Analysing the Uncertain Future of Copper with Three Exploratory System Dynamics Models

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Abstract

High copper prices, the prospect of a transition to a more sustainable energy mix and increasing copper demands from emerging economies have not led to an increased attention to the base metal copper in mineral scarcity discussions. The copper system is well documented, but especially regarding the demand of copper many uncertainties exist. In order to create insight in this systems behaviour in the coming 40 years, an Exploratory System Dynamics Modelling and Analysis study was performed. Three different models have been developed representing different views on copper supply and demand. The behaviour of these models shows crisis-like behaviour for the copper price, and often a declining consumption of refined copper. Six different policy options have been explored, individually and in combinations, for their robustness in counteracting undesirable behaviours. The results of these tests are that emphasising recycling, and the development of strategic reserves are potentially helpful.

Keywords: Copper, Mineral Scarcity, System Dynamics, EMA, ESDMA

1 Introduction

In the debate about mineral and metal scarcity, the focus is on several "risky" metals, like lithium (Angerer et al. 2009) and the rare earth metals (European Commission 2011). Almost no attention exists for copper. This bulk metal however, can be considered to be a scarce metal, in contrast to iron or aluminium (Gordon et al. 1987, 2). The vast quantity of copper use (ICSG 2010) and the current high copper prices (LME 2011) make societal problems regarding this metal, like copper theft (Klis 2011), an almost inevitable consequence.

There seem to be two causes for the current high copper price: the energy transition towards a more sustainable mix of energy sources (Kleijn and van der Voet 2010) and the growing demand for minerals in fast developing economies like China and India (European Commission 2011). The future development of copper demand however can be classified as deeply uncertain. Deep uncertainty can be defined as: „where analysts do not know, or the parties to a decision cannot agree on, (1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future, (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (3) how to value the desirability of alternative outcomes" (Lempert, Popper, and Bankes 2003). Another deeply uncertain element in the copper system is the development of the ore grade in relation with mining operations (Tilton 2003; Gordon, Bertram, and Graedel 2007; Tilton and Lagos 2007).

A novel method which allows exploring the influences deep uncertainties have on system behaviour is Exploratory System Dynamics Modelling and Analysis, or ESDMA (Pruyt 2010; Pruyt et al. 2011; Pruyt and Kwakkel 2012). ESDMA is a combination of Exploratory Modelling and Analysis (EMA), (Bankes 1993; Lempert, Popper, and Bankes 2003) and System Dynamics (SD) models especially developed to explore both parametric and structural uncertainties. In this paper, the goal is to create plausible scenarios for Key Performance Indicators (KPIs) in the copper system, explore possible undesirable effects in these scenarios, and the influences the uncertainties have on this system behaviour. In light of this, several policies that can address the identified undesirable effects have been developed and tested.

In this paper, the research methodology will be explained in section 2. This starts with an overview of SD studies on the domain of scarcity issues and commodity cycles and is followed by elaborations on EMA and ESDMA. The structure of the different copper models used in this study will be explained in section 3. In section 4, the scenarios exhibited by these models will be discussed. In section 5, some policy options for the copper system and the effects they have on the ensemble of scenarios are assessed. Section 6 contains the conclusions both on future dynamics of the copper system and the use of the ESDMA methodology for scarcity issues is presented.

2 Methodology

2.1 SD modelling of mineral and metal scarcity

System Dynamics (SD) (Forrester 1968; Sterman 2000) is a modelling method which is particularly useful for simulating systems which are characterized by strong feedback loops, delays and stock-flow structures. The simulation of SD models has as goal to investigate modes of dynamic behaviour over time.

SD modelling of mineral and metal scarcity has a long tradition. Probably the most well-known example is the Limits to growth (Meadows et al. 1972), where minerals and metals are modelled as non-renewable resources. In many other examples geological, technological and economic aspects about mineral depletion were combined (Sterman and Richardson 1985; Davidsen, Sterman, and Richardson 1987; Sterman, Richardson, and Davidsen 1988).

A more specific metal study was performed by the Dutch National Institute of Public Health and Environment (Van Vuuren, Strengers, and De Vries 1999), where the long-term structural dynamics for two categories of metals were studied. Some research aimed at certain specific metals, like the platinum group metals (Alonso, Field, and Kirchain 2008) or magnesium (Urbance et al. 2002). In these studies the use of the metal is often linked to a specific use for the metal, like electronics (Alonso, Field, and Kirchain 2008) or the automotive industry (Urbance et al. 2002). No SD model was found however which exclusively focused on the global supply and demand of copper.

The copper models presented here try to unite geological, technological and economic aspects of the copper system. This is however not be done in a traditional way, but by combining SD techniques with the Exploratory Modelling and Analysis approach.

2.2 Exploratory Modelling and Analysis

Exploratory Modelling and Analysis (EMA) is a research methodology that uses computational experiments to analyse deeply uncertain issues (Bankes 1993; Agusdinata 2008). EMA consists quantitative modelling of the set of plausible models and uncertainties, the process of exploiting the information contained in such a set through a large number of computational experiments, the analysis of the results of these experiments, and the testing of policies for robustness (Bankes 1993; Agusdinata 2008). Uncertainties may be caused by a variety of factors, including the infeasibility of critical experiments, impossibility of accurate measurements or observations, immaturity of theory, openness of the system to unpredictable outside perturbations, or nonlinearity of system behaviour, but is fundamentally a matter of not knowing enough to make predictions (Cambell et al. 1985; Hodges and Dewar 1992).

EMA can be useful when relevant information exists that can be exploited by building models, but where this information is insufficient to specify a single model that accurately describes the real system behaviour. In this circumstance, models can be constructed that are consistent with the available information, but such models are not unique, which is an important reason for specifying different model structures or even multiple models. These models combined with other uncertainties allow for computational experiments that reveal how the world would behave if the various guesses any particular combination of assumptions would be correct. By conducting many such computational experiments, the implications of the various guesses can be explored.

In this study, EMA was performed by making use of three SD models. This relatively new method, called Exploratory System Dynamics Modelling and Analysis, or ESDMA (Pruyt 2010; Pruyt et al. 2011; Pruyt and Kwakkel 2012) forms an extension to the traditional SD approach in the way that it allows exploring the effects of both structural and parametric uncertainties on the behaviour of KPIs in the explored system. By doing so, ESDMA follows suggestions from classic SD literature, e.g. the comments in Groping in the Dark by Scolnik, Cole, Rademaker and Bremer (Meadows, Richardson, and Bruckmann 1982, 149, 205, 207, 231). Thus in this case, special structures have been added to the models which allow switching between different structures about which deep uncertainty exists, apart from the different model varieties that have been built. This makes it important in the model specification to clearly distinguish which structures can be considered deeply uncertain and which possible model definitions can be made regarding these uncertainties.

2.3 EMA visualisations

Exploring the effects of deep uncertainties requires many runs to adequately cover the uncertainty space. This large amount of runs can be visualised in a way which is close to the traditional one-line base case visualisation, by plotting all runs in one figure. The result, the lines graph, can be seen in Figure 1. Since the distribution of the lines over the different states gives valuable information as well, a Kernel Density Estimation (KDE) (Rosenblatt 1956; Parzen 1962) of the end state is added at the right side of the picture. This distribution however does not allow probabilistic interpretation, since uniform distributions and cardinal switches were used as inputs for Latin Hypercube sampling (Iman, Campbell, and Helton 1981).

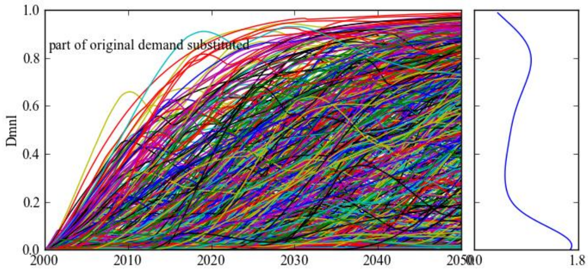

Figure 1: Lines graph with KDE for *part of original demand substituted*

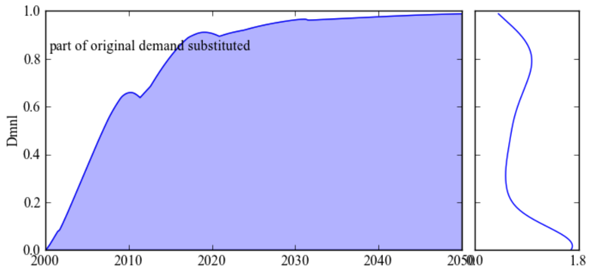

Figure 2: Envelope graph with KDE for *part of original demand substituted*

In cases where the extreme values are important for interpretation, the outer limits of the run ensemble are most important. For that purpose, the ensemble figure was developed (Figure 2). Combined with the KDE, it gives also a clear overview of the effectiveness of policies over the ensemble of runs (e.g. see Figure 15).

