options and comparing the effects of the different models.

Overall, more different analyses may be used on the data generated by the experiments in this research. In this report only visual analyses were made of the outcomes specified in the experimental setup. The large amount of data makes it however difficult to solely rely on this method. Classification of behaviour with respect to the categories of more and less desirable effects in the system by means of for example clustering or PRIM algorithms may create more insight in these matters.

An issue not explored in this research is the possibility of major copper producers exercising market power, as well as the development of copper mining capacity from a geopolitical perspective in which regional safety can be compared to local ore grades and transport distances. These points of interest may be better researched not using ESDMA, but agent based modelling, perhaps also from an EMA perspective.

11.4. Validity of the research

The most important outcomes of this research were explainable with the knowledge of the copper system, thus adding to the possible validity of the research. This validity could be further extended by letting experts in the copper system evaluate the results and compare it with their view on the issues at hand. The insights of these experts on the uncertainties could also help in generating better experimental setups, thus improving the validity from the input side.

In this research three different models were used in order to be able to model the uncertainties regarding the supply and demand of copper. The question immediately arises whether this was necessary for performing this research or whether one of these models could have generated the same results. As far as this issue concerns modelling the intrinsic demand, one of the major uncertainties in this field, all three models could have produced the same behaviour with the right input parameters. However, some conclusions about the internal functioning of the system, like the speed of the substitution or the effects of a regionalised playing field for the copper production and use, the insights the different models gave were undeniable. Therefore especially the ensemble of these models generated new insights.

11.5. Final remarks regarding the research methodology

One of the principles of EMA is that by taking more uncertainties into account, more certainty about the effects of designed policies can be derived. One of the premises necessary for policy design is however that certain value judgements exist about the exhibited behaviour of the system under consideration. These judgements are important for the stakeholders in the system. It is therefore of utmost importance that the commissioning actor, which is often also a stakeholder, is able to give quantifiable characteristics of undesirable system effects. Especially in ESDMA, where many analysis techniques depend on the knowledge of system risks (like PRIM and clustering methods), the input of the commissioning actor creates thus the value of the outcomes.
References


Bonthuis, D. J. (2011, 1 July). [Vergelijking].


Appendix A. Causal loop diagrams

A.1. Top down

Legend

External variables
Copper variables
Key performance indicators

Copper mine capacity
Copper smelter and refinery capacity
Marginal costs of producing copper
Price of copper
Demand for copper
Copper substitution
Copper consumption
Price - demand loop
Copper production
Copper recycling
Copper discarding
Copper in products
Copper scrap heap
Copper products to recycling
Lifetime of copper products

Copper resources
Copper reserves
Ore grade
Mining capacity
Copper mine capacity
Technology
Reserve development
Stance of technology
Investments
Investments in copper technology
Marginal costs of producing copper
Energy price
Copper smelter and refinery capacity
Refinery capacity
Copper refining
Recycling capacity
Recycling rate
Copper recycling
Available refined copper
Copper demand related to GDP
GDP per capita
World population
Price of substitutes
Substitution possibilities
Part of demand substituted
Copper substitution
Copper levels
Copper substitution
Copper production
Copper demand
Demand for copper
Copper consumption
Copper recycling
Copper discarding
Copper in products
Copper scrap heap
Copper products to recycling
Lifetime of copper products

Legend

External variables
Copper variables
Key performance indicators

Copper resources
Copper reserves
Ore grade
Mining capacity
Copper mine capacity
Technology
Reserve development
Stance of technology
Investments
Investments in copper technology
Marginal costs of producing copper
Energy price
Copper smelter and refinery capacity
Refinery capacity
Copper refining
Recycling capacity
Recycling rate
Copper recycling
Available refined copper
Copper demand related to GDP
GDP per capita
World population
Price of substitutes
Substitution possibilities
Part of demand substituted
Copper substitution
Copper production
Copper demand
Demand for copper
Copper consumption
Copper recycling
Copper discarding
Copper in products
Copper scrap heap
Copper products to recycling
Lifetime of copper products
A.2. Bottom up

Legend

External variables
Copper variables
Key performance indicators

Part of demand
substituted
Price of copper
Marginal costs of producing copper
Copper in products
Copper use in cars
Copper use in electricity infrastructure
Copper use in water treatment
Copper use in stationary electromotors
Copper in architecture
Copper in other use
Copper scrap heap
Copper recycling
Copper discarding
Copper in products to recycling
Lifetime of copper products

Copper resources
Copper reserves
Investments in copper technology
Stance of technology
Technology
Reserve development
Mining capacity
Copper mine capacity
Ore grade
Energy price
Copper smelter and refinery capacity
Recycling capacity
Copper refining
Copper recycling
Available refined copper
Recycling Input Rate
Raw copper available

Price - demand loop
Appendix B. Model structures

In this Annex, all model structures of the different model varieties are presented. Colour coding of the variables is the same for all models. For the equations, please consider the digitally appended Excel file containing all model variables and uncertainties.

B.1. Top down model

B.1.1. Copper stocks
B.1.2. Mine, smelting and refinery capacity

Mining capacity in preparation
World copper mining capacity
Preparation of capacity increase
Growth mine capacity
Decommissioning of mines due to age
Initial mining capacity
In preparation
average mine lifetime
Delay order mining capacity
Smelting and refining capacity in preparation
Smelting and refining capacity
Growth smelting capacity
Decommissioning of refinery capacity due to age
Initial refining capacity
in preparation
average smelting lifetime
Delay order smelting capacity
Average lifetime of copper smelters and refineries
Average smelting capacity permit term
Initial preparation of refining capacity
Initial refining capacity
Parking of copper mining capacity
Decommissioning of smelters and refineries due to losses
Recommissioning of mining capacity
Recommissioning of smelting and refining capacity
Parking of smelting and refining capacity
Decommissioning of mines due to losses
Average mine lifetime
Effect of use of mining capacity
Effect of use of smelting capacity
Mining capacity utilisation rate
Smelting capacity utilisation rate
<Relative increase in copper mine and smelter capacity>
<Marginal costs mining>
<Marginal costs smelting>
<Relative recommissioning of copper mine and smelter capacity>
<Recycling Input Rate>
<Relative recommissioning of deep sea mine capacity>
<Relative decrease in deep sea mine capacity>
<Relative decrease in deep sea mining capacity due to losses>
Total present and future smelting and refining capacity
<Relative increase in deep sea mining capacity>
Relation copper mining and refining
Total present and future deep sea mining capacity
Relation deep sea and conventional mining costs
Growth deep sea mining capacity
Deep sea mining capacity in preparation
Preparation of deep sea mining capacity increase
New capacity for deep sea mines
New capacity for conventional mines
<Recycling Input Rate>
Average deep sea mining capacity
Total used deep sea mining capacity
<One year>
<i>Delay under mining?</i>
Last years deep sea mining capacity
Last years deep sea mining capacity
<Global production of refined copper>
Difference in deep sea mining between last year
<Deep sea mining production>
Deep sea mining capacity
Percentage increase in deep sea mining capacity
<i>Delay order mining?</i>
Percentual increase in deep sea mining capacity
Disposal mine and deep sea capacity
Parking of deep sea mining capacity
Recommissioning of deep sea mining capacity
<i>Delay order deep sea mining?</i>
<i>Relative recommissioning of deep sea mining capacity</i>
<i>Relative recommissioning of deep sea mining capacity due to losses</i>
Total used deep sea mining capacity
<i>Relative recommissioning of deep sea mining capacity due to losses</i>
B.1.3. Copper demand

[Diagram of copper demand analysis]
B.1.4. Economics of copper

Diagram showing relationships between various economic factors such as copper prices, marginal costs, energy costs, and profit forecasts. The diagram illustrates how changes in copper prices and costs impact profitability and investment decisions in both deep sea and land-based mining.
B.2. Bottom up model

B.2.1. Copper stocks

[Diagram showing relationships between copper stocks, reserve base, mining capacity, and recycling input rate.]

- Initial copper stocks
- Copper reserve base
- Copper mining capacity
- Recycling input rate

[Diagram includes arrows indicating flows and relationships, such as:
- Increase in deep-sea mining capacity
- Recovery of copper from scrap
- Percentage of copper lost during refining
- Global consumption of refined copper]

[Additional notes on copper production, usage, and demand:]
- Copper score during disbanding
- Total consumption of refined copper
- Normalised scrap recycling rate
- Collection rate of copper scrap
- Average lifetime of copper products
- Initial value of global copper in scrap

[Overall, the diagram illustrates the complex interactions and flows within the copper industry, emphasizing the role of recycling and the impact of various factors on copper availability and consumption.]
B.2.2. Mine, smelting and refinery capacity
B.2.4. Economics of copper
B.3. Regional model

B.3.1. Copper stocks
B.3.2. Mine, smelting and refinery capacity
B.3.3. Copper demand
B.3.5. Copper transport

- Regional surplus or deficit of raw copper
- Regional surplus or deficit of refined copper
- Regional surplus or deficit of copper scrap

Usage of smelting capacity
Transportation time
Global stock of raw copper
Average time mining till refining
Regional surplus of raw copper
Regional deficit of raw copper
Raw copper in transit between regions
Raw copper to transit
Raw copper available to regions
Initial RawCu in transit
Total surplus raw copper
Total deficits raw copper

Export priority raw copper
Import priority raw copper
Export priority ptype
Export priority pwidth
Export priority pextra

Export of raw copper
Import of raw copper

Recycling Input Rate
Total demand for copper
Global inventories of refined copper
Global mined copper production
Global production of refined copper
Copper recovered from scrap
Global copper in scrap
Average time scrap to recycling
Global primary scrap
Global secondary copper to scrap

Regional surplus of refined copper
Regional deficit of refined copper
Refined copper in transport between regions
Refined copper to transit
Refined copper available to regions
Initial RefCu in transit
Total surplus of refined copper
Total deficits of refined copper

Export priority RefCu
Import priority RefCu
Export priority ptype
Export priority pwidth
Export priority pextra

