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On the long-term sustainability of copper, zinc and lead supply, using a system dynamics model

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ABSTRACT

The long-term supply sustainability of copper, zinc and lead was assessed. Copper will not run into physcal scarcity in the future, but increased demand and decreased resource quality will cause significant price increases. The copper price is suggested to increase significantly in the coming decades. A similar situation applies for zinc and lead with soft scarcity and increased prices for zinc. The total supply of copper reaches a maximum 2030–2045, zinc 2030–2050 and lead 2025-2030. The copper supply per person and year and decline after 2130, and the copper stock-in-use reaches a maximum in 2050 and decline afterwards. The zinc supply per person per year reach a maximum in 2100 and decline after 2100, and the zinc stock-in use shows a similar pattern. The lead supply per person reach a plateau in 1985, and decline after 2070, whereas the lead stock-in-use reach a plateau in 2080 and decline after 2100. For copper, zinc and lead, scarcity will mainly be manifested as increased metal price, with feedbacks on demand. The predicted price increase will cause recycling to increase in the future. The supply situation for copper would be much improved if the recycling of copper could be strongly promoted through policy means, as well as it would work well to limit the price increases predicted under business-as-usual. Considering the importance of these metals for society, it is essential to set adequate policies for resource efficiency and resource conservation for society.

1. Introduction

Copper, zinc and lead are among the most essential metals used in society. At present there are no really good substitutes for copper, zinc nor lead available, considering their specific technical and chemical properties (silver can substitute for copper in some cases, lead can substitute for zinc in some cases, lithium can substitute lead in a few cases). When the substitutes are produced in smaller volumes that what they should substitute for, the substitution will not work (Ragnarsdottir et al., 2017). All metals exist in finite reserves and resources on Earth and a pertinent question is whether this may become a problem for availability in the long run. The issue has been discussed in a number of publications (Heinberg, 2001; Johnson et al., 2007; Graedel et al., 2011; Rauch and Graedel, 2007; Norgate and Rankin, 2000, 2002a,b, Graedel and Erdmann, 2012; Bardi, 2013; Grandell and Thorenz, 2014, Goe and Gaustad, 2014).

We are not the first to be concerned about the global sufficiency of these metals; this was assessed in different ways in a number of studies: Meadows et al. (1972, 1974, 1992, 2004), and more recently by Gordon et al. (2006); Heinberg (2001, 2008, 2011), Laherrere (2010); Morrigan, 2010; Bardi (2013); Northey et al. (2014); Ragnarsdottir et al. (2012) and Sverdrup and Ragnarsdottir (2014). These studies presented different types of metal supply assessments and expressed worries about a potential scarcity or future peak in production. Further assessments are found in reports by the International Resource Panel (UNEP, 2011a, b, 2013a,b,c). The technology metals indium, bismuth, germanium, gallium, tellurium, cadmium, selenium, antimony, silver, and cobalt are all supplied fully or partly as dependent by-products of copper, zinc and lead primary extraction from poly-metallic ores.

The earlier sustainability assessment studies (Meadows et al. (1972, 1974, 1992, 2004, Gordon et al., 2006; Heinberg, 2001, 2008, 2011, Laherrere, 2010; Morrigan, 2010; Bardi, 2013; Northey et al. (2014); Ragnarsdottir et al., 2012) have used different types of simplified methods, this was recently criticized by Arndt et al. (2017) and Sverdrup and Ragnarsdottir (2014). We now have an opportunity to test this, by making an assessment where lot of those factors mentioned as missing (Sverdrup and Ragnarsdottir, 2014) has been included; market mechanisms, resource estimates taking into account latest research and discoveries, technological developments, feedbacks from the economy, from other sectors. In addition, a new and better resource size

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assessment was made to counter the criticizm bye Arndt et al. (2017), but this is too large for a supplement and will be published separately.

2. Background

2.1. Defining scarcity

We assess scarcity according to the following definition: Soft scarcity is when demand is reduced because of a high price. Hard scarcity is when the price modified demand cannot be satisfied, there is a shortfall in supply. Soft scarcity is frequently occurring for many commodities, and soft scarcity is well handled by society without major disruptions. For example, what we have experienced with cobalt, i.e. after the price spike around 1980, use of substitutes increased and the demand reduced (gold; Sverdrup et al., 2013a, 2013b, cobalt; Sverdrup and Ragnarsdottir, 2016a; Holmes, 2018, platinum; Sverdrup and Ragnarsdottir, 2016b, rhenium Sverdrup et al., 2018a, 2018b, 2018c). Further commodities that have experienced physical scarcity during short intervals are substances like antibiotics, vaccines, or rare blood types. For blood banks the major effect of soft scarcity is less demand. The precious metals gold, silver, platinum, palladium, rhodium, iridium, ruthenium or rhenium are all examples of metals that are in soft scarcity as the normal state of affairs. Hard scarcity is less well handled by markets (Kennedy, 1976, Greer, 2008, Heinberg, 2011), nor by society (Zhang et al., 2007) and normally lead to larger or smaller disruptions. Hard economic scarcity is when the commodity is available, but the business or citizen lacks the disposable income to purchase any significant amount.

2.2. Defining the key scarcity indicator metrics

Earlier, resource scarcity has been evaluated from burn-off times (the extractable reserves divided by the present extraction, or alternatively ultimately recoverable reserves divided by present extraction. Another approach has been bulk supply rate versus time graphs (ton per year plotted versus time). These are crude assessment tools. The outputs span times from now and several decades or centuries into the future, where both demands and population can be expected to change. In simple mass flow analysis, then most feedbacks will be missing.

Integrated systems modelling of supply dynamics in changing societies, estimating metal provision per capita per year and stocks-in-use per capita over time is what is required for an assessment. In this study, we use the integrated system dynamics model, WORLD6 as the simulation platform. Fully dynamic integrated system dynamics models do include; change in supply, change in demand, change in price, change in production rates, change in population, change in recycling, change in use efficiency, and all are linked. Supply is composed of both primary production, secondary extraction as a by-product of the production of other metals and recycling of used material. From mass balance, we have that the supply is equal to the production plus recycling. This is the same accumulation in the system plus recycling plus losses. Note carefully that recycling appears on both sides. It can mathematically be cancelled out of the equation. It expands the total flux going through the system, without demanding new primary material to be added. Recycling rates could be considerably increased for many metals based on governmental policies, but those policies need to be set in place (Sverdrup et al., 2017a). With increased talk about "circular economy", it may be expected that a greater policy focus on this matter will be in place in the future. For assessment of soft and hard physical scarcity in the WORLD6 model, we suggest two metrics for indicating if we have a scarcity or not: (1) Actual supply per person per year (kg per person^{-1} year^{-1}) and (2) Actual stocks-in-use per person (kg per person^{-1} year^{-1}). Supply per person per year is serving maintenance of stocks-in-use and the surplus over the maintenance will determine how much is left for growth or if a material contraction will occur. Stocks-in-use are a measure of the present utility of the resource. A decrease in stocks-in-use which is not paralleled by a substitute that increases, will be an indicator of reduced service provision. Definitions of hard economic scarcity will be assessed in a later study. It will require a systemic discussion of the systemic aspects of poverty and fundamental wealth distributions mechanisms of society. Strategic scarcity is a result of making evaluations for longer periods of time. Typically, the demand is integrated over a longer period of years.