Since in many cases the distribution of runs is important for other states than the end state, a visualisation was needed that allows examining the distribution of runs for all time steps. For this purpose, on the x-y-plane used for the lines or envelopes graph, the distribution is given in the third dimension. This generates the picture visible in Figure 3. By rotating this image (Figure 4), the distribution of the ensemble becomes clearer visible. The 3D envelopes are often truncated to reduce the effect extreme values have on the visibility of the ensemble.

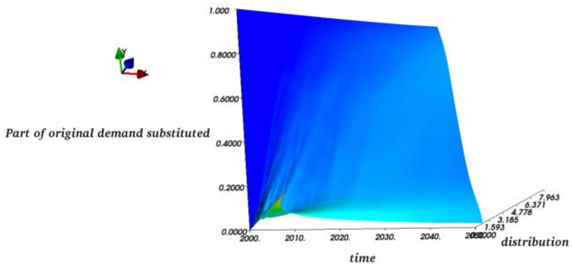

Figure 3: 3D envelopes, y axis and x axis as in 2D graph, while z axis with distribution is towards the viewer

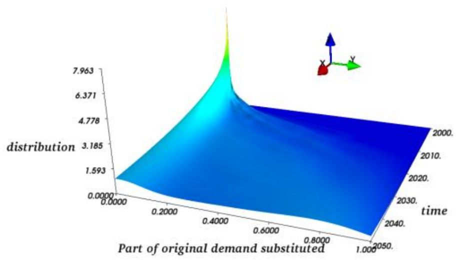

Figure 4: 3D envelopes, rotated. The x axis is from back to front, the y axis from left to right, and the z axis with the distribution from standing on this plane

For further interpretation of the data, machine learning algorithms, like the Patient Rule Induction (PRIM) (Friedman and Fisher 1999), Random Forests (Breiman 2001) and clustering the behaviour could be used on the ESDMA data. These will provide more insight in the ranges in which combinations of uncertainties cause certain behaviour.

3 Modelling the copper system

Parts of the structure of the copper system are, as was already described above, well documented, while other parts of the system are deeply uncertain. In order to develop an ensemble of models that can explore these deep uncertainties, first the major deep uncertainties in the copper system have to be identified (Table 1), for their specification will have a profound influence on the behaviour exhibited by the KPI's in the copper models. Some of these deep uncertainties are composed of elements which are each a separate deep uncertainty. An example is the demand evolution from a top down approach. This is composed of scenarios for the global population (UNPD 2011), economic growth and the relation between copper demand and the GDP per capita (Wouters and Bol 2009, 18).

Table 1: Major deep uncertainties in the copper system

Uncertainty	Type of uncertainty	Description
Demand evolution	Structural uncertainty	The intrinsic demand for copper, i.e. the demand without effects due to price and substitution
Ore grade evolution	Structural uncertainty	The ore grade declines with mining of copper
Price of energy evolution	(Dynamic) parametric uncertainty	The price of the energy needed for copper production
Prices of substitutes evolution	(Dynamic) parametric uncertainty	The evolution of the price for substitutes for copper use
Economic growth	(Dynamic) parametric uncertainty	The growth of the GDP globally or regionally
Resources/resource base	Structural uncertainty	What amount of copper is ultimately recoverable from the earth's crust
Capacity evolution	Structural uncertainty	The capacity for (deep sea) mines, smelters and refineries

Copper supply and demand can be conceptualised along two important perspectives, being the different uses for copper (Angerer et al. 2010) and the strongly regionalised mining, refining and consumption of copper (ICSG 2010). For both perspectives a higher and lower aggregate view of the system are chosen, since models designed from these views can potentially produce quite diverse behaviours. Therefore, in this study four different model varieties are possible (Table 2). The dynamic hypothesis is thus that these different models will generate partially different behaviour, thus expanding the set of plausible scenarios for the future of the copper system.

Table 2: Matrix of the copper models. Below each model name the corresponding number of model uncertainties is given.

<table>
<tr><th colspan="2" rowspan="2">Dimension</th><th colspan="2">Regions</th></tr>
<tr><th>1</th><th>3</th></tr>
<tr><td rowspan="4">Uses</td><td rowspan="2">1</td><td>Top down</td><td>Regional</td></tr>
<tr><td>112</td><td>178</td></tr>
<tr><td rowspan="2">6</td><td>Bottom up</td><td>Complete</td></tr>
<tr><td>167</td><td>341</td></tr>
</table>

The first parameter is the uses perspective, where the copper demand was conceptualised with a top down demand with a single copper use, and bottom up demand with a division in six major uses. The second parameter allows a geopolitical perspective with a global and a regionalised demand.

Together, these two dimensions result in four possible models. Out of these four, three models are discussed in this paper. For a description of these models see Appendix: model descriptions. The first variety discussed is the top down model, with a global top down perspective on the demand evolution. This model is particularly interesting to explore the consequences of the growing demand due to a growing number of people with an increasing wealth. The second model is the bottom up model, which has a globalised bottom up perspective on the demand. In the specification of this model, the effects of the energy transition on different uses of copper can be explored. In the third mode, the regional model, a regional top down perspective was chosen. This allowed looking into the effects on the system in a market which is not completely free and open. Finally, the fourth model, combining the perspectives chosen in the bottom up and regional models, was not used in this study. As is visible in Table 2, this model had a very large number of uncertainties. Besides the obvious effects this had on the computational requirements for fully exploring this uncertainty space, pinpointing the effects specific parameters have on the behaviour of the KPIs is far more difficult.

In the specification of the copper models, as far as possible information from sources describing the actual structure and functioning of the global copper supply, demand and substitution have been used, although this had as a consequence that the developed models are considerably larger than usual exploratory SD models (Pruyt 2010, 2010).

Where conflicting mental models existed about the functioning of a particular part of the system, different structures corresponding to these different views have been made to be able to explore their effects. This is in line with the approach Forrester described (Forrester 1994, 12, 13). One exception is the ore grade discussion (Tilton 2003; Gordon, Bertram, and Graedel 2007; Tilton and Lagos 2007). In the models a choice was made to explicitly let substitution influence the demand for copper and as such, via the evolution of the costs of copper mining due to the lower ore grade, influence the demand for primary (i.e. mined) copper. Technological aspects of the copper production regarding the reduction of costs due to learning effects have also been assumed to have little effect, due to the large experience in and long history of copper mining (ICSG 2010, 9).

4 Behaviour of the copper models

For each model variety, 1000 sets of input variables were generated with the Latin Hypercube sampling method (Iman, Campbell, and Helton 1981) over the uncertainty space, generating a total set of 3000 results, which will be discussed now.

4.1 Top down model results

The results from the behaviour of the top down model showed in many cases a decline of the *global consumption of copper* (Figure 5 and Figure 6). In Figure 5 the behaviour of this variable is depicted with a lines graph, while Figure 6 shows the truncated 3D envelope.