Export of refined copper
Import of refined copper

Postponed demand of copper
One over GDP as priority
Dimensionless region GDP per Capita for priority
Export priority pextra
Export priority ptype
Export priority pwidth
Import priority pextra
Import priority ptype
Import priority pwidth

Export priority pextra
Export priority ptype
Export priority pwidth
Import priority pextra
Import priority ptype
Import priority pwidth
Appendix C. Model equations and uncertainties

The next sections could present all model uncertainties and model equations per model. However, due to the enormous number of equation, this would make mean many extra pages, even with a font so small, that it would be difficult to read the information stated. The information about equations and uncertainties is available in the models and at the author.
Appendix D. Setup of ESDMA

D.1. Typical script for running ESDMA models

The following script was used for generating EMA runs with the Top down model. In order to be able to produce this script easier, the "self.uncertainties" have been generated using the Excel worksheet digitally attached to this report. Since this worksheet is generated digitally using the Vensim-to-csv script, the chance for making mistakes in the external factors names, is greatly reduced.

```python
from __future__ import division

Created on 2 sept. 2011

For use with the EMA of the copper model varieties part of the graduation project
"The Future of Copper in a Sustainable World"
W.L. Aoping, 101413

This script only allows running to generate a pickle file. For making graphs, use CopperGraphs
Author: wauping

# The Copper2 model

class Copper2(VensimModelStructureInterface):
    def __init__ (self, workingDirectory, name):
        super(Copper2, self).__init__(workingDirectory, name)

        self.modelFileName = r"\20110828 WL Aoping Kopernol 2 ESDMA Policies NoEconFeed.vvm"

        # outcomes, or key performance indicators
        self.outcomes.append(Outcome('Year left of copper mining', time=True))
        self.outcomes.append(Outcome('Recycling Input Rate', time=True))
        self.outcomes.append(Outcome('Global consumption of refined copper', time=True))
        self.outcomes.append(Outcome('Part of original demand substituted', time=True))
        self.outcomes.append(Outcome('Real price of copper', time=True))
        self.outcomes.append(Outcome('Marginal costs of copper', time=True))
        self.outcomes.append(Outcome('Marginal costs deep sea copper', time=True))
        self.outcomes.append(Outcome('Relative part of deep sea mining', time=True))
        self.outcomes.append(Outcome('Relative growth GDP', time=True))
        self.outcomes.append(Outcome('TIME', time=True))

        # uncertainties
        # floats
        self.uncertainties.append(ParameterUncertainty((0.25, 2), "One year"))
        self.uncertainties.append(ParameterUncertainty((0.25, 2), "Administration time"))
        self.uncertainties.append(ParameterUncertainty((-2, 2), "Amplification factor for substitution")
        self.uncertainties.append(ParameterUncertainty((-2, 2), "Amplification factor of intrinsic demand")
        self.uncertainties.append(ParameterUncertainty((0, 2), "Amplification factor of relative price effect")
        self.uncertainties.append(ParameterUncertainty((0, 1), "Amplifier GDP growth effect on energy price")
        self.uncertainties.append(ParameterUncertainty((0.4, 1), "Amplitude medium sinus")
        self.uncertainties.append(ParameterUncertainty((0.4, 1), "Amplitude medium sinus")
        self.uncertainties.append(ParameterUncertainty((0.21, 1), "Amplitude short sinus")
        self.uncertainties.append(ParameterUncertainty(0.0005, 0.05, "New autonomous reserve development")
        self.uncertainties.append(ParameterUncertainty(0.0005, 0.05, "New autonomous reserve development")
        self.uncertainties.append(ParameterUncertainty((11.5, 1), "Average deep sea permit term"))
        self.uncertainties.append(ParameterUncertainty((10.5, 1), "Average lifetime of copper in use")
        self.uncertainties.append(ParameterUncertainty((10.5, 1), "Average deep sea permit term"))
        self.uncertainties.append(ParameterUncertainty((10.5, 1), "Average lifetime of deep sea capacity")
        self.uncertainties.append(ParameterUncertainty((10.5, 1), "Average deep sea capacity")
        self.uncertainties.append(ParameterUncertainty((11.2, 1), "Average deep sea permit term")

        self.uncertainties.append(ParameterUncertainty((11.2, 1), "Average smelting capacity permit term")
        self.uncertainties.append(ParameterUncertainty((0.005, 0.25), "Average time mining till refining")
        self.uncertainties.append(ParameterUncertainty((-1, 1), "Base economic growth")
        self.uncertainties.append(ParameterUncertainty((0.5, 1), "Capital investment fraction")
        self.uncertainties.append(ParameterUncertainty((0.01, 1), "Collection rate copper products")
        self.uncertainties.append(ParameterUncertainty((0.5, 1), "Copper price Elasticity of Supply short term")
        self.uncertainties.append(ParameterUncertainty((0.01, 1), "Copper price Elasticity of Supply long term")
        self.uncertainties.append(ParameterUncertainty((0.5, 1), "Copper score during dismantling")
        self.uncertainties.append(ParameterUncertainty((0.5, 1), "Copper score during dismantling")
        self.uncertainties.append(ParameterUncertainty((0.1, 1), "Copper score during treatment")

        # others
        #\frac{d}{dt} x(t) + c x(t) = f(t)
```

```
from expWorkbench.vensim import VensimModelStructureInterface
from expWorkbench.uncertaintySpace import ParameterUncertainty,
from expWorkbench.outcomeSpace import Outcome
from expWorkbench.EMAlogging import EMAlogging
import expWorkbench
```

"The Future of Copper in a Sustainable World"

For use with the EMA of the copper model varieties part of the graduation project
"The Future of Copper in a Sustainable World"
W.L. Aoping, 101413

This script only allows running to generate a pickle file. For making graphs, use CopperGraphs
Author: wauping

# The Copper2 model

```python
class Copper2(VensimModelStructureInterface):
    def __init__ (self, workingDirectory, name):
        super(Copper2, self).__init__(workingDirectory, name)

        self.modelFileName = r"\20110828 WL Aoping Kopernol 2 ESDMA Policies NoEconFeed.vvm"

        # outcomes, or key performance indicators
        self.outcomes.append(Outcome('Year left of copper mining', time=True))
        self.outcomes.append(Outcome('Recycling Input Rate', time=True))
        self.outcomes.append(Outcome('Global consumption of refined copper', time=True))
        self.outcomes.append(Outcome('Part of original demand substituted', time=True))
        self.outcomes.append(Outcome('Real price of copper', time=True))
        self.outcomes.append(Outcome('Marginal costs of copper', time=True))
        self.outcomes.append(Outcome('Marginal costs deep sea copper', time=True))
        self.outcomes.append(Outcome('Relative part of deep sea mining', time=True))
        self.outcomes.append(Outcome('Relative growth GDP', time=True))
        self.outcomes.append(Outcome('TIME', time=True))

        # uncertainties
        # floats
        self.uncertainties.append(ParameterUncertainty((0.25, 2), "One year")
        self.uncertainties.append(ParameterUncertainty((0.25, 2), "Administration time")
        self.uncertainties.append(ParameterUncertainty((-2, 2), "Amplification factor for substitution")
        self.uncertainties.append(ParameterUncertainty((-2, 2), "Amplification factor of intrinsic demand")
        self.uncertainties.append(ParameterUncertainty((0, 2), "Amplification factor of relative price effect")
        self.uncertainties.append(ParameterUncertainty((0, 1), "Amplifier GDP growth effect on energy price")
        self.uncertainties.append(ParameterUncertainty((0.4, 1), "Amplitude medium sinus")
        self.uncertainties.append(ParameterUncertainty((0.4, 1), "Amplitude medium sinus")
        self.uncertainties.append(ParameterUncertainty((0.21, 1), "Amplitude short sinus")
        self.uncertainties.append(ParameterUncertainty(0.0005, 0.05, "New autonomous reserve development")
        self.uncertainties.append(ParameterUncertainty(0.0005, 0.05, "New autonomous reserve development")
        self.uncertainties.append(ParameterUncertainty((11.5, 1), "Average deep sea permit term")
        self.uncertainties.append(ParameterUncertainty((10.5, 1), "Average lifetime of copper in use")
        self.uncertainties.append(ParameterUncertainty((10.5, 1), "Average deep sea permit term")
        self.uncertainties.append(ParameterUncertainty((10.5, 1), "Average lifetime of deep sea capacity")
        self.uncertainties.append(ParameterUncertainty((10.5, 1), "Average deep sea capacity")
        self.uncertainties.append(ParameterUncertainty((11.2, 1), "Average deep sea permit term")

        self.uncertainties.append(ParameterUncertainty((11.2, 1), "Average smelting capacity permit term")
        self.uncertainties.append(ParameterUncertainty((0.005, 0.25), "Average time mining till refining")
        self.uncertainties.append(ParameterUncertainty((-1, 1), "Base economic growth")
        self.uncertainties.append(ParameterUncertainty((0.5, 1), "Capital investment fraction")
        self.uncertainties.append(ParameterUncertainty((0.01, 1), "Collection rate copper products")
        self.uncertainties.append(ParameterUncertainty((0.5, 1), "Copper price Elasticity of Supply short term")
        self.uncertainties.append(ParameterUncertainty((0.01, 1), "Copper price Elasticity of Supply long term")
        self.uncertainties.append(ParameterUncertainty((0.5, 1), "Copper score during dismantling")
        self.uncertainties.append(ParameterUncertainty((0.5, 1), "Copper score during dismantling")
        self.uncertainties.append(ParameterUncertainty((0.1, 1), "Copper score during treatment")

        # others
        #\frac{d}{dt} x(t) + c x(t) = f(t)
```

```
from expWorkbench.vensim import VensimModelStructureInterface
from expWorkbench.uncertaintySpace import ParameterUncertainty,
from expWorkbench.outcomeSpace import Outcome
from expWorkbench.EMAlogging import EMAlogging
import expWorkbench
```
```python
self.uncertainties.append(ParameterUncertainty((0.25,1), "Period short sinus amplitudes\))
self.uncertainties.append(ParameterUncertainty((1,3), "Period medium sinus amplitudes\))
self.uncertainties.append(ParameterUncertainty((1,3), "Period medium sinus\))
self.uncertainties.append(ParameterUncertainty((3,20), "Period long sinus\))
def self.uncertainties.append(ParameterUncertainty((0.25,1), "Period short sinus\))
```

class CopperBottomUp(PermisoModelStructureInterface):

def __init__(self, workingDirectory, name):
    super(CopperBottomUp, self).__init__(workingDirectory, name)