2.3. Earlier modelling work

There have been several earlier attempts at modelling copper extraction rates. Roper (2009) used empirical Hubbert-like functions for assessing copper, zinc and lead mining rates and estimated when the production would peak. Roper (2009) used low reserve estimates based on the USGS, ignoring hidden resources and the peaks were predicted to come far too early. van Vuuren et al. (1999) outlined the principles of a model for global metal cycling, looking at copper. Glöser et al. (2013a, 2013b) applied a mass and flows model to the global copper cycle. Northey et al. (2014) and Mohr et al. (2014) used a Mass Flow Analysis model for copper, reaching results similar to some of the results obtained out earlier modelling study, they used a relatively low estimate for the ultimately extractable amount. Common for Mass Flow Analysis models are that they are quite simplified models, they do not incorporate feedbacks, nor do they have any market dynamics and cannot generate metal prices internally to the models. Laherrere (2010) used Hubbert's model for copper, but used a too small resource estimate for the assessment. There is no earlier process-oriented fully integrated systems dynamics model for copper, zinc or lead known to us. We have earlier used simple back-of-the-envelope methods like burn-off rates, but these methods only give a diagnostic indication of potential problems. Earlier, we have developed simple stand-alone system dynamics models for gold, silver, copper, aluminium, iron, lithium and platinum group metals (Sverdrup et al., 2012, 2014a,2014b, 2015a,b,c, 2016a,2016b). In these models, one of the major advances were the development of a reality-based metal price model, allowing for price estimation from market fundamentals inside the models, without external forcing functions or calibration. The World3 model of Meadows et al. (1972) has been very important for developing the WORLD6-WORLD7. This work was developed on WORLD6 and finished on WORLD7, illustrating that the model is under constant development and improvement.

This study represents a substantial improvement upon the earlier stand-alone model for copper extraction and supply dynamics, as the metal modules are embedded in a large integrated model structure. The metal extractions are coupled physically and through the economic system, and secondary extraction with other metals can better be accounted for. A substantial effort went into estimating the reserves and resources, leaning on a lot of new data from recent assessments.

3. Objectives, scope and linkages

The model must be able to simulate production rates for extraction from mines, secondary extraction from polymetallic ores, recycling, market supply as well as be able to simulate extraction costs, the world market price, to predict the development of the known and hidden extractable amounts and how ore grades will develop with time. The scope is to model and simulate the global sourcing and supply dynamics of copper, zinc and lead, including market dynamics and a large number of systemic feedbacks. In addition, the supply, demand and market price dynamics will be simulated and the supply per person and year and stock-in-use per person addressed. The first simulation run is to establish the base case as business-as-usual and to verify that the model is able to reasonably well reconstruct the observed mining and price history since 1850. In this paper we will explore the metal supply system and explore how to make the supply of the metals modelled more sustainable. Important questions concerning copper in particular, but also the metals zinc and lead are:

A What will the copper, zinc and lead future provision and stock in use per capita per year be?
B Supply sustainability
  a Is there a risk for physical shortage?
  b Is there a risk for soft scarcity where the increasing prices reduce demand significantly?
C How will the resource quality develop over time and what does this mean for supply and availability in the future?

We would like to have the provision per capita per year and as stock-in-use per capita for copper, zinc and lead as one way of assessing the above. We will return to these questions at the end of the study after the simulation results have been presented. The secondary metals, where many are derived from copper, zinc and lead to a substantial amount are not within the scope of this study. Treating the subject is more than enough for a separate study. The paper deals with both primary mining and secondary mining. Often all the metals are recovered in significant amounts, and mining is moving towards multi-metal mining. The diagram shows that we need deposit information, secondary metal content (Cu, Zn, Pb) extractable resource estimates per metal in addition to the primary resources. The resource estimates are described in a separate study, and we only use the results from that study here. All of the primary metals are also important for a number of technology metals, most of which have no primary mines; indium, tellurium, germanium, gallium, selenium, cadmium, antimony, bismuth (Fig. 2, Nassar et al., 2012). The extraction dynamics of these will be subject of a separate study and publication and not dealt with here. There are links between this study and two studies on iron, manganese, chromium and nickel (Sverdrup et al., 2019a; and stainless steel (Sverdrup et al., 2019b), as nickel is often coproduced with copper and vice versa. It is linked to a study on molybdenum, as molybdenum is sometimes co-produced with copper and vice versa (Sverdrup et al., 2018b). The market mechanism is explained in detail in a forthcoming study by Sverdrup and Olafsdottir (2019a,b,c) in the Journal of Mineral Economics. This paper is the third in a series of three papers that are all tied together with the overall objective to prepare for the use of an integrated model to assess the long term supply sustainability of copper, zinc and lead and the metals that depend on them for their extraction, as a sub-module in the WORLD6 model (Sverdrup et al., 2012a,b, 2013a, 2013b, 2014a,b,c, 2015a,b,c, 2016a,b, Sverdrup and Ragnarsdottir, 2014, 2017, Sverdrup, 2017).

4. Methods and theory used

The methodology used here uses systems analysis as the standard tool for conceptualization, as the preparation for building a simulation model using the STELLA software. The main standard methods of systems analysis and system dynamics modelling are used (Forrester, 1971; Meadows et al., 1972, 1992, 2005, Roberts et al., 1982; Senge, 1990; Haraldsson and Sverdrup, 2005, Haraldsson et al., 2006). We analyse the system using stock-and-flow charts and causal loop diagrams. The learning loop is the adaptive learning procedure followed in our studies (Senge, 1990; Kim, 1992; Senge et al., 2008). The entering of the code follows from the causal loop diagrams and flow charts developed in the conceptualization stage. The mass balance expressed differential equations resulting from the flow charts and the causal loop diagrams will be numerically solved using the STELLA® modelling environment (Sterman, 2000; Senge, 1990; Senge et al., 2008; Haraldsson and Sverdrup, 2005, 2017). To the largest degree, all constants and settings have been based on observed system parameters, in order to eliminate the need for calibration. It is not a part of the methodology to calibrate the model to any time-series of data, nor that it is driven by fed-in time-series. The “data” is divided on harvest into several different categories: (1) system boundary and initial conditions, (2) system structures, (3) system parameters settings and (4) system states. Of these, categories 1–3 are used to parameterize the model before the simulations start. The state data (4), are not used for model initialization, but saved and used for evaluation of model performance. The model is not using state data (4) for calibrating the WORLD6 model. A feature is to check how well the embedded understanding reproduces the observed data.