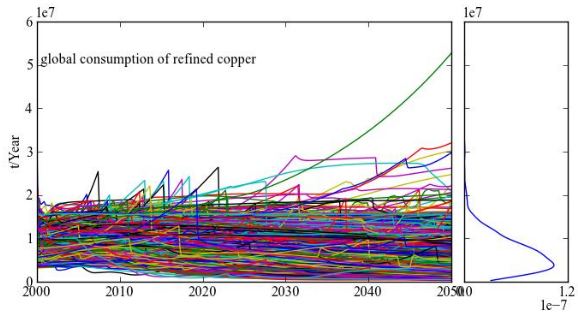

Figure 5: Run lines for global consumption of copper, top down model

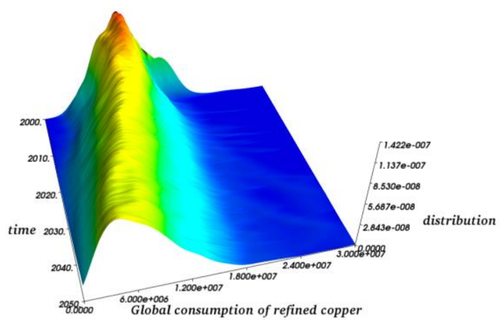

Figure 6: Distribution of global consumption of copper over time, top down model. Truncated at 30 million t/Year

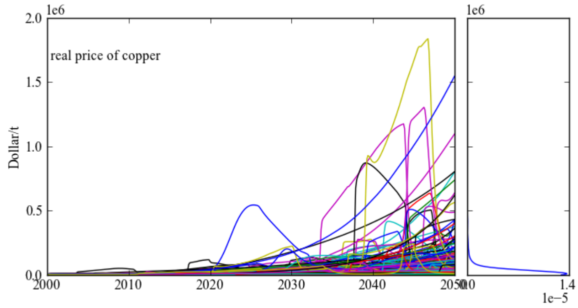

Figure 7: Run lines for real price of copper, top down model

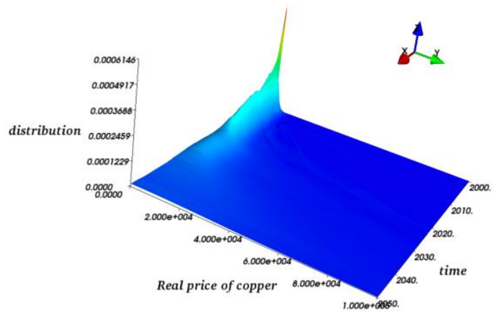

Figure 8: Distribution of real price of copper over time, top down model. Truncated at 100000 Dollar/t

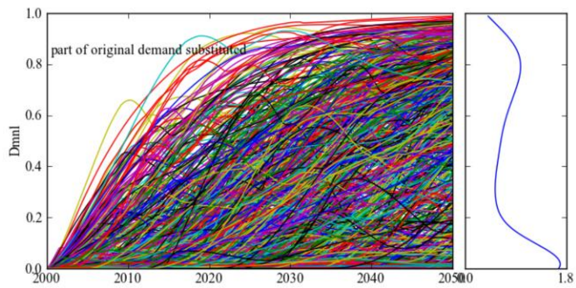

Figure 9: Run lines for part of original demand substituted, top down model

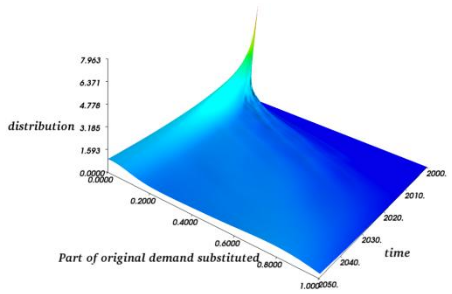

Figure 10: Distribution of *part of original demand substituted* over time, top down model

A typical characteristic of the copper consumption are the small boom and busts visible in many runs. These are caused by an increased demand in times of a low copper price, which will be limited when the *global inventories of refined copper* are declining due to this higher demand and the lower refining capacity, due to the lower prices in times of a relative high availability of the metal.

The *real price of copper* shows behaviour characterised by strong rises and declines (Figure 7). These are caused by disbalance between availability and *intrinsic global demand of copper*. The long period for adjusting the capacities for mining and refining, combined with long term effects of high and low copper prices and the substitution of copper have the biggest influence in this lack of adaptability in the copper supply system. On average, the behaviour in the runs for price is exponential growth, which is caused by the declining ore grades and consequentially the rising marginal costs. This can be seen in the lower values for the KDE in the later years of the run set (Figure 8).

Finally, the *part of original demand substituted* (Figure 9 and Figure 10) shows very strong rises in substitution, mainly caused by long term price effects. A strong rise in substitution can form the basis for a strong decline in demand, causing the copper price to collapse. This was potential copper system risk, identified already by (Rademaker and Kooroshy 2010, 3) and thus visible in the modelled copper system.

4.2 Bottom up model results

The bottom up model shows on average a higher copper consumption than the top down model (Figure 11). This indicates that the top down method for estimating copper consumption may not be accurate with regard to increases in copper demand due to the energy transition.

Another difference in the copper is the behaviour of the copper substitution. Since the *substitution threshold* is also subscripted, the substitution happens at different moments, also reducing the long term substitution effects and as a consequence, also the slopes of the *part of original demand substituted* (Figure 12).

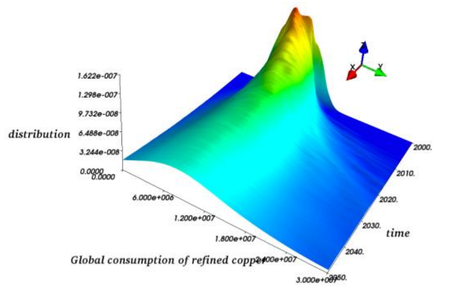

Figure 11: Distribution of *global consumption of refined copper* over time, bottom up model. Truncated at 30 million t/Year

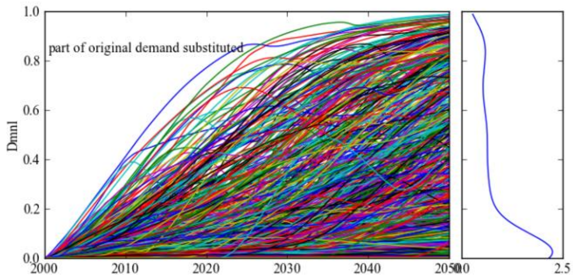

Figure 12: Run lines for *part of original demand substituted*, bottom up model

4.3 Regional model results

The behaviour of the *global consumption of refined copper* in the regional model showed even more booms and busts than the original top down model, but the declines after the copper consumption peak were often less steep (Figure 13). This different behaviour can be explained by the ex- and import of different copper products and the resulting slower reaction time of the model on copper scarcity, which develops regionally.

The regional model showed a stronger decline in copper consumption, more specific copper mining, than the other two copper models. The lower rate of *global mined copper production* depletes the reserve base, making the value of the *global reserve base of copper* divided by the mining production, in the models called *year left of copper mining*, higher (Figure 14). This figure shows after 2010 very low values for the KDE. This can thus only be caused by a strong decline in the *global mined copper production*.

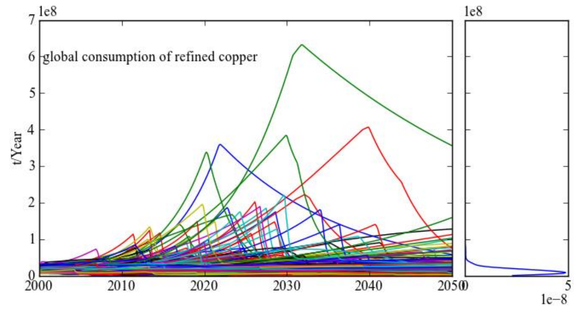

Figure 13: Run lines for *global consumption of copper*, regional model

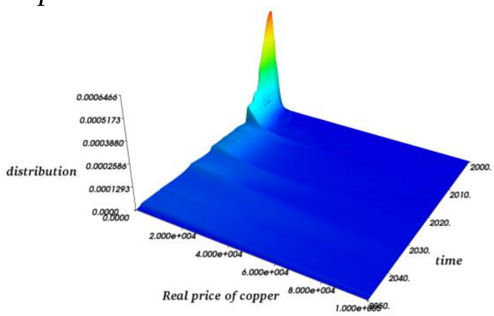

Figure 14: Distribution of *year left of copper mining* over time, regional model. Truncated at 500 year

4.4 Assessment of the outcomes

The declining copper consumption, the strong substitution effects and the volatile price development are well perceivable in the real world copper system when existing dynamics regarding the development of mine, smelter and refinery capacity in combination with dynamics of substitution and demand are taken into consideration.

The gradually declining copper consumption can be explained by the falling grade of copper ore, which is a main factor in the increase of the marginal costs of copper mining. The substitutes of copper, like aluminium, do not have this problem (Gordon et al. 1987). It is therefore very likely that copper will become more expensive compared to its substitutes in the coming period.

The strong substitution effects are most prone to exist after a longer period of high copper prices. When these high prices first occur, consumers will in the short term take their loss, while in the long term they will seek for alternatives for the high price asset. This long term effect probably generates high substitution of copper products, causing the price to drop when this reaches a certain turning point, reversing the situation. Especially with current high copper prices, this is a very likely scenario to occur.