#model
self.modelFile = r'C:\20110902 KL Auping Kopermodel Bottom up vraag ESDMA policies No EconFeed.vpm'

#outcomes, or key performance indicators
self.outcomes.append(Outcome('Year left of copper mining', time=True))
self.outcomes.append(Outcome('Recycling Input Rate', time=True))
self.outcomes.append(Outcome('Global consumption of refined copper', time=True))
self.outcomes.append(Outcome('Part of original demand substituted', time=True))
self.outcomes.append(Outcome('Real price of copper', True))
self.outcomes.append(Outcome('Marginal costs of copper', time=True))
self.outcomes.append(Outcome('Marginal costs deep sea copper', time=True))
self.outcomes.append(Outcome('Relative part of deep sea mining', time=True))
self.outcomes.append(Outcome('Relative growth GDP', time=True))
self.outcomes.append(Outcome('TUN', time=True))

#Uncertainties
## floats
self.uncertainties.append(ParameterUncertainty(0.25, 1, "Administration time") # Original value: 1 # Original value: 0 self.uncertainties.append(ParameterUncertainty(0.25, 0, "Amplification factor for substitution") # Original value: 0 self.uncertainties.append(ParameterUncertainty(0.25, 0, "Amplification factor of intrinsic demand") # Original value: 0 self.uncertainties.append(ParameterUncertainty(0.25, 1, "Amplification factor of relative price effect") # Original value: 0 self.uncertainties.append(ParameterUncertainty(0.6, 2, "Amplitude long minus") # Original value: 3 self.uncertainties.append(ParameterUncertainty(0.4, 1, "Amplitude medium minus") # Original value: 2 self.uncertainties.append(ParameterUncertainty(0.4, 0, "Amplitude short minus") # Original value: 0 self.uncertainties.append(ParameterUncertainty(0.1, 1, "Automatic decay of unfilled demand") # Original value: 0.8 self.uncertainties.append(ParameterUncertainty(0.1, 0, "Base economic growth") # Original value: 0.004 self.uncertainties.append(ParameterUncertainty(1, 0, "Average deep sea permit term") # Original value: 10 self.uncertainties.append(ParameterUncertainty(1, 0, "Average lifetime of copper in use Architecture") # Original value: 80 self.uncertainties.append(ParameterUncertainty(1, 0, "Relative part of deep sea mining") # Original value: 10 self.uncertainties.append(ParameterUncertainty(1, 0, "Aver age lifetime of copper in use EnergyInfrastructure") # Original value: 200 self.uncertainties.append(ParameterUncertainty(1, 0, "Aver age lifetime of copper in use OtherUse") # Original value: 10 self.uncertainties.append(ParameterUncertainty(1, 0, "Aver age lifetime of copper in use StationaryElectromotors") # Original value: 60 self.uncertainties.append(ParameterUncertainty(1, 0, "Average lifetime of copper in use Transportation") # Original value: 100 self.uncertainties.append(ParameterUncertainty(1, 0, "Average lifetime of copper in WaterTreatment") # Original value: 80 self.uncertainties.append(ParameterUncertainty(1, 0, "Average lifetime of deep sea capacity") # Original value: 30 self.uncertainties.append(ParameterUncertainty(1, 0, "Average mine lifetime") # Original value: 30 self.uncertainties.append(ParameterUncertainty(1, 0, "Average mine permit term") # Original value: 10 self.uncertainties.append(ParameterUncertainty(1, 0, "Average smelting capacity permit term") # Original value: 10 self.uncertainties.append(ParameterUncertainty(1, 0, "Average time mining till refining") # Original value: 0.03 self.uncertainties.append(ParameterUncertainty(1, 0, "Base economic growth") # Original value: 1.5 self.uncertainties.append(ParameterUncertainty(1, 0, "Capital investment fraction") # Original value: 0.5 self.uncertainties.append(ParameterUncertainty(1, 0, "Collection rate copper products Architecture") # Original value: 0.8 self.uncertainties.append(ParameterUncertainty(1, 0, "Collection rate copper products Automotive") # Original value: 0.8 self.uncertainties.append(ParameterUncertainty(1, 0, "Collection rate copper products EnergyInfrastructure") # Original value: 0.8 self.uncertainties.append(ParameterUncertainty(1, 0, "Collection rate copper products OtherUse") # Original value: 0.5 self.uncertainties.append(ParameterUncertainty(0.05, 0.09, "Collection rate copper products StationaryElectromotors") # Original value: 0.5 self.uncertainties.append(ParameterUncertainty(0.01, 0.06, "Collection rate copper products WaterTreatment") # Original value: 0.3 self.uncertainties.append(ParameterUncertainty(0.1, 0.2, "Copper price Elasticity of Supply long term") # Original value: 0.1 self.uncertainties.append(ParameterUncertainty(0.05, 0.05, "Copper price Elasticity of Supply short term") # Original value: 0.05 self.uncertainties.append(ParameterUncertainty(0.01, 0.05, "Copper score during dismantling") # Original value: 0.9 self.uncertainties.append(ParameterUncertainty(0.05, 0.03, "Copper score during treatment Automotive") # Original value: 0.9 self.uncertainties.append(ParameterUncertainty(0.05, 0.03, "Copper score during treatment EnergyInfrastructure") # Original value: 0.1 self.uncertainties.append(ParameterUncertainty(0.05, 0.05, "Copper score during treatment OtherUse") # Original value: 0.8 self.uncertainties.append(ParameterUncertainty(0.05, 0.03, "Copper score during treatment StationaryElectromotors") # Original value: 0.8 self.uncertainties.append(ParameterUncertainty(0.05, 0.05, "Cu in vehicle cityBEV") # Original value: 0.0688 self.uncertainties.append(ParameterUncertainty(0.05, 0.075, "Cu in vehicles cityBEV") # Original value: 0.0652 self.uncertainties.append(ParameterUncertainty(0.05, 0.035, "Cu in vehicles Conventional") # Original value: 0.025 self.uncertainties.append(ParameterUncertainty(0.05, 0.05, "Cu in vehicles NEV") # Original value: 0.0435 self.uncertainties.append(ParameterUncertainty(0.05, 0.085, "Cu in vehicles PHEV") # Original value: 0.736 self.uncertainties.append(ParameterUncertainty(0.1, 0.1, "Deep sea capital investment fraction") # Original value: 0.2 self.uncertainties.append(ParameterUncertainty(0.1, 0.1, "Deep sea mined copper before 2000") # Original value: 5 self.uncertainties.append(ParameterUncertainty(0.1, 0.1, "Energy costs of copper smelting and refining") # Original value: 50 self.uncertainties.append(ParameterUncertainty(0.1, 0.1, "GDP growth difference amplifier") # Original value: 1 self.uncertainties.append(ParameterUncertainty(0.1, 0.1, "GDP growth difference amplifier energy") # Original value: 0.6
self.uncertainties.append(ParameterUncertainty(0.1, 0.1, "Growth of copper in architecture") # Original value: 0.01
self.uncertainties.append(ParameterUncertainty(0.05, 0.015, "Growth of copper in architecture") # Original value: 0.01
self.uncertainties.append(ParameterUncertainty(0.03, 0.075, "Growth of copper in water treatment") # Original value: 0.05
self.uncertainties.append(ParameterUncertainty(0.015, 0.025, "Growth of copper in water treatment") # Original value: 0.025
self.uncertainties.append(ParameterUncertainty(0.075, 0.125, "Growth percentage for infrastructure growth") # Original value: 0.1
self.uncertainties.append(ParameterUncertainty(0.125, 0.25, "Influence of technology on copper mining energy costs") # Original value: 0.17
self.uncertainties.append(ParameterUncertainty(0.2, 0.2, "Long term copper price elasticity") # Original value: 0.1
self.uncertainties.append(ParameterUncertainty(0.5, 0.15, "Long term effect intrinsic demand") # Original value: 5
self.uncertainties.append(ParameterUncertainty(0.5, 0.15, "Long term effect substitution period") # Original value: 10
self.uncertainties.append(ParameterUncertainty(0.5, 0.15, "Long term effect on demand period") # Original value: 10
self.uncertainties.append(ParameterUncertainty(0.5, 0.15, "Long term increase demand due to intrinsic demand") # Original value: 5
self.uncertainties.append(ParameterUncertainty(0.5, 0.15, "Long term market period") # Original value: 5
self.uncertainties.append(ParameterUncertainty(0.01, 0.1, "Long term substitution strength") # Original value: 0.15

85
self.uncertainties.append(ParameterUncertainty((0.01, 1.01), "Initial value of long term interest rate substitution WaterTreat")

# Original value: 0
self.uncertainties.append(ParameterUncertainty((0.00000000, 0.000000000000000001), "Mined copper before 2000")
# Original value: 6.5e+008
self.uncertainties.append(ParameterUncertainty((0.000000000000000001, 0.000000000000000001), "Number of cars in 2000")
# Original value: 4.5e+008
self.uncertainties.append(ParameterUncertainty((0.000000000000000001, 0.000000000000000001), "Start GDP per capita")
# Original value: 9000