4.1. Data sources and estimations

Data was obtained from different types of sources; scientific, peer reviewed publications in international journals, from research project reports and reports from agencies and UN bodies and from documentation obtained from the metal industry, either directly or through materials assembled by metal market consultants. The reports assembled by market consultants have a wealth of information but are normally only available when access has been purchased. Few researchers have access to them because of the cost. We have had access to some to them through our business contacts. Most actors trade metals through the market, trade takes place geographically dispersed, but is linked through the price systems at the London and New York Metal Exchanges. The available data was closely inspected for inconsistencies and averages and adjustments were made when the input data were not internally consistent. Several of the numbers given in the literature are uncertain as some of them severely mismatch in the overall mass balance. Generally, the recycling numbers often appear inconsistent (UNEP, 2011a, b, 2013a,b). The beneficiation and refining process from extracted ore to chemically separable metal concentrate (with rock residuals) has about 85–90% efficiency for copper, lead and zinc. Further refining runs with 95–97% efficiency, thus the overall efficiency from mine output to metal to market is about 81–87% at the best (Table 1). Table 1 shows the parameter settings for ore grade, production cost and yield as used in the WORLD6 model for copper, zinc and lead.

In 2010–2011, the copper stock in the global society was estimated to be about 46 kg per person, the demand on provision from the market was 2.4 kg primary extracted copper per person per year, with 7.3 billion people in the world, corresponding to a demand of about 17.5 million ton of primary produced copper per year. Average global GDP per person was about 7000 $/capita in 2015, the copper primary production was about 17 million ton, and the price was about 9 $/kg in the market. The market was supplied with about 30 million to copper metal in total during 2017, the excess over primary supplied coming from recycled copper (13 million ton per year, or about 43% of the total supply). This corresponds to a demand for copper of about 4.1 kg copper per person and year.

The data on available extractable resources has been stratified with respect to ore metal content and relative extraction cost (Table 2). The full causal loop diagram for metal mining and copper in particular has been published earlier (Sverdrup et al., 2014a,b, 2015a, 2017). The numbers from Tables 1–3 and experiences were learned and extracted from studying corporate reports and scientific literature discussed in the text were reworked into the resource data and the estimates of costs of extraction. This is referred to as the opportunity cost approach (Tilton, 2002, 2007, 2009, 2010). We have in the estimation of the extractable amounts of copper (Table 1), considered both porphyric (70% of land deposits, and 65% of all global extractable deposits), sulphide land deposits (30% of land deposits, 28% of all global extractable deposits), and ocean floor copper resources in cobalt crusts and subsea hydrothermal massive sulphides for copper (7% of all global extractable deposits).

Brewster (2009) suggested that the total demand for copper could rise to about 10 kg per person per year by 2100 in a world predicted to have about 10 billion people (Gordon et al., 2006; Rauch and Graedel, 2007; Rauch and Pacyna, 2009; Rauch, 2009; Gerst, 2008, Gloser et al., 2013), which would correspond to a demand of 100 million ton of

Table 1
The resource input data to the model (Sverdrup and Ragnarsdottir, 2014; Sverdrup et al., 2017a, and forthcoming study by Sverdrup and Olafsdottir, 2019a,b,c on Cu, Zn and Pb resources and a forthcoming study on by Sverdrup and Olafsdottir, 2019a,b,c Fe, Mn, Cr and Ni resources).

COPPER					
Ore grade. **Copper**; porphyr deposits (70% of all)	Million ton copper				
	Known	Hidden	Sum	%	Cumulative
Rich	10	4	14	0.5	14
High	7	571	578	22	592
Low	70	1,313	1,383	53	1,975
Ultralow	10	403	418	16	2,393
Extralow	10	212	222	8.5	2,615
Sums	107	2,508	2,615	100	–
Ore grade, **Copper**; sulphide deposits (30% of all), excluding ocean massive sulphides	Million ton copper				
	Known	Hidden	Sum	%	Cumulative
Rich	5	1	6	0.5	6
High	3	111	114	10	120
Low	30	270	300	27	420
Ultralow	5	359	364	33	784
Extralow	5	330	335	30	1,119
Sums	58	1,061	1,119	100	–
Ore grade, **Copper**, Extractable ocean massive sulphides and cobalt crusts	Million ton copper				
	Known	Hidden	Sum	%	Cumulative
Rich	0	6	6	2	6
High	0	45	45	15	51
Low	0	95	95	32	146
Ultralow	0	80	80	27	246
Extralow	0	70	70	24	296
Sums	0	296	296	100	–
Ore grade, **Copper**; Deposits on land and ocean floor potentially extractable resources	Million ton copper				
	Known	Hidden	Sum	%	Cumulative
Rich	15	5	20	0.5	20
High	10	670	692	19	845
Low	100	1,583	1,683	45	2,822
Ultralow	15	767	782	21	3,419
Extralow	15	540	555	15	3,736
Sums	155	3,579	**3,734**	100	–
Ocean floor	0	296	296	–	4,030
Total URR	155	3,875	4,030	–	–
ZINC					
Ore grade	Million ton zinc				
	Known	Hidden	Sum	%	Cumulative
Rich	1	28	29	1	29
High	5	310	315	12	344
Low	1	976	977	37	1,321
Ultralow	0	1,355	1,355	50	2,676
Sum	7	2,669	**2,676**	100	–
LEAD					
Ore grade	Million ton lead				
	Known	Hidden	Sum	%	Cumulative
Rich	20	10	30	1	40
High	5	40	45	1.5	75
Low	1	1,084	1,085	36	1,160
Ultralow	210	1,640	1,855	61.5	3,015
Sums	20	2,995	**3,015**	100	–

copper per year. If the global population peaks out at 8 billion people, and the global demand per capita peaks at 6 kg copper per person and year, this would imply supplying about 50 million ton of copper per year to the market, or 2 times more than today. That would be a major challenge, emptying out known and anticipated resources in less than 75 years. All extraction requires energy, and Fig. 1 shows the energy required to produce copper from different substrates, a comparison between different metals and pathways from raw material to finished metal. This is dependent on several factors;