The alternating prices cannot be explained however with the long term oscillating substitution effects alone, since in isolation these effects would have a goal seeking behaviour for the copper price in the direction of the price of the main substitute. The reactions of the demand on the price level however can cause the disbalance between supply and demand, since the demand changes in such a case faster than the delays in the form of permit terms allow the supply to adjust. In this way, price volatility is almost inevitable to occur.

Not all behaviour exhibited by the models seems valid however. The small boom and busts visible in Figure 5 were not observed in the historical data. Further the values of the *global consumption of copper* seem to be rather low compared to the estimated consumption of over 15 million tonne in 2000 and over 19 million ton in 2010 (ICSG 2010, 2011). A reason for this could be that the copper models presented here do not take into account that additional profits can be made by coproduction of other potentially high valued metals present in the ore, amongst which are gold, silver and several other metals (Verhoef, Dijkema, and Reuter 2004). Coproduction will essentially lower the marginal costs for copper, making it more competitive compared to the substitutes and thus allowing more consumption before the metal is being substituted.

5 Policy options to avoid plausible undesirable behaviour

5.1 Potential copper system risks

Despite the lack of predefined system risks by the commissioning actor of this research, it is possible to define some potentially undesirable behaviour and system risks for stakeholders from a European perspective (Table 3). These risks allow thinking about ways in which these effects can be countered by introducing policy options.

Table 3: Potential copper system risks

Nr.	Name	Criterion	Stakeholder
1	High price	Real copper price > 100000 Dollar/t	Consumers
2	Copper crisis	Change in price > factor 2 in 1/8th of a year	Consumers, producers
3	High substitution	Part of original demand substituted > 0.8	Producers, investors
4	Low R/P ratio	Year left of copper mining < 10 Year	Consumers
5	High R/P ratio	Year left of copper mining > 500 Year	Producers, investors

5.2 Policy design

For the design of policy options in an ESDMA context, roughly two approaches can be chosen. The first approach can be seen as closing the circle. The modeller selects problematic behaviour patterns, tries to find which selection of input parameters cause these behaviour , for example with the random forest method (Breiman 2001), selects those that can be influenced by policy makers, companies or investors and tries to develop policies that (combined) have the biggest impact.

The second option is having an 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". This influence needs to be developed into possible policy options.

In this research, the second method for policy design was chosen. This resulted in the policies visible in Table 4. These policies were tested on the same experimental setup as discussed in section 4. Per policy option, 1000 additional runs were performed. In the runs, the policies were tested individually, but also in four combinations. These were the recycling policies (1 and 2), substitution policies (4 and 5), strategic recycling policies (1, 2 and 3) and all policies (1 till 6). Therefore, in total 30000 runs were performed to test the policies on the three model varieties.

Table 4: 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

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

5.3 Results of the policy options

As a result of the recycling policies, it was possible to increase the *global consumption of refined copper* (Figure 15 and Figure 16). The combination of these policies with the strategic reserve policy even further amplified this effect, while the other policies did not add much to this reduction of unwanted behaviour. The combination of all policies finally also has a positive effect on the crisis behaviour visible in the *real price of copper* (Figure 17).

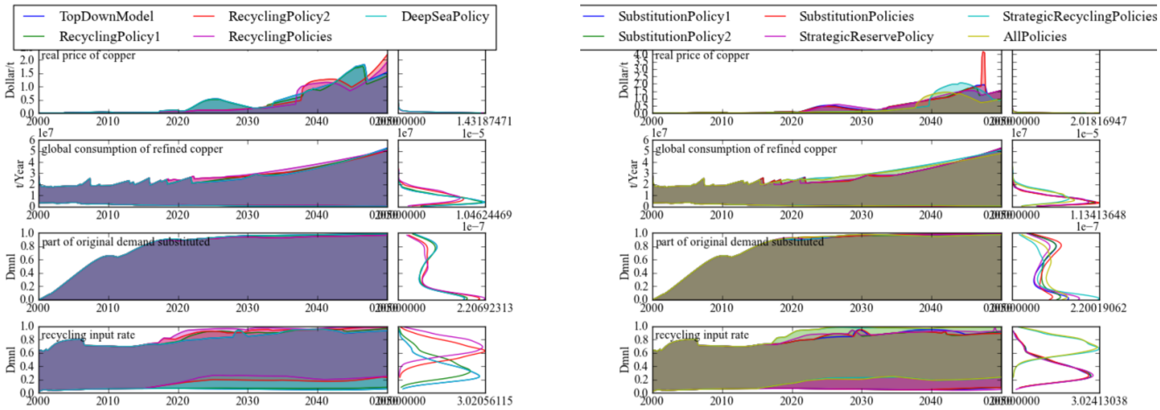

Figure 15: Envelopes for different system performance indicators and all policy options and combinations, top down model

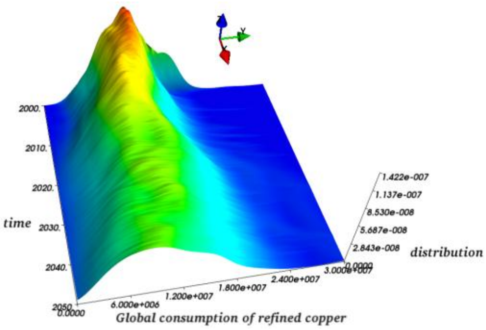

Figure 16: Global consumption of refined copper, top down model with recycling policies

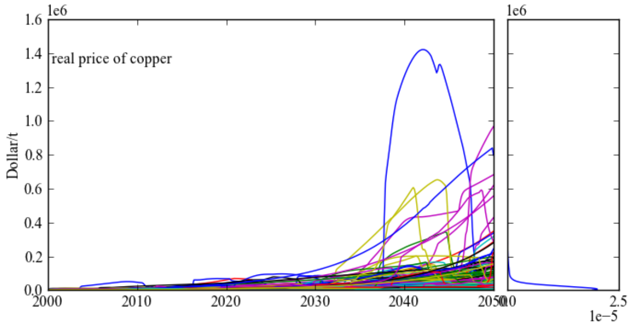

Figure 17: Real price of copper, top down model with all policies

The other policies, more in particular the two substitution policies and the deep sea policy did not seem to have a positive effect in reducing unwanted behaviour in the copper system. The policies showed similar behaviour in the other model varieties.

6 Conclusions and discussion

The global copper system is, besides being well documented on the supply side, heavily influenced by deep uncertainties. In order to explore the effects these uncertainties have on the behaviour of the copper system, three model varieties were built. All models showed scenarios with on average rising copper prices, which however are characterised often by large periodic fluctuations. The high average price levels can however, also with periodic fluctuations, cause substitution on large scale of the use of copper. When all run data is taken together, this will create an image of a decreasing demand of copper in the coming 40 years.

Although the copper models all showed these general conclusions, some distinct differences in behaviour between the different model varieties were distinguishable. The top down model often showed crisis like behaviour, due to a very fast substitution of copper demand. In the other models, substitution behaviour showed less intensity. This is probably due to the fact that when the effects of different uses and regions are strong, substitution of all uses or in all regions will not happen synchronous. Further, it was visible that the demand growth as modelled in the bottom up model was bigger than the effect solely due to the emerging economies, which also resulted in higher prices for copper. Finally, the regional model showed longer periods for the fluctuations in model behaviour. This is probably due to the slower reactions in the system in the case of less transparency in the system.

Several policy options were tested over the set of scenarios generated by the three model varieties. This resulted in the observation that especially improving the collection rate of end-of-life copper products, the recycling efficiency rate and the counter cyclic investment in strategic reserves showed effectiveness in countering undesirable behaviour in the copper system.

By combining the methodologies EMA and SD in an ESDMA research, it was possible to explore a wide variety of different scenarios for the copper system. Creating three model varieties highlighting different perspectives on the copper system enriched this set of scenarios and added extra insights on the effects of the growing demand from the upcoming economies, the energy transition and the effects of a less transparent copper market which would not have been possible without using this extensive methodology.

An extra remark needs to be made regarding the size of the models. While modelling, an explicit aim was to keep a connection between the terms used in literature regarding the copper system and the terms used in the copper models. This resulted in a relative low aggregation level, especially when compared to other ESDMA studies (see for example Pruyt 2010). While this may have added to the validity of the model structure, it also posed problem in exploring the uncertainty space created by the models. It was therefore with these large models not possible to fully explore all possible behaviour. Further, it was also more difficult to pinpoint certain behaviour to specific parameters in the models.