# Delays
self.uncertainties.append(CategoricalUncertainty((1, 3, 10, 100), "Runoff delay", default = 3)
# Original value: 3
self.uncertainties.append(CategoricalUncertainty((1, 3, 10, 100), "Copper price forecast delay", default = 3)
# Original value: 3
self.uncertainties.append(CategoricalUncertainty((1, 3, 10, 100), "Copper price forecast delay", default = 3)
# Original value: 3
self.uncertainties.append(CategoricalUncertainty((1, 3, 10, 100), "Delay order GDP", default = 3)
# Original value: 3
self.uncertainties.append(CategoricalUncertainty((1, 3, 10, 100), "Delay order mining", default = 3)
# Original value: 3
self.uncertainties.append(CategoricalUncertainty((1, 3, 10, 100), "Delay order mining", default = 3)
# Original value: 3
self.uncertainties.append(CategoricalUncertainty((1, 3, 10, 100), "Delay order of smelting capacity", default = 3)
# Original value: 3
self.uncertainties.append(CategoricalUncertainty((1, 3, 10, 100), "Delay order of smelting capacity", default = 3)
# Original value: 3

# Switches
self.uncertainties.append(ParameterUncertainty((1, 2), "Switch economic growth", integer=True)
# Original value: 2
self.uncertainties.append(ParameterUncertainty((1, 2), "Switch economic growth", integer=True)
# Original value: 2
self.uncertainties.append(ParameterUncertainty((1, 2), "Switch economic growth", integer=True)
# Original value: 2
self.uncertainties.append(ParameterUncertainty((1, 2), "Switch forecast capacity", integer=True)
# Original value: 1
self.uncertainties.append(ParameterUncertainty((1, 2), "Switch forecast capacity", integer=True)
# Original value: 1
self.uncertainties.append(ParameterUncertainty((1, 2), "Switch new cars", integer=True)
# Original value: 1
self.uncertainties.append(ParameterUncertainty((1, 2), "Switch new cars", integer=True)
# Original value: 1
self.uncertainties.append(ParameterUncertainty((1, 2), "Switch World population", integer=True)
# Original value: 1
self.uncertainties.append(ParameterUncertainty((1, 2), "Switch World population", integer=True)
# Original value: 1

# model_init(self, policy, kwargs):
  # "Initializes the model"
  try:
    self.modelFile = policy["file"]
    self.resultFile = r"\CurrentTopBottom.vdf"
  except:
    print("No policies specified")

super(CopperBottomUp, self).model_init(policy, kwargs)

# Results
CopperRegions = VensimModelStructureInterface()
self.uncertainties.append(ParameterUncertainty((0.01, 1), "Collection rate copper products r3\)) # Original value: 0.1
self.uncertainties.append(ParameterUncertainty((0.01, 1), "Copper price Elasticity of Supply long term\) # Original value: 0.1
self.uncertainties.append(ParameterUncertainty((0.01, 1), "Copper price Elasticity of Supply short term\)) # Original value: 0.03
self.uncertainties.append(ParameterUncertainty((0.01, 1), "Copper price short term\)) # Original value: 0.9
self.uncertainties.append(ParameterUncertainty((0.01, 1), "Copper price during dismembering\) # Original value: 0.2
self.uncertainties.append(ParameterUncertainty((0.01, 1), "Copper price during treatment\) # Original value: 0.1
self.uncertainties.append(ParameterUncertainty((17.5, 1), "Deep sea capital investment fraction\)) # Original value: 0.2
self.uncertainties.append(ParameterUncertainty((17.5, 1), "Discount rate of copper smelting and refining\)) # Original value: 50
self.uncertainties.append(ParameterUncertainty((0.25, 1), "Export priority type pwidth r2\) # Original value: 2
self.uncertainties.append(ParameterUncertainty((0.25, 1), "Export priority type pwidth r3\) # Original value: 2
self.uncertainties.append(ParameterUncertainty((0.25, 1), "Import priority type pwidth r3\) # Original value: 2
self.uncertainties.append(ParameterUncertainty((0.25, 1), "Import priority type pwidth r2\) # Original value: 2
self.uncertainties.append(ParameterUncertainty((0.25, 1), "Import priority ptype r2\) # Original value: 1
self.uncertainties.append(ParameterUncertainty((0.25, 1), "Import priority ptype r3\) # Original value: 1
self.uncertainties.append(ParameterUncertainty((0.25, 1), "Import priority ptype r1\) # Original value: 1
self.uncertainties.append(ParameterUncertainty((0.25, 1), "Mining usage investment cap\) # Original value: 0.8
self.uncertainties.append(ParameterUncertainty((1000, 10000), "Normalization value GDP\) # Original value: 1e+008
self.uncertainties.append(ParameterUncertainty((10000, 100000), "Normalization value GSO\) # Original value: 9000
self.uncertainties.append(ParameterUncertainty((1, 20000), "One year\) # Original value: 1
self.uncertainties.append(ParameterUncertainty((1, 20000), "Part of resource base seabased\) # Original value: 0.708
self.uncertainties.append(ParameterUncertainty((0.05, 0.9)), "Percentage copper recovered from scrap\) # Original value: 0.95
self.uncertainties.append(ParameterUncertainty((0.05, 0.9)), "Percentage lost during mining\) # Original value: 0.75
self.uncertainties.append(ParameterUncertainty((0.05, 0.9)), "Percentage lost during refining\) # Original value: 0.05
self.uncertainties.append(ParameterUncertainty((0.05, 0.9)), "Percentage of copper lost during production\) # Original value: 0.05
self.uncertainties.append(ParameterUncertainty((0.1, 0.5)), "Percentage of primary scrap\) # Original value: 0.3
self.uncertainties.append(ParameterUncertainty((0.1, 0.5)), "Percentage of grey scrap\) # Original value: 0.1
self.uncertainties.append(ParameterUncertainty((1, 0.05)), "Period long sinus\) # Original value: 7
self.uncertainties.append(ParameterUncertainty((1, 0.05)), "Period long sinus amplitudes r3\) # Original value: 4
self.uncertainties.append(ParameterUncertainty((1, 0.05)), "Period long sinus amplitudes r2\) # Original value: 5
self.uncertainties.append(ParameterUncertainty((1, 0.05)), "Period long sinus amplitudes r1\) # Original value: 3
self.uncertainties.append(ParameterUncertainty((1, 0.05)), "Period medium sinus\) # Original value: 3.1
self.uncertainties.append(ParameterUncertainty((1, 0.05)), "Period medium sinus amplitudes r3\) # Original value: 2.5
self.uncertainties.append(ParameterUncertainty((1, 0.05)), "Period medium sinus amplitudes r2\) # Original value: 3
self.uncertainties.append(ParameterUncertainty((1, 0.05)), "Period medium sinus amplitudes r1\) # Original value: 1.2
self.uncertainties.append(ParameterUncertainty((1, 0.05)), "Period short sinus\) # Original value: 1.5
self.uncertainties.append(ParameterUncertainty((1, 0.05)), "Period short sinus amplitudes r2\) # Original value: 2
self.uncertainties.append(ParameterUncertainty((1, 0.05)), "Period short sinus amplitudes r1\) # Original value: 2.2
self.uncertainties.append(ParameterUncertainty((1, 0.05)), "Power for coregrades\) # Original value: 0.5
self.uncertainties.append(ParameterUncertainty((0.5, 3.0), "Price amplifying factor\) # Original value: 1.5
self.uncertainties.append(ParameterUncertainty((0.01, 0.1), "Price degenerating period\) # Original value: 0.25
self.uncertainties.append(ParameterUncertainty((150, 10000), "Production costs deep sea copper\) # Original value: 3500
self.uncertainties.append(ParameterUncertainty((0.01, 0.1), "Production time\) # Original value: 0.05
self.uncertainties.append(ParameterUncertainty((0.02, 0.2), "Regional difference with calculated resources and reserves r2\) # Original value: 0
self.uncertainties.append(ParameterUncertainty((0.02, 0.2), "Regional difference with calculated resources and reserves r3\) # Original value: 0
self.uncertainties.append(ParameterUncertainty((0.02, 0.2), "Regional difference with calculated resources and reserves r4\) # Original value: 0
self.uncertainties.append(ParameterUncertainty((0.05, 0.05), "Short term copper price elasticity\) # Original value: 0.01
self.uncertainties.append(ParameterUncertainty((0.05, 0.05), "Short term copper product price\) # Original value: 0.12
self.uncertainties.append(ParameterUncertainty((0.05, 0.05), "Short term increase demand due to intrinsic demand\)) # Original value: 0.1
self.uncertainties.append(ParameterUncertainty((0.05, 0.05), "Short term substitution strength\) # Original value: 0.02
self.uncertainties.append(ParameterUncertainty((0.05, 0.05), "Smelter and refiner usage investment cap\) # Original value: 0
self.uncertainties.append(ParameterUncertainty((0.5, 0.5), "Substitution amplifying factor\) # Original value: 1
self.uncertainties.append(ParameterUncertainty((0.00005, 0.01), "Threshold for junior companies to start deep sea reserve base development\) # Original value: 0.001
self.uncertainties.append(ParameterUncertainty((500, 20000), "Transport costs of copper\) # Original value: 1000
self.uncertainties.append(ParameterUncertainty((500, 20000), "Transportation time\) # Original value: 0
self.uncertainties.append(ParameterUncertainty((500, 20000), "Yearly copper usage related to GDP\) # Original value: 0.0025
self.uncertainties.append(ParameterUncertainty((10, 10000), "Deep sea mined copper before 2000\) # Original value: 5
self.uncertainties.append(ParameterUncertainty((11, 4e+005, 6.2e+008), "Initial copper in use r1\) # Original value: 3.1e+008
self.uncertainties.append(ParameterUncertainty((10, 10000), "Initial copper in use r2\) # Original value: 1.4e+005
self.uncertainties.append(ParameterUncertainty((10, 10000), "Initial copper in use r3\) # Original value: 1.5e+008
self.uncertainties.append(ParameterUncertainty((10, 10000), "Initial copper price\) # Original value: 1814
self.uncertainties.append(ParameterUncertainty((10, 10000), "Initial CuScrap in transit\) # Original value: 100000
self.uncertainties.append(ParameterUncertainty((10, 10000), "Initial deep sea capacity in preparation r1\) # Original value: 100
self.uncertainties.append(ParameterUncertainty((10, 10000), "Initial deep sea mining capacity r2\) # Original value: 1000
self.uncertainties.append(ParameterUncertainty((10, 10000), "Initial deep sea profitable r\) # Original value: 0
self.uncertainties.append(ParameterUncertainty((0.5, 0.5), "Initial long term profit forecast\) # Original value: 0
self.uncertainties.append(ParameterUncertainty((0.5, 0.5), "Long term profitable\) # Original value: 0
self.uncertainties.append(ParameterUncertainty((1200000, 20000000), "Initial mining capacity in preparation r2\) # Original value: 1e+006
self.uncertainties.append(ParameterUncertainty((1750000, 1250000), "Initial mining capacity in preparation r3\) # Original value: 3e+006
The run specifications

```python
self.uncertainties.append(ParameterUncertainty(400000, 5000000), "Initial mining capacity r1")  # Original value: 5e+006
self.uncertainties.append(ParameterUncertainty(1200000, 16500000), "Initial mining capacity r2")  # Original value: 1.5e+007
self.uncertainties.append(ParameterUncertainty(1125000, 18750000), "Initial preparation of refining capacity r1")  # Original value: 1.5e+007
self.uncertainties.append(ParameterUncertainty(1225000, 37500000), "Initial preparation of refining capacity r2")  # Original value: 3e+006
```

```python
def model_init(self, policy, kwargs):
    
    try:
        self.modelFile = policy['File']
        self.resultFile = r"CurrentRegions.vdf"
    except:
        EMALogging.debug("No policies specified")

super(CopperRegions, self).model_init(policy, kwargs)
```

```python
def runfile():
    EMALogging.info("starting run...")
```

```python
model = Copper2(r'C:\ema workspace\copper\models\', 'copper')
```

```python
numberExperiments = 10
```
```python
if __name__ == '__main__':
    import logging, multiprocessing
    import EMAlogging
    from collections import defaultdict

    if_name__ = 'main

    EMAlogging.info("...finishing run1")
    EMAlogging.info("...finishing run2")
    EMAlogging.info("...finishing run3")
```
D.2. Script for generating graphs