- Oil and coal market price, because metal production process is energy demanding for mining in mountains, moving stone, crushing, smelting and refining and transporting and manufacturing copper, zinc or lead into products. This is coupled to the ore metal content, an indicator of how much effort must be spent to extract metal (Singer, 2007, Mudd, 2007, 2009, 2010a,b, Northey et al., 2014, Glöser et al., 2013a, 2013b). When the ore quality decline, the extraction costs rise proportionally with it.
- The work cost determined by the wage level and the amount of labour input required. The labour input tends to increase with declining ore grade and mining depth but this is somewhat is off-set by technological advances leading to automatization and robotization, making each work hour input produce more. Increased labour costs and standard of living is a reflection of increasing salaries.
- The flexibility of the supply infrastructure, and delays in increasing or decreasing production. In the past, a mine had a delay in 3–6 years to increase production, at present this has increased to 7–15 years. The increased technical challenges associated with lower ore grades, more complicated operations permission systems and deeper or more remote mining locations are among the causes for this increased delay.
- Capital costs of stating a mining operation or enlarging capacity is increasing, due to more complicated and expensive infrastructures, and more regulations.

The Ultimately Recoverable Reserves (URR) is one of the key input parameters in the assessment, and great care was put into getting good estimates for it. The estimates shown in Table 1 indicate that porphyry deposits make up 65–70% of all copper deposits, sulphide deposits make up about 28–30% of all copper deposits and ocean bottom copper resources make about 4–5% of the extractable copper resources. The cost of extraction rises with declining ore grade, and unless the market price is above the cost of extraction, it will not be extracted. The lower ore grades will not be extracted if the price persists at a low level. Secondary production of copper is also an important source of copper. Table 2 shows some of the parameter settings for ore grade, production cost and yield as used in the WORLD6 model for copper, zinc and lead. The energy needs associated with mining, crushing, milling, beneficiation, and metal extraction was worked out carefully for all ore grades applied here, and has been tabulated in the supplement. The full explanation of the table is a longer text and will be published separately. Significant uncertainty is attached to the zinc resources estimates, and the literature shows some inconsistencies (Sverdrup and Olafsdottir, 2018 and compare with Mudd and Jowitt, 2018). Table 3 shows the estimation of the contents of dependent metals in different mother metals for secondary production used for the simulations. These contents represent approximate estimates as there is very little information available on this aspect in the literature.

The ultimately recoverable resources (URR) for copper, zinc and lead were reassessed and a thorough review was made. The methodology for how the resources were estimated has been described in a separate study, and some selected parts of that is included as a supplement to this publication.

5. Model description

5.1. *Structural description*

The WORLD6 sub-model for copper, zinc and lead is based on the earlier COPPER, SILVER and GOLD models and experiences learned from them (see Sverdrup et al., 2013c, 2014a,b). There is a detailed technical description of the model and its uses available, it is available from an open source and listed in the references (Hirschnitz-Garbers et al., 2015, 2017, 2018, Koca et al., 2017; Sverdrup and Koca, 2017; Sverdrup and Koca, 2018). There are primary and secondary sources for copper, the secondary are derived from different mother metals. This is shown in the flow chart in Fig. 2. It shows a flow chart for how copper, zinc and lead is extracted in the WORLD6 model, and how silver, nickel

Table 2
The parameter settings for ore grade, production cost and yield as used in the WORLD6 model for copper, zinc and lead. The numbers are approximate for 2012–2015 and are based on data from gold, silver, copper, zinc and uranium mining from many countries (Ataei and Osanloo, 2003, Gerst, 2008; Northey et al., 2014; Phillips and Edwards, 1976; Robinson and Menzie, 2012; Schlesinger et al., 2011; Singer, 1993, 2007, 2013, 2017, Singer and Menzie, 2010; Singer et al., 2008, 2009). The websites of Boliden Metal, Sweden and Norilsk Nickel and several large copper mining companies were visited.

Ore grade	Ore metal content, %			Step extraction yield, %	Production cost, $ per ton		
	Cu	Zn	Pb		Cu	Zn	Pb
Rich	36	25	50	99	500	250	300
High	18	12	10	99	1,000	650	600
Low	4	2.5	3	97	2,000	1,500	1,200
Ultralow	0.8	0.5	0.5	94	4,000	3,500	3,000
Extra-low	0.15	0.1	0.06	90	8,000	6,100	5,300
Trace	0.03	–	–	77	14,000	10,000	9,000

Table 3
Estimation of contents of dependent metals used in the simulations. These are average values after looking into compilations such as Crowson (2011); Gutowski et al. (2016), Koca et al. (2007), Mudd et al. (2017a,b, 2018), Norgate and Rankin (2000); Elshkaki et al. (2016); Sverdrup et al. (2018d). The units used is fraction of weight of mother metal flow. The websites of Boliden Metal, Sweden and Norilsk Nickel and several large copper mining companies were visited.

Mother metal	Cu	Zn	Pb	Ag	Ni	Mo
	Weight proportion in the mined metal flow in addition to the mother metal.					
Copper	1	0.14	0.006	0.00032	1	0.5
Zinc	0.14	1	0.05	0.00040	–	–
Lead	0.006	0.01	1	0.00008	–	–
Silver	0.08	–	–	1	–	–
Nickel	1	–	–	–	1	–
Molybdenum	1	–	–	–	–	1

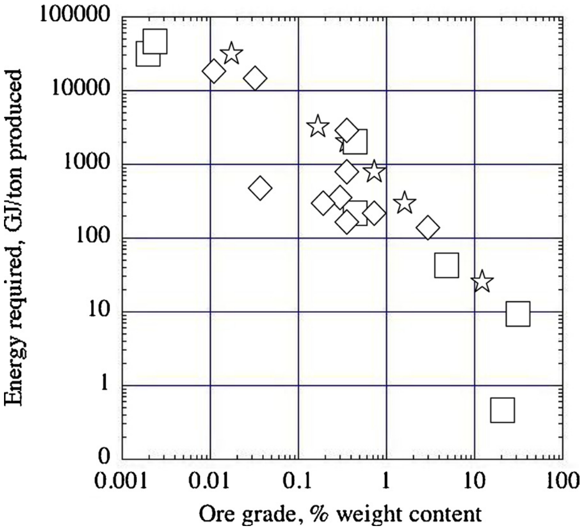


Fig. 1. The energy cost rise with declining copper ore grade. The squares, circles and stars represent data from copper, nickel and gold from the literature (see Gutowski et al., 2008).

and molybdenum are involved in secondary mining of these metals, both as mother metals and how these metals (Cu, Zn, Pb) contributes to the production of silver, nickel and molybdenum. The complexity of the flow chart makes the modelling of the system a large and complex task. Zinc is insoluble in liquid lead, explaining why there is no flow from lead to zinc and little zinc in lead ore. Lead ores normally contain no zinc (Mudd and Jowitt, 2018). An overview of all the modules included in the WORLD6 model at present can be found in the supplement, and also a flow chart for the sub-model for copper, zinc and lead in the WORLD6 model, with the parent ores, the primary extraction. The following metal modules have a full market dynamics and calculation of the market metal price used for assessment in the WORLD6 model: Cu, Zn, Pb, Ag, Au, Ni, Mo, Re, Nb, Ta, W, Sn, In, Ga, Te, Ge, Mn, Cr, Fe, Pt, Li, Co, Al, Pd, Rh, Rare Earth Elements, Sb, Cd, Bi, Se, Ti, Zr, Hf, U and Th. These modules are interconnected and run simultaneously.