Future research that builds on the experiences from this study are possible both on the topic of modelling the copper system and a more extensive use of ESDMA. For building the copper models some input from experts was used, but this could have been extended. This could have added to the validity of the models and the interpretation of the outcomes. For the outcomes, it is interesting to use clustering algorithms on the scenarios generated by the copper models. This would create more insight in the different dynamics visible in the results and the drivers of this behaviour. Finally, adding more adaptive policy design working on these drivers could make it possible to counter undesirable effects in the copper system in a more robust way.

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A Appendix: model descriptions

A.1 Top down model

The smallest of the models in this study is the copper model with top down demand (Gordon, Betram, and Graedel 2006). This intrinsic demand is calculated by looking at the development of the *world population*, the *GDP per capita* and the *effect of GDP on copper demand*. A conceptualisation is visible in the causal loop diagram (CLD. Sterman 2000; Lane 2008) of Figure 18. In this figure, three important balancing feedback loops can be distinguished: the supply, demand and substitution loop. Major external uncertain influences (compare Table 1) are coloured pink.

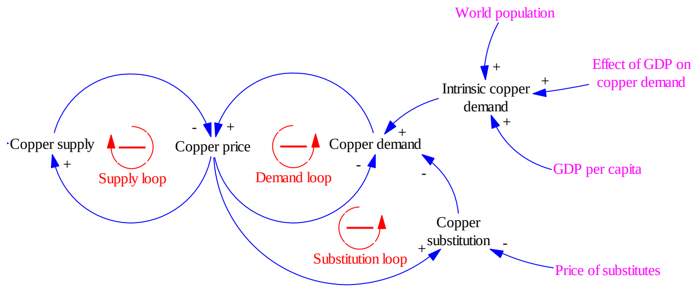

Figure 18: Simple CLD of the top down copper model

A.1.1 Copper stocks

The copper stocks sub model (Figure 20) forms a well-documented, possibly even the best documented part of system (Lossin 2005; ICSG 2010). This sub model contains a stock flow structure from resource base, resources, reserve base via mining and refining to the *global consumption of refined copper* to copper use. When *global copper in use* has reached the end of its lifetime, it is partially collected via the *global secondary copper to scrap* and recycled in *copper recovered from scrap.* These stocks and flows outline the physical and technical backbone of the system.

As was mentioned above, some discussion exists about the relevance of the resource base for the availability of copper in relation with the development of the ore grade of copper (Tilton and Lagos 2007; Gordon, Bertram, and Graedel 2007). In this research the assumption is made that the price of copper, which is in the basis defined by the amount of energy needed to mine and the price of energy, ultimately defines how much copper can be mined. Hence Tilton and Lagos are followed in that respect.

<table>
<tr><td rowspan="3"></td><td colspan="3">Identified resources</td><td colspan="2">Undiscovered resources</td></tr>
<tr><td colspan="2">Demonstrated</td><td rowspan="2">Inferred</td><td colspan="2">Probability range</td></tr>
<tr><td>Measured</td><td>Indicated</td><td>Hypothetical</td><td>Speculative</td></tr>
<tr><td>Economic</td><td colspan="2" rowspan="3">Reserve Base</td><td rowspan="3">Inferred Reserve Base</td><td colspan="2" rowspan="3">Resources</td></tr>
<tr><td>Marginally economic</td></tr>
<tr><td>Sub-Economic</td></tr>
<tr><td>Other occurrences</td><td colspan="5">Resource base</td></tr>
</table>

Figure 19: Relation between reserves and resources. Based on the McKelvey Box (McKelvey 1973)

The structure of resources and reserves further largely follows the McKelvey classification box (McKelvey 1973), which is visible in Figure 19, but some simplifications have been made with regard to official classification rules like the JORC code (JORC 2004). First, this model makes no difference between the reserve base and the reserves of copper. The difference between these two concepts is defined by the cut off ore grade, which is the lowest ore grade that can be mined with the current copper price. This makes it possible to model the system without an explicit cut of grade for copper ore. The second difference is the simplification of the relation between resource base and resources, which is here strictly economical and the relation between resources and reserve base, which happens here by semi-autonomous findings (and classifications) of the independent exploration or junior companies. The performance indicator *year left of copper mining* is therefore not calculated by using the reserves, but the reserve base divided by the *global mined copper production.*

This model allows deep sea mining to develop, if the *marginal costs of copper* are higher than the *marginal costs deep sea copper*. The performance indicator *relative part of deep sea mining* is calculated by dividing the *deep sea mining production* by the sum of *deep sea mining production* and the *global mined copper production*.

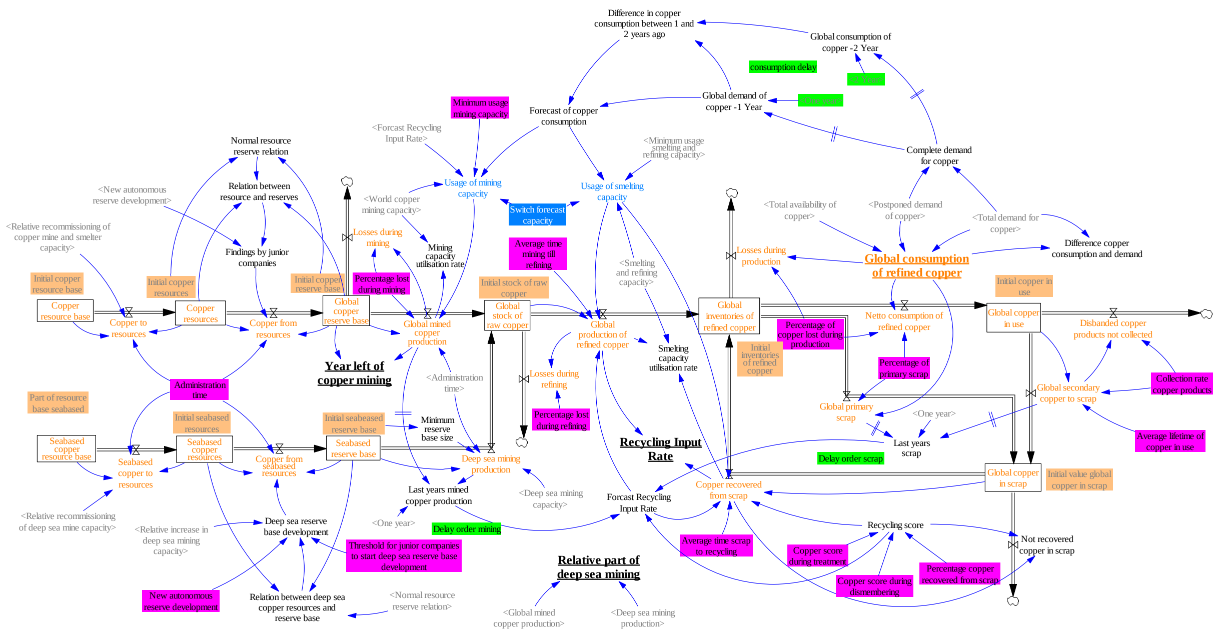

Figure 20: Copper stocks view in the top down model

The amount of copper mined or refined is dependent on the capacities from the mine, smelting and refinery capacity sub model and possibly by a forecast of the copper demand. The *global consumption of refined copper* is mainly determined in the *total demand for copper* from the copper demand sub model and the availability of copper, which is dependent on the *global inventories of refined copper*.

The inflow in this last stock is formed by two flows, the primary copper or *global production of refined copper* and the secondary copper or *copper recovered from scrap*. The relation between these two, more particular the relation between *copper recovered from scrap* and the sum of the *global production of copper* and the *copper recovered from scrap*, form the performance indicator *Recycling Input Rate* (RIR).

A.1.2 Mine, smelting and refinery capacity

The sub model Mine, smelting and refinery capacity is visible in Figure 21. This figure contains the structures which determine growth and decline of the *world copper mining capacity*, the *smelting and refining capacity* and the *deep sea mining capacity*.

For all three capacities a similar structure was used, which makes use of three possible states for the capacity. This structure resembles the two state structure used by Pruyt (Pruyt 2010, 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 for example the mining capacity, from the state *Mining capacity in preparation* to the *World copper mining capacity*, uses a delay structure with uncertain order:

Growth mining capacity =
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 the *mining capacity in preparation*. 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.