### Created on 11 aug. 2011

*For use with the EMA of the copper model varieties part of the graduation project*

*"The Future of Copper in a Sustainable World"

W.L. Auping, 1014153

*Delft*

This file is only intended to generate graphs. The outcomes are only specified to be able to select them for the graphs.

@copyright: wauping

```python
if __name__ == '__main__':
    logging.log_to_stder(logging.DEFAULT_LEVEL) # DEFAULT_LEVEL

    # needed for the old graphs
    results = load_results(fileName)
    outcomes1 = [
        'Real price of copper',
        'Global consumption of refined copper',
        'Part of original demand substituted',
        'Recycling Input Rate',
        'Year left of copper mining'
    ]

    outcomes2 = [
        'Marginal costs of copper',
        'Marginal costs deep sea copper',
        'Relative part of deep sea mining',
        'Year left of copper mining'
    ]

    outcomes3 = [
        'Relative part of deep sea mining r1',
        'Relative part of deep sea mining r2',
        'Relative part of deep sea mining r3'
    ]

    outcomes1Out = [Outcome('Year left of copper mining', time=True),
                    Outcome('Recycling Input Rate', time=True),
                    Outcome('Global consumption of refined copper', time=True),
                    Outcome('Part of original demand substituted', time=True),
                    Outcome('TIME', time=True)]

    policiesWWEconFeed = [{
        'name': 'NoEconomicFeed'},
        {
        'name': 'WithEconomicFeed'}]

    policiesCopper2 = [
        {
        'name': 'BaseModel'},
        {
        'name': 'RecyclingPolicy1'},
        {
        'name': 'RecyclingPolicy2'},
        {
        'name': 'SubstitutionPolicy1'},
        {
        'name': 'SubstitutionPolicy2'},
        {
        'name': 'StrategicReservePolicy'},
        {
        'name': 'AllPolicies'}]

    policiesBottomUp = [
        {
        'name': 'BottomUpBaseModel'},
        {
        'name': 'BottomUpRecyclingPolicy1'},
        {
        'name': 'BottomUpRecyclingPolicy2'},
        {
        'name': 'BottomUpSubstitutionPolicy1'},
        {
        'name': 'BottomUpSubstitutionPolicy2'},
        {
        'name': 'BottomUpStrategicReservePolicy'},
        {
        'name': 'BottomUpAllPolicies'}]

    policiesRegions = [
        {
        'name': 'RegionsModel'},
        {
        'name': 'RegionsRecyclingPolicy1'},
        {
        'name': 'RegionsRecyclingPolicy2'},
        {
        'name': 'RegionsSubstitutionPolicy1'},
        {
        'name': 'RegionsSubstitutionPolicy2'},
        {
        'name': 'RegionsDeepSeaPolicy'},
        {
        'name': 'RegionsStrategicReservePolicy'},
        {
        'name': 'RegionsAllPolicies'}]
D.3. Script for sorting Vensim variables to a csv file

Created on 4 Aug 2011

This script intends to sort the vensim variables to a csv file.

Author: Willem L. Auping, with much thanks to Jan Kwakkel

```python
import csv
from expWorkbench.vensim DLL wrapper import get_varnames, get_varattrib
from expWorkbench.vensim import load_model

vensimRootName = r'C:\ema workspace\copper\models\'
vensimFileName = r'\20110809 WL Auping Kopermodel Regions ESDMA'
# The name of the vensim model of interest
vensimExtension = r'.vpm'
csvArray = vensimFileName + vensimExtension
# The name of the csv file
csvFileName = csvArray[20:]
# The order of the elements in the array of every row
firstLine = ['\Equation', '\Unit', '\Comments', '\Type', '\Float', '\Int']
secondLine = ['\Model title', vensimFileName]
thirdLine = ['\Time unit', '\Year']
# Write here the time unit of the model (or can it be found in the
# model?)
blank = ''

randomString = 'Delay everything till tomorrow'

attributeNames = ['\Units', '\Comment', '\Equation', '\Causes', '\Uses', '\Initial causes', '\Active causes', '\Subscripts', '\Combination Subscripts', '\Minimum value', '\Maximum value', '\Range', '\Variable type', '\Main group']

attributes = range(len(attributeNames))

attributeInterest = [3, 4, 12]

varTypeNames = ['\AI', '\Levels', '\Auxiliary', '\Data', '\Initial', '\Constant', '\Lookup', '\Group', '\Subscript Ranges', '\Constraint', '\Test Input', '\Time Base', '\Gaming']

varTypes = range(len(varTypeNames))

varTypes[0:2] = [1]  # Do not look at all types

varTypeNames[0:2] = [1, 15]  # Do not look after lookup

Vensim file: \vensimRootName + vensimFileName + vensimExtension
print 'Vensim file: ' + vensimRootName + vensimFileName + vensimExtension
print 'Converting starts...

load_model(vensimRootName + vensimFileName + vensimExtension)