The WORLD6 model addresses a large number of metals, and they are all in some way all linked in their extraction. In addition, the WORLD6 model handles sand, gravel, stone, cement, wood, oil, natural gas, coal, phosphorus among the natural resources used as raw materials by man. The WORLD6 energy module supplies energy from fossil fuels, renewables and nuclear power, with a market price generated by supply and demand in the model. Energy for metal extraction is taken from this module. For these metals, the price has an effect on demand, but not any significant impact on the supply, as this is dependent on the mother metal extraction rate. All modules are interconnected. This implies that demand for copper comes from both population as well as quantified demands for copper in other modules (vehicles, power generation technologies, aircraft, etc.).

Fig. 4 shows the causal loop diagram explaining how profits drive mining and extraction. B are balancing loops, balancing the reinforcing loops (R) and slowing them down. Four main reinforcing loops involved in the mining activity are presented in the diagram, all marked with R. These are the mining and supply loop (R1), the exploration loop (R2) and two recycling loops (R3a, R3b). The mining supply loop, (R1) describes how the operation profit affects the mining activity as the system is profit driven. More profit means more mining and less profit means less mining. Mining naturally adds to the supply of mined metals that has a positive effect on the profit resulting in a reinforcing loop. The exploration loop (R2) describes how the relationship between the prospect and profit results in a reinforcing loop. An increase in the operation profit results in an increase in the mining and therefore an increase in the known ore. When there is more in the known ore it is less left to find and the prospect goes down. With less prospect there is also less operation profit. The two recycling loops are both reinforcing (R3a and R3b). R3a runs through the recycling profit making a push to the amount being recycled and R3b runs through the amount in society that makes a push on how much is being recycled adding to the total supply which adds more to the market.

Fig. 2 shows some loops that balance the system, all are marked with B. The main balancing loops presented are the price market loop and the exhaustion loops. The price market loop describes the relationship between demand, modified demand, price and the market. With more amount in the marked the price goes down, and with higher price the modified demand goes down. The difference between the demand and the modified demand is that when the price gets higher the modified demand decreases as people are willing to get less than they actually want when the price is high. The modified demand controls how much is taken from the market which decreases the amount in the market. The exhaustion loops are three and they describe how the

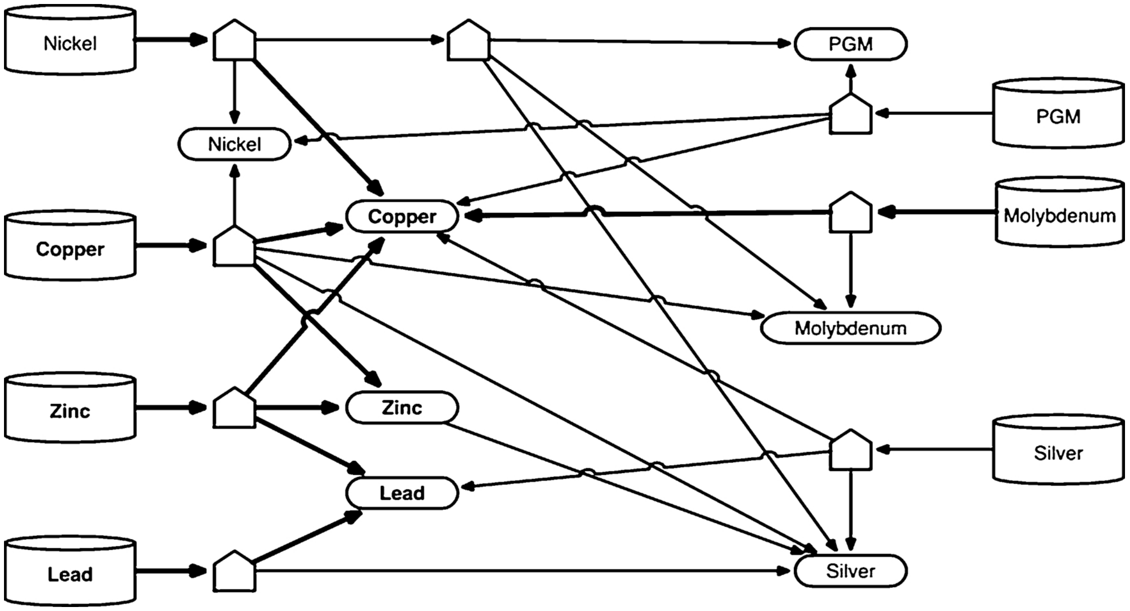


Fig. 2. The flow chart for the metals focused on here is represented above. This shows the flow chart for the metals as implemented in the WORLD6 model used for the study. Modern mining has become a multi-metal mining puzzle, where many metals are extracted from each source. The concept of primary and secondary mining has become blurred to multi-metal mining.