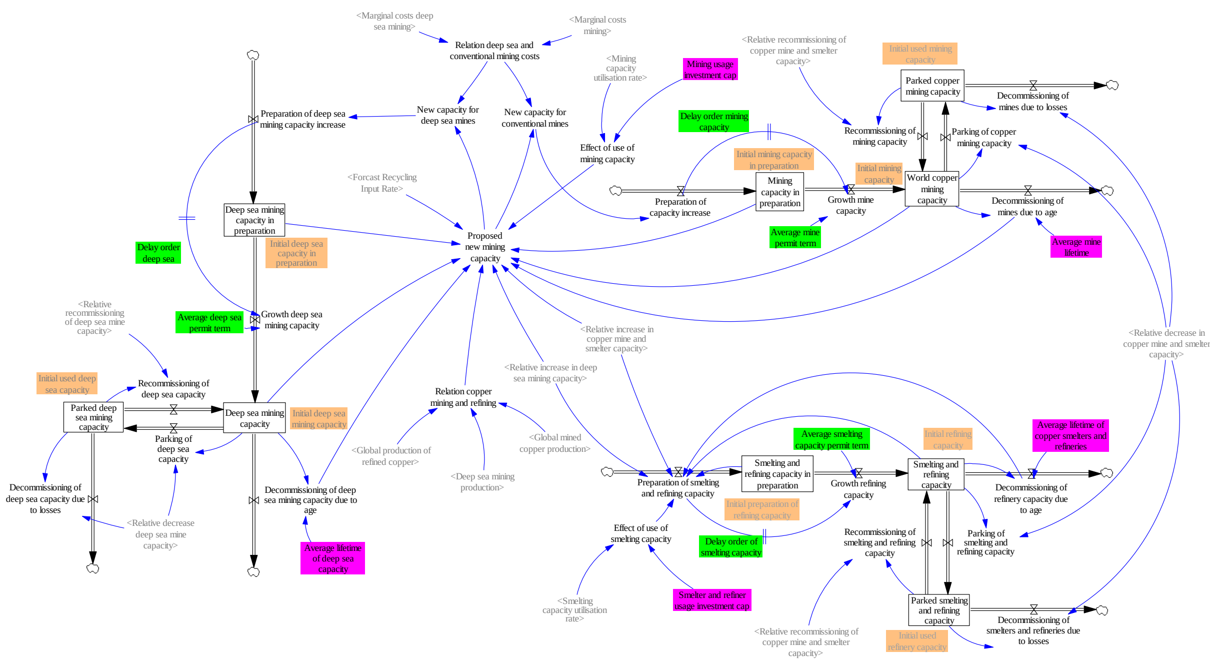

Figure 21: Mine, smelting and refinery capacity view in the top down model

No separate capacity for the recycling is modelled, since in the real world copper system the recycling happens with smelter and refinery capacity, as is demonstrated by the data of the ICSG (ICSG 2010, 2011). The *smelting and refinery capacity* is thus bigger than the *world copper mining capacity*. In the copper stocks sub model, the *forecast recycling input rate* is used to divide the refinery capacity between the flows of primary (mined) and secondary (recycled) copper.

A.1.3 Copper demand

In the copper demand sub model (Figure 22), the *total demand for copper* is modelled by influences caused by developments in the *intrinsic global demand for copper*, the *total availability of copper* and the *relation between copper and aluminium price*, which is assumed to be representative for all copper substitutes.

Calculating the effects of these developments starts by comparing each element with its relevant counterpart to calculate their relation. These are intrinsic demand (A) and availability (B) for the copper price, price of copper (A) with the price of aluminium (B) for the substitution and finally the intrinsic demand with the demand (A) and substituted demand (B) for the effect of the intrinsic demand. The formulas are of the form:

Relation = (A / B) ^ 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.

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):

Effect = 1 – 2 ^ (1 – Relation)

The values for effect are between -1 for Relation = 0, 0 for Relation = 1 and 1 for Relation = ∞. 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 de- or increase in demand, since all three relations are comparable to next equation for the *loss in demand due to price elasticity*:

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.

The intrinsic demand is, as was already explained in section A.1, dependent on the *average global GDP per capita* and the *copper use related to GDP*. The GDP per capita is modelled by a typical ESDMA structure for random economic growth, which is formed by six super positioned sinuses, for which the amplitudes and periods are set in the python shell. For the world population the four different scenarios of the United Nations were used (UNPD 2011). For the *copper use related to GDP* also four distinct lookup functions were used, which roughly represent the ideas presented in (Wouters and Bol 2009, 18).

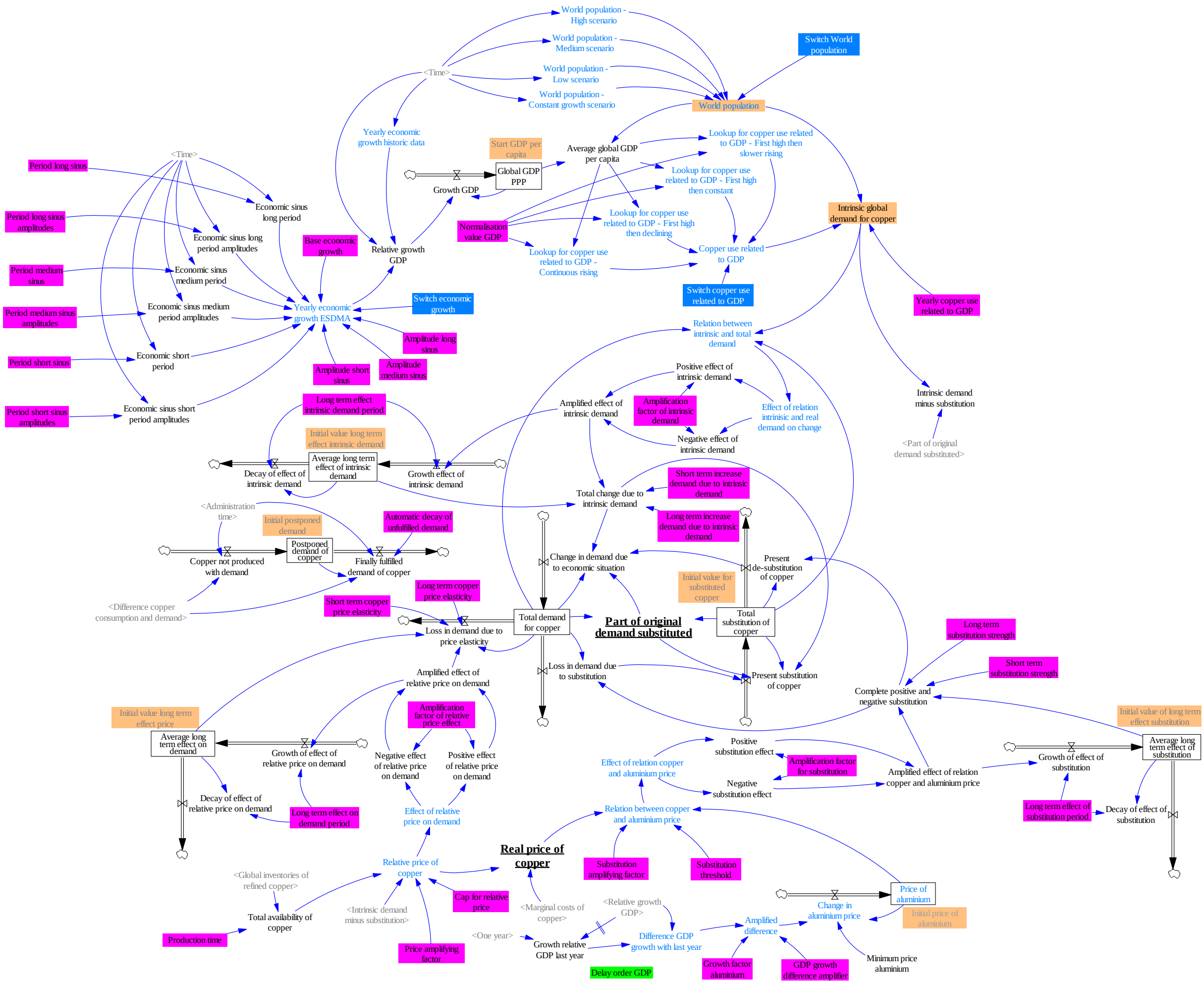

Figure 22: Copper demand view in the top down model

Substitution of copper demand takes place when the *real price of copper* (Svedberg and Tilton 2006), which is equal to the *marginal costs of copper* when *intrinsic global demand for copper* and *total availability of copper* balance, is at such an amount that it is cheaper to use the substitute than the original resource. This is modelled by using a *substitution 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.