with open(vensimRootName + csvFileName, 'w') as f:
    writer = csv.writer(f)
    writer.writerow(firstLine)
    writer.writerow(secondLine)
    writer.writerow(thirdLine)
    writer.writerow(blank)
    for varType in varTypes:
        type = varTypeNames[varType]
        typeNr = varType
        varNames = get_varnames(0, varType)
        for varName in varNames:
            csvArray[0] = lineNumber
            csvArray[1] = varName
            csvArray[5] = varTypeNames[varType]
            for attributeInterest in attributesInterest:
                csvArray[attributeInterest] = varName
                writer.writerow(csvArray)
```

92
attribute = get_varattr(varName, attributeInterest)
if attribute == []:
  attribute = [blank]
if attributeInterest == 1:
  Unit = attribute[0]
csvArray[3] = Unit
elif attributeInterest == 2:
  comment = attribute[0]
csvArray[4] = comment
elif attributeInterest == 3:
  equation = attribute[0]
equation = equation.lstrip(varName)
equation = equation.replace(r'\n', '')
equation = equation.replace(r'\t', '')
equation = equation.replace(r'\n', '')
equation = equation.replace(r'\t', '')
equation = equation.replace(r'  ', '')
equation = equation.lstrip('="
equation = equation.lstrip(r' ')
csvArray[2] = equation
if typeNr == 4:
  if varName[0:5] == 'Delay':
    csvArray[6] = blank
    csvArray[7] = ', integer=True'
  elif varName[0:6] == 'Switch':
    csvArray[6] = blank
    csvArray[7] = blank
  else:
    csvArray[6] = 'x'
csvArray[7] = blank
else:
  csvArray[6] = blank
  csvArray[7] = blank

# print csvArray
writer.writerow(csvArray)
# print varTypes
lineNumber += 1
print 'Converting ended.'

D.4. Script for creating a debugging model

After building a SD model and using it with ESDMA, often sensitivities of the model result in different problems. With the copper models, some floating point errors occurred and further the models had some runs which were extremely slow to run, i.e. run times per run of over 10 minutes, while a "normal" run required less than a second. This script allows using the initial values of a problematic run together with the text version of the Vensim model of interest to create a new model, with the proper variables. This allows the researcher to experiment with the errors which occurred and by doing so, learn more about strengths and weaknesses of the model.

... Created on 11 aug. 2011
@author: wauping, jkwakkel
...

To be able to debug the vensim model, a few steps are needed:
1. The input of the model run that gave a bug, needs to be saved in a text file (.txt). If this information comes from the debugger, the separator is a ';', from a cPickle file, it is ','. Refine and clean your model (In the vensim menu: Model, Reform and Clean).
2. Choose Equation Order: Alphabetical by group (not really necessary)
   Equation Format: Terse
3. Save your model as text (File, Save as..., Save as Type: Text Format Models)
4. Run this script
5. If the print in the end is not set([]), but set([array]), the array gives the values that were not found and changed
6. Vensim tells you about your critical mistake

...
variable[variableElement] = valueElement
define variable
print variable

# This generates a new (text-formatted) model
changeNextLine = False
file = open(r'C:\ema workspace\copper\models\Debugging Model.mdl', 'w') # The name of the new model
settedValues = []
for line in open(r'C:\ema workspace\copper\models\20110809 WL Auping Kopermodel Regions ESDMA text.mdl'): # The name of your text model
    if line.find('"="') != -1:
        elements = line.split('"="')
        value = elements[0]
        value = value.strip()
        if variable.has_key(value):
            elements[1] = variable.get(value)
            line = elements[0] + ' = "' + elements[1] + '"'
            settedValues.append(value)
            print line
            file.write(line)
notSet = set(variable.keys()) - set(settedValues)
print notSet

# This runs your model directly
# variables = variable
define variables = variable
# file = r'C:\ema workspace\copper\models\20110809 WL Auping Kopermodel_2_ESDMA jan.vpm'
# load_model(file)
# for key, value in variable.items():
#     set_value(key, value)
# vensimEILogger.bw_quiet(0)
# command("SETTING>SHOWWARNING=1")
# vensim.run_simulation(r'C:\ema workspace\copper\models\Current.vdf')
Appendix E. Results of ESDMA experiments

The following text is a complete experimental report of the different runs of the ESDMA experiments. This appendix contains the experimental setup of the experiments, the effect of the economic feed structure on the results, the behavioural description of all (K)PIs.

E.1. Experimental setup

In this research, essentially two experiments were performed, using three different SD models for the copper system. First some characteristics will be given about the SD models.

All SD models, built in Vensim (Ventana Systems, 2010), had a run time from the year 2000 till 2050. The time step for these models was 0.007812 year, or $2^{-7}$, while the results were not saved every time step but per 0.125 year to save memory. The time unit for the models was thus year. For integrating the model, the fourth order Runge-Kutta integration method was used (Borelli & Coleman, 2004: 122-129; Ventana Systems, 2010: 213).

The first ESDMA experiment regarded the effects of the economic feed discussed in Box II. For this experiment, 200 runs were performed with the same input parameters for each model, except of course the economic feed input parameters, which were only used in the model with economic feed. Essentially this means that 100 different sets of input variables were generated by sampling with the Latin Hypercube method (Iman et al., 1981) over the uncertainty space. Two runs were performed per set, one for the model with economic feed and one for the model without economic feed.

For the main experiment the same idea was used, except that the variations in the different model varieties were now the different policy measures. For each model variety, 1000 sets of input variables were generated, also with the Latin Hypercube method. The base model was compared with the six policy options defined in Table 8.1 and the three combinations of options, resulting in a total of 10 runs per model variety per parameter set. In total thus $3 \times 1000 \times 10 = 30000$ runs were performed in the main ESDMA experiment.

E.2. The effect of the ESDMA economic growth structure

In chapter 4 (Box II) it was mentioned that a SD structure was added to the models to simulate the unpredictable economic growth. It is interesting to see how large the influence is of this structure on the behaviour of the copper system, as it was modelled. This is done by making two sets of hundred runs with the same set of parameters, but with the economic growth turned respectively off and on. The results can be seen in Figure E.1.

At first sight, the economic growth does not seem to make a large difference in behaviour. In the envelope visualisations of the (K)PIs it is visible that the envelopes are largely overlapping, just like the Kernel density estimations (KDE, see Parzen, 1962; Rosenblatt, 1956) at the right sides. The lines, where a run with or without economic growth has the same colour, result in the same insight. The economic growth seems to only add variation around the behaviour patterns generated by the model without economic growth.

This can be proven with a regret analysis, but this has not been performed due to the scope of the research. There is however some logic behind the little difference: the economic growth drives stocks: the GDP, the aluminium price and the energy price. These stocks smooth the capricious behaviour of the economic growth. Some difference could have been expected due to the substitution threshold, where a small difference can already cause substitution or resubstitution. Long term effects are however, as well with substitution, more important than the fluctuations generated by the economic growth.
E.3. Top down model

E.3.1. Real price of copper

The first KPI to be discussed is the Real price of copper. In lines graph (Figure E.2) it is visible that the copper price show diverse and extreme behaviour. The highest prices found in this case are well over 1 million Dollars per ton. Most strikingly is the behaviour the price shows. In many runs, sharp in- and decreases are visible, or copper crises as defined in section 6.3. These crises seem to occur multiple times in a run, alternating between a strong drop and strong rise in price. They indicate a strong disbalance between the availability and the demand of copper over a prolonged period of time. In the line graph it is unclear whether these crises tend to increase in severity during the run time, stay rather stable or are dampened and what the chances are for either of these options. The lines graph cannot help in this case, but clustering of the behaviour could. This analysis has however not been performed here.

Figure E.2: Lines graph for the Real price of copper
The trends for the price show a different picture (Figure E.3). The trend in the price seems to be rather constant, but the decreasing distribution height (the z-axis) shows the ever increasing uncertainty towards the end of the run time. To be able to explain this trend, it is important to look at further (K)PIs.

![Figure E.3: 3D envelopes of the Real price of copper [Dollar/t]. The red, green and blue arrows show the respective direction of x, y and z axis. The price is truncated at 10000 Dollar/t](image)

E.3.2. Global consumption of copper

The next outcome of interest is the Global consumption of copper. The consumption shows some values over twenty million t/Year, but all higher values are followed by a sudden drop in behaviour. This behaviour can again be explained by the disbalance between supply and demand of refined copper. When the supply of refined copper is too high for a period of time, the stocks will be rising globally, while these cause the copper price to drop below the marginal costs. This relatively low price will let the demand rise. In this case, the price stabilises as soon as the production and consumption are equal. The high stocks keep the price still low, resulting in a further increase in demand, with no increase or even a decrease in the production due to the losses made. At the moment the stocks cannot comply with the demand, the consumption drops. This is a well perceivable situation, which is linked to the crises in price described above.

Another mechanism which can cause this behaviour is the postponing of demand in case of a shortage in copper. As soon as the refined copper stocks increase, this will form an addition to the new demand. As soon as this demand is satisfied, a drop in the copper consumption can be observed.

![Figure E.4: Lines graph for the Global consumption of copper](image)

Now it is interesting to look at the overall trends for the global consumption (Figure E.4). This seems to be slowly decreasing after 2010. This is probably due to the relatively high marginal costs of copper compared to the costs of substitutes. This makes it interesting to look at the next PI, the Part of original demand substituted. Overall the
global copper consumption explored by the ESDMA effort seems low however, since the present consumption (see Table 5.1) was considerably higher than the values displayed in Figure E.5. There are two possible explanations for this low value. First, the RIR, which will be discussed in section E.3.4, is probably an underestimation of the true RIR. Second, the assumption about the composition of the global consumption of refined copper in the model may have been wrong. In this variable, both the losses during production and the primary scrap flow have been considered part of the copper consumption. Adding these relative losses to the demand copper would change this picture as well.

The initial value problem visible in Figure E.5 is caused by the way in which the availability of copper, crucial for the amount of copper which can be consumed, is calculated. This happens by dividing the global inventories of copper by the production time. The first variable is a stock, while the second is modelled as a constant. Both values are in essence uncertain, but the range of the first is considerably smaller due to the latter given its well documented nature. Since the consumption is defined as the smallest value of either the availability of refined copper, or the copper demand combined with the postponed demand, a relatively high availability in the initial state may cause a very short termed higher consumption of copper.

Figure E.5: 3D envelopes of the Global consumption of refined copper [t/Year]. The graph is truncated at 30 million tonne per Year

E.3.3. Part of original demand substituted

The substitution of the copper demand tends to be increasing during the run time in many cases, but it is also visible that this happens with oscillatory behaviour (Figure E.6). This movement is caused by the copper price which oscillates around the price of the substitutes. This behaviour can be explained with the modelling assumptions for substitution (Box IV). For example, when at a certain moment in time 20% of the demand is substituted and new demand arises due to the economic situation, this percentage will remain the same only when the copper price is equal to the substitution threshold on short term and when the average copper price over a longer period is also comparable to this value. Especially the long term effect is important here. A prolonged period of time with a higher price for copper than the substitution threshold will cause a rapid increase in the part of the demand that is substituted. The subsequent strong decrease in demand for copper will result in a lower copper price, which can in term become lower than the substitution threshold for a longer period of time, reversing the process.