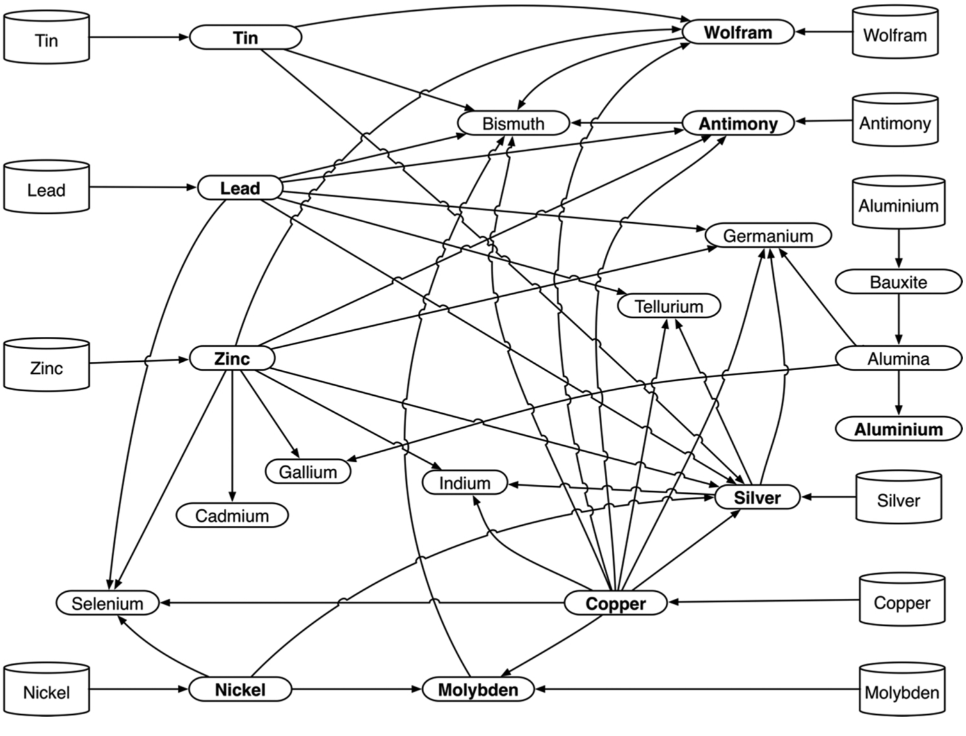


Fig. 3. The mining of copper, zinc and lead is instrumental for being able to produce most of the technology metals. These metals are not dealt with in this study, but this study is a prerequisite for being able to deal with the technology metals. They will be dealt with in a follow up study being developed.

system is balanced from the known and hidden ore.

With an increase in known ore the prospecting decreases and the finding rate also decreases (with less prospecting). With a decrease in the find rate the action of finding ore also goes down and more is left as hidden ore. If there is more left as a hidden ore there is more left to find. In a nutshell, as the extractable amounts run low, more money must be spent on prospecting. When the hidden extractable amounts run low, then it will get more expensive to find the dwindling extractable amounts remaining out there to be found. It shows how mining rate is driven by demand from society and promoted by metal price and mining profit to generate supply to the market.

5.2. The price mechanism

Price is used with transaction flows to generate income and profits in the larger scheme of the WORLD6 model. Thus, a dynamic mechanism for creating a price is required in the model. Every time the supply, demand, or recycling changes, a new price must be calculated. The WORLD6 price model operates according to how the metal is traded at the London and New York Commodity exchanges for copper,

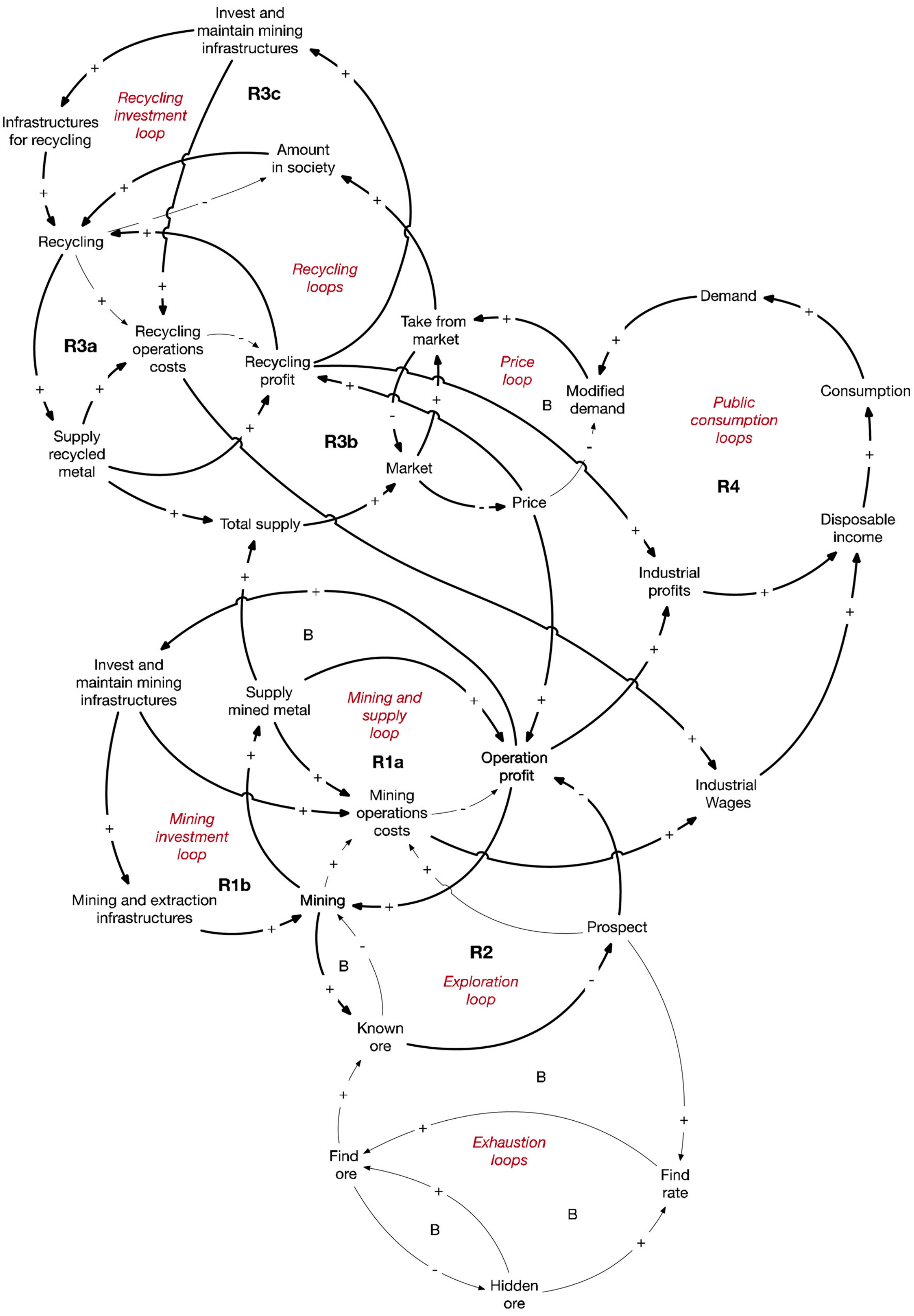


Fig. 4. The causal loop diagram showing the market mechanisms and their effect on extraction, supply, demand and actual delivery from the market. This part of the model generates market price inside the model and eliminate the need for externally fed price time series. There are a number of reinforcing loops that drive the system towards more extraction. Mining created profits by selling the product, causing more extraction (R1). Recycling creates recycling profits, driving more recycling (R3a, R3b). Exploration finds more resources, allowing for more mining (R2). The price is used to modify the demand to become "Take from market". In the broader picture, industrial activities contribute through wages and profits to the overall disposable income in society, which in turn contributes to consumption and demand, a reinforcing loop (R4).