Relation between copper and aluminium price =
(*Real price of copper* / (*Substitution threshold* * *Price of aluminium*)) ^ *Substitution amplifying factor*

The method of modelling different uses is by changing the threshold value (Gordon et al. 1987, 66, 67). This assumes a similar price development of the different substitutes.

The two-stock structure for substitution, which is based on the one-stock-structure of E. Pruyt (2010, 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.

A.1.4 Economics of copper

Finally, in the sub model economics of copper (Figure 23, the *marginal costs of copper* and *marginal costs deep sea copper* are calculated and with these values and the potential profit due to the *real price of copper*, the in- and decreases of the capacities described in section A.1.2.

Both marginal costs are calculated by looking at the *cumulative mined copper* and an ore grade which corresponds to that amount. For any particular ore grade a certain amount of energy is needed, which, together with some other cost factors, determines the marginal costs.

The marginal costs are compared to the copper price by either a forecast value, calculated with the first and second order derivatives, or the present costs and price. In a similar manner as used for the effects on the demand, the potential profit has both direct and long term effects on the development of new capacities.

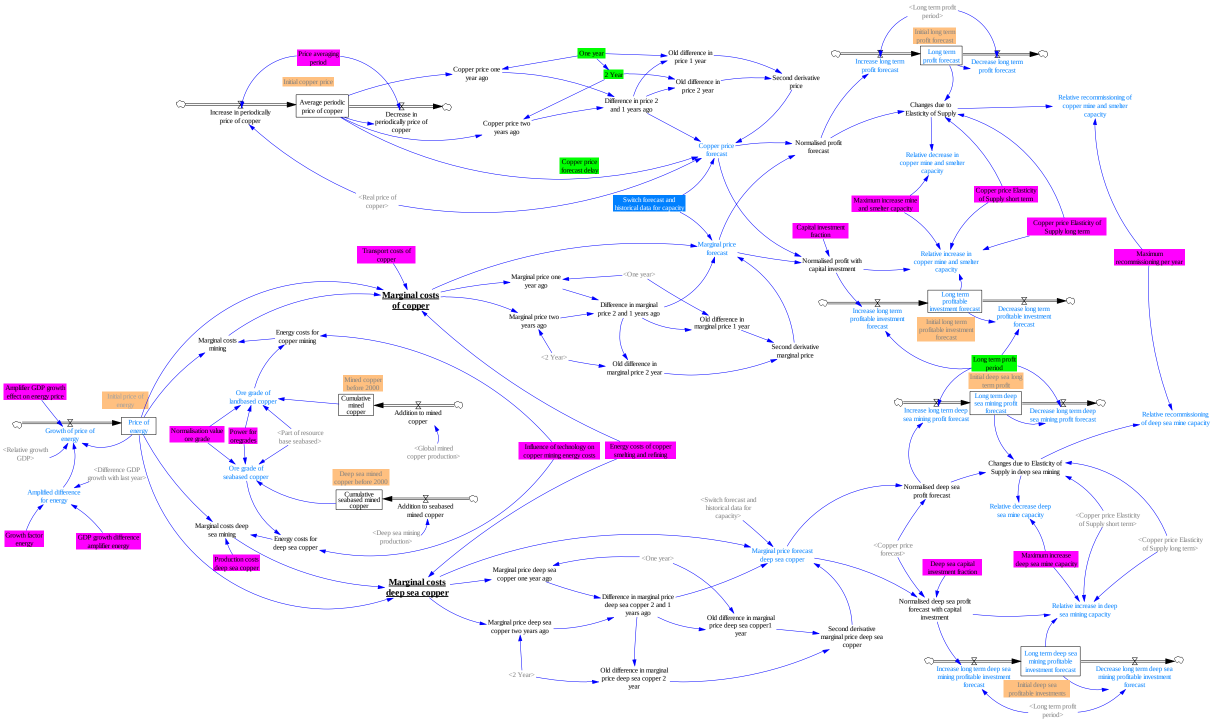

Figure 23: Economics of copper view in the top down model

A.2 Bottom up model

In the bottom up model, the intrinsic demand is calculated by looking at the (quasi) autonomous increase in demand for separate uses of copper (Figure 24). These different uses are modelled (Angerer et al. 2010) as subscripts of relevant elements which are further similar to the top down model. The substitution is also dependent on the *substitution possibilities* and the *price of substitutes*.

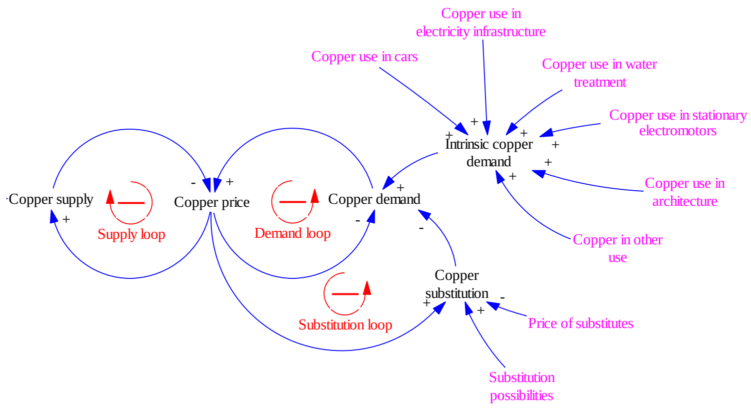

Figure 24: Simple CLD of the bottom up copper model

A.2.1 Differences with the top down model

In the bottom up demand are due to the differences explained earlier in this section, some alternative structures modelled for the six different uses of copper visible in Figure 24. For this purpose, all variables related to the use of copper are subscripted, just as the *total demand for copper* and the rates to and from this stock and the substitution threshold values. The different uses thus have different points at which substitution starts. These differences are therefore mainly found in the sub models copper stocks and copper demand. Further, an extra sub model was added for modelling the autonomous increases for the different uses, the sub model bottom up demand.

A.2.2 Bottom up demand

In this sub model (Figure 25) the different major uses of copper, categorised in the same way as presented in (Angerer et al. 2010), are modelled. 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 form input for the bottom up model.

The “dominance” and “pluralism” scenarios of electric vehicles for the automotive industry, developed by the Fraunhofer ISI, have been used for the automotive sector (Angerer et al. 2010, 18, 19). These scenarios regard the relative part of new cars build 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).

With these embedded scenarios the model gives the opportunity to research the feasibility of these scenarios from a copper availability perspective. Another option is that substitution of copper will limit the amount of copper needed to make this world view possible.

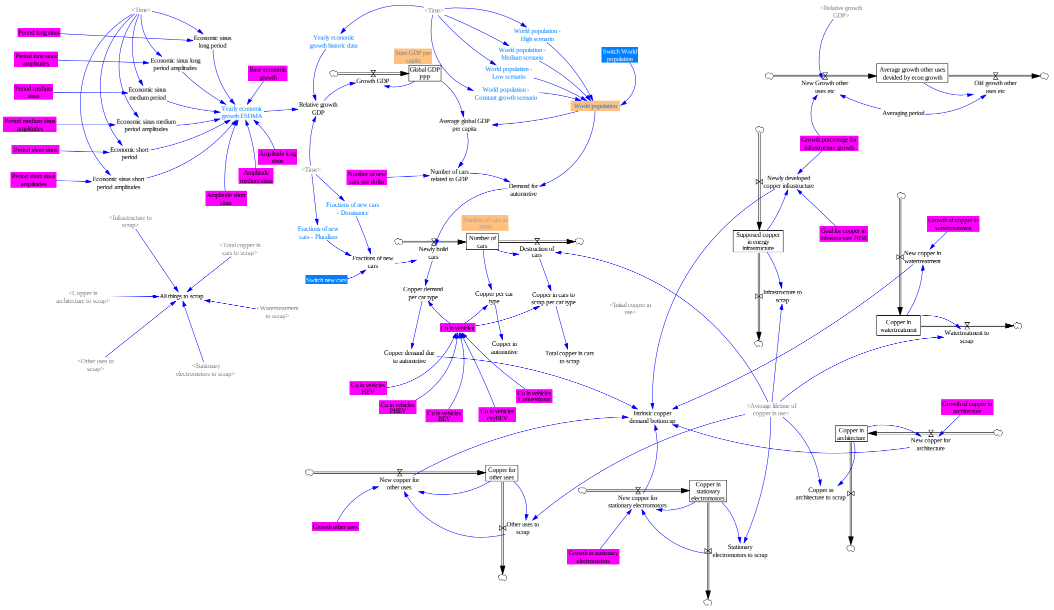

Figure 25: Bottom up demand view in the bottom up model

A.3 Regional model

Finally, the regional model (Figure 26), which uses the top down approach for the intrinsic demand, tries to shed more light on the geopolitical sides of the copper system. The regions have a resource dependant and not necessarily topographical division. Region 1 has most money (the developed world), region 2 has the largest population (the upcoming economies) and region 3 has most resources (the rest). This difference is also reached by subscripting the relevant variables, which in this case of course also contains the supply variables.