The trends of substitution show some bifurcation, as can be seen both in Figure E.7 and the KDE of Figure E.6. This means that two trends seem plausible, one with relatively little substitution (up to 30%) and one with relatively much substitution (over 30%, with a peak around 90%). This bifurcation probably caused by the long term effects described above.

**E.3.4. Recycling Input Rate**

After the substitution, it is interesting to look at the RIR (Figure E.8), which was defined as the relation between the input of primary and secondary refined copper. The behaviour of this KPI is not always stable. In this research the assumption was made that both the collection rate and the end of life recycling efficiency rate remain constant during the runs. Since much oscillation is not to be expected from the discarding of copper products to waste, which was calculated by dividing the stock of copper in use by the average lifetime of copper products. It therefore directly related to fluctuations in the production of primary copper.
The main trend of the RIR seems to be a gradually rising percentage (Figure E.9). This can be explained by the trend in the global copper consumption and the stock of copper in use. In a stable system, the amount of End of Life (EOL) copper is equal to the copper consumption. The output of secondary copper is then equal to the Recycling Efficiency Rate (RER), while when we assume that all recycled copper is used, this is exactly the RIR. Since in this research both the collection rate and the RER are modelled statically, change in the RIR is only dependent on changes in the copper consumption. A growing copper consumption will thus result in a lower RIR and vice versa. The higher RIR here is consequently caused by the gradually declining copper consumption visible in Figure E.5.

It is typical to notice however that the RIR generated by the ESDMA research is lower than the RIR of around one third mentioned by the ICSG (2010b). The easiest, and probably partly true, way of explaining this is by an exaggeration of the uncertainties regarding the collection rate and the RER. The four uncertainties relevant in this case (collection rate, copper score during treatment, copper score during dismembering, and the percentage of copper recovered from scrap) (Angerer et al., 2010) need however to have an average value of almost 76% to create an RIR of 33.3%, while an average value of 50% gives an RIR of no greater than 6.25%, both in a system in equilibrium. This indicates the importance of both high collection rates and RER, despite the fact that the values presented in Figure E.9 might be an underestimate of reality. When thinking about the possible RIR however, these values indicate clear the fact that with growing marginal costs for copper mining it is of utmost importance to increase both collection rate of EOL copper and the RER. In chapter 8 and 9 is more focus on the RIR and the effect of a higher RER and before that in the discussion of the bottom up model, where on average higher values for the (use dependent) recycling coefficients were used.

![Figure E.9: 3D envelopes of the Recycling Input Rate [Dmnl]. The graph is not truncated, so the values for the substitution lie between 0 and 1, or 0% and 100%](image)

**E.3.5. Marginal costs of conventional and deep sea copper**

The marginal costs of (conventional) copper and the marginal costs of deep copper show an exponential growth without much fluctuation. Since the colours of both PIs are similar per run, i.e. the red line with high values in Figure E.10 is the same run as the red line with high values in Figure E.11, both marginal costs can be compared. By doing so, it seems that the run values lie for most runs relatively close together.
When looking at the trends of both the marginal costs of copper and the marginal costs deep sea copper it is clear however that on initial average the marginal costs of deep sea copper are higher than their equivalent for conventional copper. The conclusion should thus be that on average deep sea mining remains more expensive for some time, but that deep sea mining will be developed with marginal costs comparable with, but just under the marginal costs of conventional copper.

This idea is confirmed by comparing the marginal costs of copper with the marginal costs deep sea copper (Figure E.13). This makes clear that the marginal costs of deep sea mining never rise above the marginal costs of copper.

E.3.6. Relative part of deep sea mining

The same image is generated by the next (K)PI, the relative part of deep sea mining (Figure E.15 and Figure E.16). In some cases the deep sea mining will form a substantial part of the total amount of mined copper. In the behaviour of the runs it is visible that some violent oscillation takes place. This is caused by a discrepancy in the development of deep sea copper resources and copper mining, as was described in Box VI. The strong expansions of the relative part of deep sea mining can be explained in the same way: the development of deep sea mining capacity than the development of the deep sea reserve base. At the moment when a new part of the deep sea resources has been explored, the deep sea mining capacity can be finally used and the relative part of deep sea mining suddenly increases.
The trends for deep sea mining follow the same pattern as expected comparing the marginal costs. The coming forty years some deep sea mining will be developed, but most likely it is not going to be more than a few percent of total mining. Please note however that, considering the size of the yearly copper production, that this will be very large operations.

E.3.7. Year left of copper mining

The lines graph for year left of copper mining shows a remarkable empty view (Figure E.17). This has to do with the extraordinary high values for this KPI that some runs show. This variable is calculated by looking dividing the reserve base (contrary what was done for example by Koppelaar (2011), who looked at the reserves) by the global mine production. The reserve base can only decrease by mining, while it grows semi-autonomous by findings of the junior companies. The drastic growth of the year left of mining can thus only be explained by cases in which the production declines heavily compared to the reserve base present. This can be caused by strong substitution, of which cases were visible in Figure E.6.
Figure E.18 shows a similar view as the copper price development in Figure E.3. After some time the year left of copper mining has diverged so much, that not many trends can be seen, other than the divergence itself. This view corresponds with the idea that the copper production is likely to decrease in the coming period of forty years. This is also clearly visible when the year left of copper mining is plotted against the copper consumption (Figure E.19). A high value for the year left of copper mining only exists with a low value for the global consumption of refined copper.

![Figure E.18: 3D envelopes of the Year left of copper mining [Year]. The graph is truncated at 500 year](image1)

![Figure E.19: Multiplot of Global consumption of refined copper [t/Year] and year left of copper mining [Year]](image2)

### E.4. Bottom up model

In this section the outcomes of the bottom up model will be discussed. This will not be done by discussing all (K)PIs in the same depth as in section E.3, but by emphasizing on the differences in behaviour and trends between the model varieties.

#### E.4.1. Real price of copper

The Real price of copper in the bottom up model seems to have a strong tendency for cyclical, oscillatory behaviour, which seems to have a far more constant period than the behaviour of the top down model. This is visible in both Figure E.20 and Figure E.21. It is unclear what causes this very distinct behaviour, since all parameters of the model were varied in the ESDMA experimental setup. Further analysis by means of the Patient Rule Induction Method (PRIM) (Friedman & Fisher, 1999), Random Forests (Breiman, 2001), clustering the behaviour or other machine learning methods might help in this case. It is interesting to see however that the prices are on average less high than the prices in the top down model. This is also indicated by the highest value of the KDE, which is almost $1.8 \times 10^5$, which is significantly higher than the value just under $1.0 \times 10^5$ in Figure E.2.
E.4.2. Global consumption of copper

The first big difference of the global consumption of refined copper generated by the Bottom up model is higher than the consumption displayed in Figure E.4 and Figure E.5, but in the period 2000 – 2010 on average still lower than the historical data found in Table 5.1. A second feature of the top down consumption behaviour, the serration in the different run lines, seems to be less distinguished, although it is still visible.

The overall higher consumption of copper, which was just noticed, is probably caused by a higher average value for the RIR, which is discussed in E.4.4. The same assumption was made however for the relation between primary scrap and copper consumption, causing the values to be too low again.

E.4.3. Part of original demand substituted

The behaviour of the demand substitution in the bottom up model (Figure E.24) is largely the same as the substitution displayed in Figure E.6 and Figure E.7, although the form of the end state KDE is slightly different. On close examination of the behavioural patterns of Figure E.6 the slopes of the substitution patterns are less steep. Further, on average some less demand was substituted, which could also have been caused by the slightly higher availability of copper due to the higher RIR. The slope of the runs seems also to be less steep. This is well understandable with some knowledge of the structural differences between both models. The top down model used only one substitution threshold, while the bottom up model used six, one for each major use of copper (the different uses were visible in Figure 4.4). When the copper reaches the threshold of one of the uses, this particular use will be more substituted, while other uses, with higher thresholds, may even experience resubstitution. Since the speed of substitution seems to have a great influence on price volatility in the copper
system due to sudden drops and increases of the demand, this would explain fewer occurrences of copper crises, as defined in section 6.3, in the bottom up model.

Figure E.24: Lines graph for the Part of original demand substituted

E.4.4. Recycling Input Rate

The bottom up generated RIR (Figure E.25 and Figure E.26) is clearly higher than the top down generated RIR. This is mainly due to different input values for the different elements regarding the RER and the collection rates per copper use. The RIR seems still considerably lower than the values displayed in Table 5.1. This is mainly due to an exaggerated lower bound for the percentage copper recovered from scrap, just like the top down model had.

Development in the RIR is in the bottom up model also possible due to shifts in the usage of the different copper product categories, contrary to the top down model. Without further analysis it is nevertheless difficult to attribute changes in the RIR to these changes. The RIR seems to show less increase during the run time period. This is can be related to a less drastic decline in the copper consumption, which was visible in Figure E.23.

Figure E.25: Lines graph for the RIR

Figure E.26: 3D envelopes of the RIR [Dmnl]. The graph is not truncated

E.4.5. Marginal costs of conventional and deep sea copper

The behaviour of the marginal costs for conventional and deep sea copper (Figure E.27 and Figure E.28) are largely similar to the modes seen in Figure E.10 and Figure E.11, and show exponential growth with some fluctuations. On average, the marginal costs seem to be a little lower compared to the top down model. The marginal costs of deep sea copper are considerably lower however than the values which can be seen in Figure E.11 and results a slightly higher relative part deep sea mining (Figure E.29 and Figure E.30). It is unclear why this variable does not develop in the same way as the top down equivalent, since the model structures concerning the marginal costs are identical for both models. Further analysis could create more insight in this issue.
E.4.6. Relative part deep sea mining

As was noticed in the former section, the relative part of deep sea mining is on average higher in the bottom up model (Figure E.29 and Figure E.30), compared to the top down model. This is most likely due to the larger difference between the marginal costs of conventional and deep sea copper. The behaviour of the runs seems to be similar, which can be explained by the identical structure regarding (deep sea) mining development in both models.

E.4.7. Year left of copper mining