zinc and lead. The price is determined by how much metal is immediately available for trade in the market. A high metal price will stimulate the mining rate through profits and with a delay, increase supply to the market, and limit demand. More supply to the market will increase the amount available for trade and that will lower the price. The profit is affected by the mining cost and how that is modified with changing oil price and variations in ore grade. A lower ore grade implies that more rock must be moved to mine the copper. The implication is that a higher copper price is necessary to keep the copper production up when the ore grade declines. The price is set relative to how much metal there is available in the market (Eqs. (1)–(3)). The traders come to the trading floor with their lots to sell or to buy and adjusts their amounts as the price increase or decrease. When there is a match between supply and demand, the price is set. If demand is higher than production, the price increase; in the opposite case the price is moved down. This is a self-adjusting mechanism that balances the trade by adjusting the prices until the demand to buy an amount at a price match the offers to sell an amount at a price. In the market, several types of transactions occur:

- The metal is sold in the market to a buyer, shipped and physically supplied at once. Supply to market and take from market is the same.
- Forward sale; The metal is sold at once and payment received, but the metal is physically delivered at a later date. Ownership shifts at once, but the money later. Many mines do this to improve liquid funds.
- The metal is shipped at once but payment is received at a later date. Ownership shifts at once, but the money moves later.

The causality in profits go to income from supply when the amount is supplied and paid at once into the metal exchange warehouse. The same applies with a forward sale when the metal is paid upfront but physically delivered later. If not, all or part may be paid when the supplied amount has been cleared out from the physical warehouse. This description is based on personal experience from the trading floors at the metal markets in New York and London by one of the authors. For some metals, the amounts in the markets are recorded. On investigation, the price is correlated to the market amounts (Sverdrup et al., 2017a,b,c; Sverdrup, 2018). The price curves found were (Sverdrup and Olafsdottir, 2019a,b,c see Fig. 5):

$$\text{Copper price} = 2{,}212 * \text{Cu-market amount}^{-0.57} \quad r^2 = 0.80 \tag{1}$$

$$\text{Zinc price} = 572 * \text{Zn-market amount}^{-0.80} \quad r^2 = 0.75 \tag{2}$$

$$\text{Lead price} = 124 * \text{Pb-market amount}^{-0.85} \quad r^2 = 0.87 \tag{3}$$

The market stock is in million ton of copper, zinc or lead in the equations. With market stock, we imply the amount available in the market for immediate transaction with ownership transfer and if necessary, physical supply. This excludes derivatives trade, hedging and forwards, which are not counted as immediately physically deliverable. The scrapping process for stock-in-use in society is driven by price, and from that the infrastructure where it is incorporated has become obsolete or worn out. Once the metal is available as scrap not in service, the recycling from scrap is driven by profits. After the metal has arrived at the scrap heap, the metal price will have a promotion effect in causing somebody to recover it. The metal price in the market will not go below the cost of actual production and extraction, because then the profit falls below zero and supply stops. There needs to be profit above the extraction cost, normally about 10–20%. The prices are set at all markets every time step, and resources are traded and cleared off the market every time step.

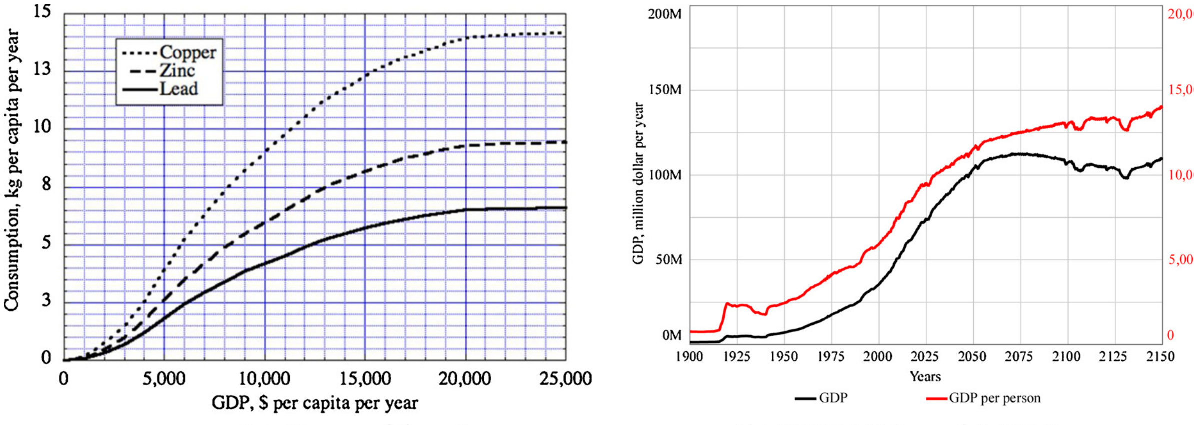
5.3. The extraction and market dynamics equations

There are fundamental differences in how mining in an individual mine is modelled on the business level and what happens when a whole population of mines are operated. Then host dynamics and group behaviour come into play, changing the equations. Many of the particulars of a single mine are distributed over time in a population of mines, leading to the good sense of working with averages and where discrete events become continuous when they are many and distributed over time. The modelling here is on global level, thus working with populations of mnes and their collective behaviour.

In the model market sector we find refining, trade markets, copper stored in society, scrapped copper, and the actions in/out of refinery, refinery output, market input, and market supply. Recycling is in principle mining from society and from waste dumps and provides a substantial flow of copper in comparison with rock mining. Mining is the action that extracts copper from “known” and puts it to refining. The general mining rate equation used is:

$$r_{Mining} = k_{Mining} * m_{Known} * f(\text{Technology}) * g(\text{Profit}) * h(\text{Yield}) \tag{1}$$

where r_{Mining} is the rate of mining, k_{Mining} is the rate coefficient and m_{Known} is the mass of the ore body, where f(Technology) is a technology factor describing mining efficiency improvement dependent on time, g (Profit) is a feed-back from profit of the mining operation. h(Yield) is a rate adjustment factor to account for differences in extraction yield when the ore grade decreases. The basic driving mechanism of basic



(a) Demand functions *(b) WORLD6 model GDP*

Fig. 5. The general demand trend curves generated for copper, zinc and lead (See the text for explanation) (a). This figure was used to relate GDP as calculated in the economic module of WORLD6 to copper demand. The GDP (b) was taken from the WORLD6 model, where it is generated internally from the sum of all incomes in the model.