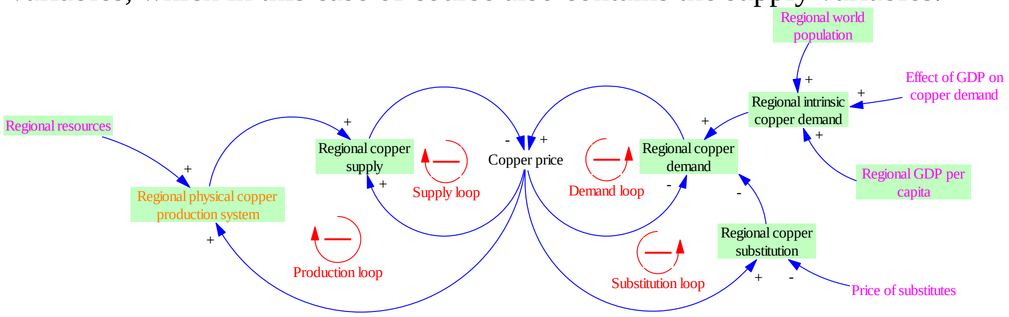

Figure 26: Simple CLD of the top down copper model. All variables with a light green background are regionalised

A.3.1 Differences with the top down model

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 2011).

In this model, just like in the bottom up model, the relevant variables have been subscripted. In this case, these are all physical copper flows (the orange variables in Figure 27), the capacities in the mine, smelting and refinery capacity sub model, the (intrinsic) demand variables (including the economic situation and the population scenarios) in the copper demand sub model and finally the marginal costs and everything related in the economics of copper sub model. Another change is the presence of flow for import and export of different copper fabricates. The values for these flows are calculated in the copper transport sub model discussed in next section.

Deep sea mining is 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, this is the moment to bring in the regional division. The regional "preference" to develop deep sea mining, is linked to the *regional GDP per capita*, since this can be considered an indicator for development.

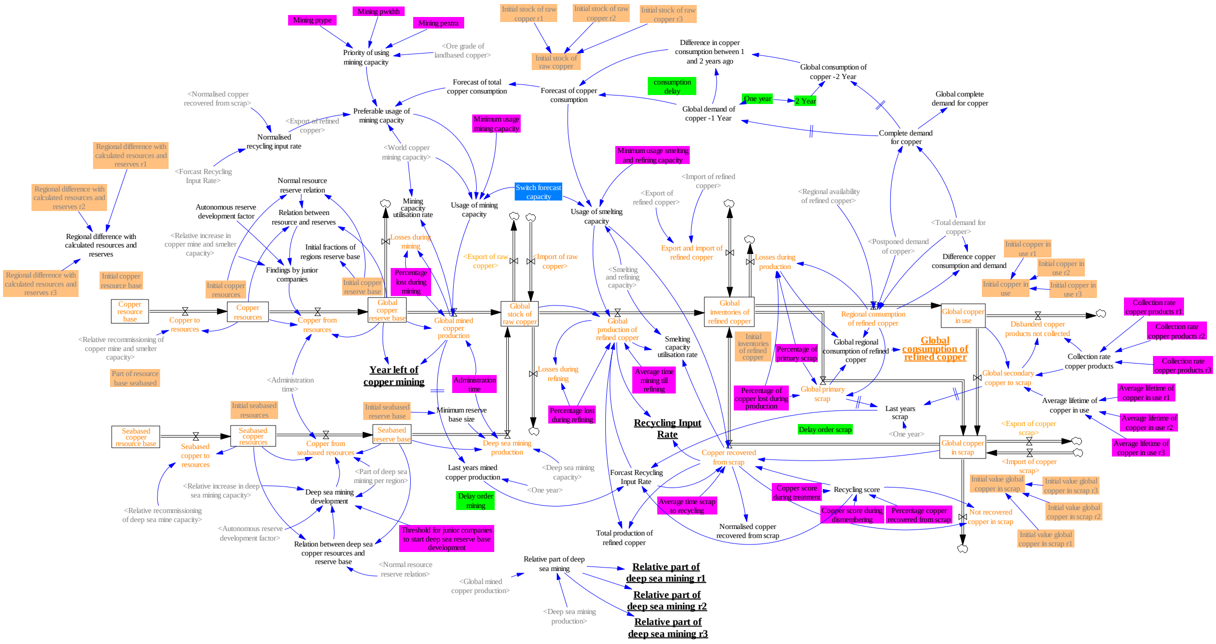

Figure 27: Copper stocks view in the regional model

A.3.2 Copper transport

Import and export of copper products is modelled in the copper transport sub model (Figure 28). This happens by calculating the *regional surplus and deficit for raw copper*, the *regional surplus and deficit for copper scrap* and the *regional surplus and deficit for refined copper*. Regional surpluses are exported to regions with deficits. Both the exports and imports are allocated by looking at the *regional GDP per capita*, where export is allocated from regions with a lower GDP per capita and import to regions with a higher GDP per capita.

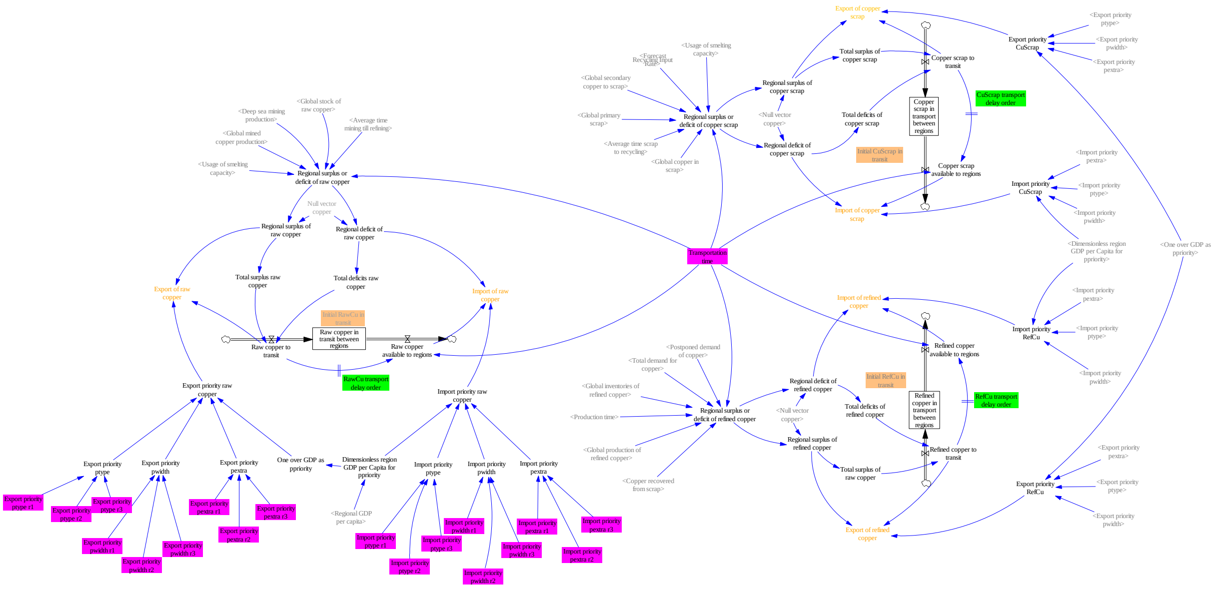

Figure 28: Copper transport view in the regional model