Despite the fact that the extreme values are slightly lower in Figure E.31 than in Figure E.17, the overall behaviour of this indicator is similar to the behaviour observed earlier, as is also demonstrated by Figure E.32. The lower extreme values could be caused by the slightly higher RIR, which causes higher consumption.
E.5. Regional model

The outcomes of the Regional model will now be discussed. Again, emphasis will lie on the differences between this model and the other model varieties.

E.5.1. Real price of copper

The real price of copper for the regional model shows the most extreme view for possible price developments in the coming forty years. While clustering could shed more light on the exact behavioural modes of the runs, the behaviour of the copper price seems to be characterised by strong surges followed by a gradual decreases (Figure E.33). The strong increases can be caused by the same disbalance noticed in section E.3.1. Figure E.34 shows no distribution of data after approximately 2020. This is due to the fact that the differences between the runs are so great, that no concentration of values can be seen. Between 2010 and 2020 this already happens, but to a lesser extent. It is unclear why specifically in this model variety the prices show this wide distribution of possible values. Further analysis could help in this case by distinguishing which uncertainties play a major role in causing the price volatility and distribution.

![Figure E.33: Lines graph for the Real price of copper](image)

![Figure E.34: 3D envelopes of the Real price of copper [Dollar/t]. The graph is truncated at 100000 Dollar/t](image)

E.5.2. Global consumption of copper

The global consumption of copper in the regional model, obtained by summing the consumption from the three regions, shows more extreme peaks than the top down model (compare Figure E.35 with Figure E.4). Probably this booms and busts are caused by the same mechanisms that were discussed earlier in E.3.2. The peaks in the consumption behaviour also cause a wider distribution of possible values in the period between roughly 2010 and 2040.

This behaviour can be explained by looking into the difference in structure of the regional model. In contrast with the other models, this model has a regionalised supply and demand structure. Regarding the supply structure, this also means that export and import of raw and refined copper, as well as copper scrap takes place. This means that while one or two regions experience a shortage, the surplus of the other region(s) can fill the gap between regional supply and demand. The result of this may be that production of copper is reduced in one region is being reduced, while the other regions already experience ongoing shortages. The global pricing of the metal limits possibilities for an earlier reaction of the market in this case. This could be a good reason to develop adaptive policies (Walker et al., 2001) regarding the development of copper production capacity, which would react to early warning mechanisms in the copper system.
E.5.3. Part of original demand substituted

The substitution of copper demand in the regional model (Figure E.37) shows similar behaviour as the substitution of the models discussed above. It is typical to see however that the bifurcation that was visible in the part of original demand substituted for the top down and bottom up model (respectively Figure E.6 and Figure E.24) is not visible in these results, which show on average less substitution. The reason for this could be the differences in regional availability of copper and fluctuation in copper import and export related to that. In the regional model regional shortages of refined copper are no reason for extra substitution, solely the price mechanisms discussed in Box IV are. The substitution lines thus show less steep slopes than the top down model and are more comparable to the bottom up model, despite the fact that the underlying structure is practically identical to the top down model. The regional system seems to react consequently slower than the models with a global market paradigm.

E.5.4. Recycling Input Rate

The inputs for the RIR are comparable to the values used in the top down model, again resulting in a distribution of run values which shows relatively much low values. The behavioural modes of the RIR show much volatility (Figure E.38) just like the RIR of the top down model, but the behaviour is more smoothed. This has to do with the fact that this outcome is an aggregated, global version of the regional RIRs. The regional differences, not visible here, showed a behaviour similar to the data provided by the ICSG (2010b: 53), where the resource abundant regions had a considerably lower RIR than the other regions. Higher values for the regional collection rates of copper and the coefficients regarding the RER could however still add more validity to the model and this outcome in specific.
E.5.5. Marginal costs of conventional and deep sea copper

The marginal costs of copper in the regional model are calculated by taking the highest marginal costs for copper in any copper producing region. This could explain the strange behaviour visible in Figure E.39 which is understandable with the possibility of declining energy prices, a already low regional initial ore grade and with practically no copper mining capacity,, causing little rise in costs due to the falling ore grades. This distinguishes the regional model from both globalised models.

The further behaviour is similar to the other models, being on average exponential growth without much fluctuation. The relation between the marginal costs of conventional (Figure E.39) and deep sea copper (Figure E.40) is however more similar to the bottom up model than the top down model, since the marginal costs of deep sea copper do not seem to reach the values for conventional copper mining, making it interesting to investigate whether the same mechanisms cause this cost differences.

E.5.6. Relative part of deep sea mining

The development of deep sea mining is modelled different in the regional model. The assumption is that the possibility for deep sea mining is dependent on the regional GDP per capita, in order to simulate the higher technological demands necessary for this kind of mining and which is probably not available in lower income countries. A threshold was thus built in, only enabling the possibility for deep sea mining development when the GDP per capita in a certain region is higher than this value.

The behaviour visible in Figure E.41 resembles this assumption. The wealthiest region, region 1, starts first with the development of deep sea mining, followed in time by respectively region 2 and 3. The strong fluctuations in the relative part of deep sea mining in regions 1 and 2 probably originate in an overall low amount of regional conventional copper mine production. The behaviour of deep sea mining in the third region is therefore, when it finally starts, more fluent in nature. Despite this, only the first region seems to give the possibility for a substantial contribution of deep sea copper relative to the production of conventional copper, which is in line with the assumption discusses earlier in this section.
E.5.7. Year left of copper mining

The regional model shows the highest values for the outcome year left of copper mining (Figure E.42). Earlier in this report high value for this KPI were coupled to a strong decrease in copper consumption. The slower reaction of the regional model to fluctuations in the copper system might cause this extreme behaviour. A consequence is also the bigger spread in year left of copper mining compared to the results of the other model varieties (Figure E.43).
Appendix F. Minutes of personal communication with P.H. van der Kleijn

This appendix contains the minutes of the personal communications with Ir. P.H. van der Kleijn and e-mails before and after the meeting with him. The initial e-mail is to Ir. J.J. de Ruiter, faculty CITG, department Resources Engineering, who recommended contacting Van der Kleijn. All communication is in Dutch. For translation, please contact the author.

F.1. Initial e-mail to Hans de Ruiter

Geachte heer De Ruiter,

In verband met mijn afstudeerproject bij Technische Bestuurskunde ben ik bezig met het maken van een exploratieve System Dynamics model en analyse, dus een exploratieve modelstudie, over de globale kopermarkt tot 2050. Hiervoor heb ik enkele vragen over de winning van koper. Mijn broer, Thomas Auping, suggereerde dat ik hiervoor met u contact op zou nemen.

Het voornamste probleem dat ik momenteel heb zit in het feit dat (volgens de International Copper Study Group) het gebruik van de globale kopermijn capaciteit de afgelopen jaren is afgenomen van 92,5% in 2000 tot 80,9% in 2010, terwijl de koperprijs in deze tijd sterk is gestegen.

Ik heb hier de volgende vragen over:

- Hoe defineert men de capaciteit van een mijn?
- Wat zijn motieven om die capaciteit niet te gebruiken?
- Als de mijn zijn capaciteit niet geheel wil gebruiken, hoe gaat dat dan fysiek in zijn werk: wat wordt er dan precies niet gebruikt?
- Weet u wat in dit geval de reden is om de capaciteit niet te gebruiken, terwijl de marktprijs daar wel aanleiding toe geeft?

Verder heb ik nog wat algemener vragen over koperwinning:

- Op basis van wat voor soort informatie wordt besloten tot het uitbreiden van de capaciteit van mijn/het ontwikkelen van nieuwe mijnen?
- Wat voor termijn wordt aangehouden voor het besluit om een mijn te ontwikkelen tot de opening van deze mijn?
- Over reserves/resources: in de jaren 70 heeft B.J. Skinner een hypothese geponeerd over een zogenaamde “mineralogical barrier” tussen koper in normale rots (common rock) en koper in erts. Is er consensus over het (on)gelijk van deze stelling?

Ik zou graag over deze vragen met u willen praten, zodat ik dit mee kan nemen in mijn onderzoek.

Bij voorbaat dank,

Willem Auping
Skinners Thesis (Gordon, Koopmans, Nordhaus & Skinner, 1987: 39; Skinner, 1976) lijkt afkomstig te zijn van een som van de verdeling van reserve en reserve base in een typische mijn (Figuur G.1). De reserve bevindt zich dus rechts van de cut-off ore grade, die tegenwoordig rond de 0,2 – 0,3% koper ligt. De bewezen reserve is daarmee ook afhankelijk van de marktprijs.

De definities van reserve, reserve base en resources en hoe deze bepaald moeten worden, zijn gedefinieerd door de Joint Ore Reserve Committee (JORC, 2004).

Nieuwe resources worden grotendeels gevonden door zogenaamde “Junior Companies” die de nieuwe kennis verkopen aan mijnbouwbedrijven.

Het recovery percentage is ongeveer gelijk aan 90%: dit is dus de hoeveelheid koper die beschikbaar komt in de winning ten opzichte van het totale gewicht aan koper dat in de rots gezeten heeft. Zodra het feedgehalte omlaag gaat, gaat ook het recovery percentage omlaag.

De kosten van het mijnen wordt grotendeels door het volgende bepaald:

Kosten = overburden + winnen & (kwaliteit + ertsgraad)

De kwaliteit wordt bepaald tot de types van de ertsen die zich in de reserve bevinden.

De capaciteit van de mijn wordt traditioneel bepaald door de capaciteit van de breker (breaker), die naast de mijn staat. Als de reserves niet verwerkbaar blijken (door bijvoorbeeld de overburden), dan wordt niet alle capaciteit gebruikt.

Een onbekend deel van de grondstoffen wordt ook illegaal gewonnen

**F.3. Further e-mail communication**

Beste Willem,

**Re. Mijn productiecapaciteit**

Betreffende je vraag naar mijn capaciteiten en daaraan gekoppeld levensduren van reserves na aanvang van productie bijgesloten Hfd B, Production lifetime.

Erg theoretisch wordt de produktiegrootte (capaciteit van de eerste breker) afgeleid van de ratio Reserve/Levensduur.

In de zeventiger jaren heeft Taylor in Noord Amerika/Canada een empirische correlatie gelegd tussen ertsvoorraden en mijn-levensduren. Er valt het nodige hierop af te dingen. Er wordt b.v. geen rekening gehouden dat gedurende de levensduur nieuw gevonden en gedefinieerde ertsvoorraden in-en rond de mijn worden bijgevonden en/of de cut off grade omlaag gebracht kan worden waardoor de berekende ertsvoorraad groter wordt. De spreiding van de getallen rond de correlatiecurve is aanzienlijk. Maar laten we zeggen dat met correlatie-statistiek gefilterd wordt met behoud van een relatie tussen X en Y. Mogelijk kan je (vlp.) eens kijken of deze benadering in je model valt toe te passen om levensduren en productiecapaciteiten mee te laten wegen in je uitkomst.


Re. Ertreserves classification. JORC code

Het is belangrijk dat je de begrippen rond ertsreserve en resources definitie op de juiste wijze hanteert. Zoals besproken bijgaand een verwijzing naar de Australische definitie die ± in lijn is met wat later in de USA en Canada op initiatief van de stock exchanges is gedefinieerd. Zie de Quick Reference ver.2 en de JORC site voor meer informatie.

http://www.jorc.org/

Ik zal naar kontakten om mee te praten nog rondkijken.

Het was leuk om te praten maar ik moet bekennen dat ik de fundamenten van jullie model nog niet goed kan overzien.

Een thema waarover we niet hebben gesproken is de toekomstige beperking tot het in exploitatie nemen van prospects voortvloeiend uit eisen aan de duurzaamheid en milieu milieuwetgeving en regulations.

Tevens is het nuttig denk ik om gegevens te verzamelen rond het begrip exploratie, uitgaven en success rate en toename van de voorraden t.o.v. de productie. Of zit dat al in je model?

Met groeten,

Piet Hein