mining comes from profits and availability of a mineable resource used in the model. These functions are given exogenously as generic curves containing the observed relationship between the tradable amount and the price. The size of the extractable ore body is determined by extraction (r_{Mining}) and prospecting ($r_{Discovery}$). We get Eq. (2):

$$\frac{dm_{Known}}{dt} = r_{Discovery} - r_{Mining} \tag{2}$$

The ore discovery is a function of how much prospecting we do and how much there is left to find. The amount hidden resource (m_{Hidden}) decrease with the rate of discovery ($r_{Discovery}$). The rate of discovery is dependent on the amount metal hidden (m_h) and the prospecting coefficient $k_{Prospecting}$. The prospecting coefficient depend on the amount of effort spent and the technical method used for prospecting. We get Eq. (3):

$$-\frac{dm_{Hidden}}{dt} = r_{Discovery} = k_{Prospecting} * m_{Hidden} * f(Tech)*g(Profit)*j(m_{Known}) \tag{3}$$

The modifying functions for technology development f(Tech) and the drive on mining from profit drive on prospecting g(Prop), and *j* (m_{Known}) is a curve expressing the urgency to prospect more. The price is set relative to how much iron or steel there is available in the market. The rate of corrosion of the stock-in-use ad from scrapped metal are defined as Eq. (4):

$$r_{Corrosion} = -k_{Corrosion} * m^{s}_{Stock-in-use} \tag{4}$$

We have assumed corrosion to be a first order process on large scale (s = 0.6-0.9). Scrap is both lost physically by dropping it where it is not likely to be found or retrieved (at random and in landfills) and by corrosion:

$$r_{Scrap\,loss} = -(k_{Scrap\,loss} + k_{Corrosion}) * m_{Scrap} \tag{5}$$

The WORLD6 model has several sectors, and we are utilizing the modules built for copper, zinc, lead and silver, and one for all the different technology metals. The mining modules where the resources are divided into known reserves and hidden resources, and stratified into 5 levels of ore quality; rich grade, high grade, low grade, ultra low grade and extreme low grade. Reserves move from hidden to known because of prospecting. The extractable amounts were set at the beginning of the model simulation in 1900, stratified with respect to ore metal content and relative extraction cost based on yield of extraction and energy requirements. The distribution of copper to ore grades is based on Fig. 4c. Ore beneficiation, processing and subsequent smelting yield is defined as:

$$r_{smelting\,supply} = k_{Smelting\,yield} * r_{Mining} \tag{6}$$

Ore beneficiation implies that the raw rock extracted from the mine is treated to an ore concentrate. This implies that the rock is crushed, milled and enriched using froth flotation, magnetic sorting or gravimetric separation methods to separate rock minerals from metal-containing parts of the ore. The model as a causal loop diagram for the system is in principle the same as those published earlier for silver, copper, wolfram, niobium, tantalum and aluminium (Sverdrup et al., 2014a, b, 2015a).

5.4. Dependence of recycling on price

The dependence of the recycling rate (the fraction of the total supply not coming from mining) as a function of the metal price was used and was determined in an earlier study (Sverdrup and Ragnarsdottir, 2014). This shows what the market mechanisms alone will do. Additional effects can be derived but changing policies and introducing incentives and increasing the costs of not recycling. We can derive the equation for the market mechanism based recycling as % of total supply to the market:

$$r_R = \left(\frac{m_{scrap}}{t_{residence}}\right) * f(technology)*(0.24 + 0.12* \log_{10}(price)) \tag{7}$$

r_R is the recycling rate (million ton per year), $t_{Residence}$ is the average time the metal stay as scrap before being refined. The price has the units $ per kg. f(technology) is a scaling function describing how the indium recycling efficiency has evolved over time. This is used as a basis for the market drive on recycling. The correlation between price and recycling is $r^2 = 0.61$, (Sverdrup and Ragnarsdottir, 2014; Sverdrup, 2018). It was made with data from Lenzen (2008), Gutowski et al. (2016) and Prior et al. (2013). In 2015, the lead recycling rate was reported to be about 55–60%. This is better that price alone would dictate, the additional effect comes from regulation of battery recycling and conditional training of the populations.

5.5. Economic feedback on mining and extraction dynamics

The extraction leading to ability to supply is driven by profit in the model. Profit in the extraction activity was defined by the following equation:

$$Profit = Income\ from\ sales - mining\ costs \tag{8}$$

Where the costs are defined as:

$$Total\ costs = Mining\ costs + refining\ costs + prospecting\ costs \tag{9}$$

In this equation, mining costs, refining costs and prospecting costs all include both variable operations costs and capital costs for infrastructures and equipment. In the model, purchases from the market are driven by demand, put copper into society where it stays until scrapped or removed by wear and losses. A part of the scrapped copper, zinc and lead is recycled and returned to the refinery. Copper stock in use per person as related to global GDP and as it has developed over time. The demand for copper and zinc can be expected to increase in the future. Copper has many uses in society, in infrastructures and in all types of technologies. About 40% of all copper use goes into electronics and electrical equipment, 31% goes into construction as wiring, nails and tubes, 11% is used in transportation technologies, 10% in industrial machinery and about 10% for consumer products. Copper plays a prominent role in new energy technologies, existing and proposed. Zinc plays an important role in many infrastructures and especially for corrosion protection of iron and steel (50%), 17% is used in diecasting and 17% for brass and bronze alloys. Lead is used to 80% for batteries, 6% for rolled and extruded products, 5% in chemicals and pigments and thest for many smaller applications. Lead is on the UN-ECE LRTAP convention list for metals to be phased out of all use, the demand should be expected to decline in the future. The feedback functions can be found in the supplement file to this paper.

5.6. Demand dynamics

Demand in the model is driven by population and copper use per person, but is adjusted up or down with price. Demand acts by causing metals and materials to be taken from the markets, decreasing the amounts there. Demand is affected by the market price, the market price in turn depends on how much is available in the market. The demand is estimated from affluence and global population using outputs of the WORLD6 model system (Ragnarsdottir et al., 2011, 2012, Sverdrup et al. 2005, 2011, 2012a,c, 2014a,2014b, 2015a,b, Sverdrup et al., 2011; Sverdrup and Ragnarsdottir, 2014). The demand in the model is generated from two sources: Demand from other modules in the WORLD6 model where the metal in question is used, and secondly, a generic demand (other use) based on use per capita and the total population. This has been expressed in the causal loop diagram shown in Fig. 2.

The data shown in Fig. 5 shows how there is a linear proportionality with GDP up to about 20,000 $ per capita, and then the curve stays flat.

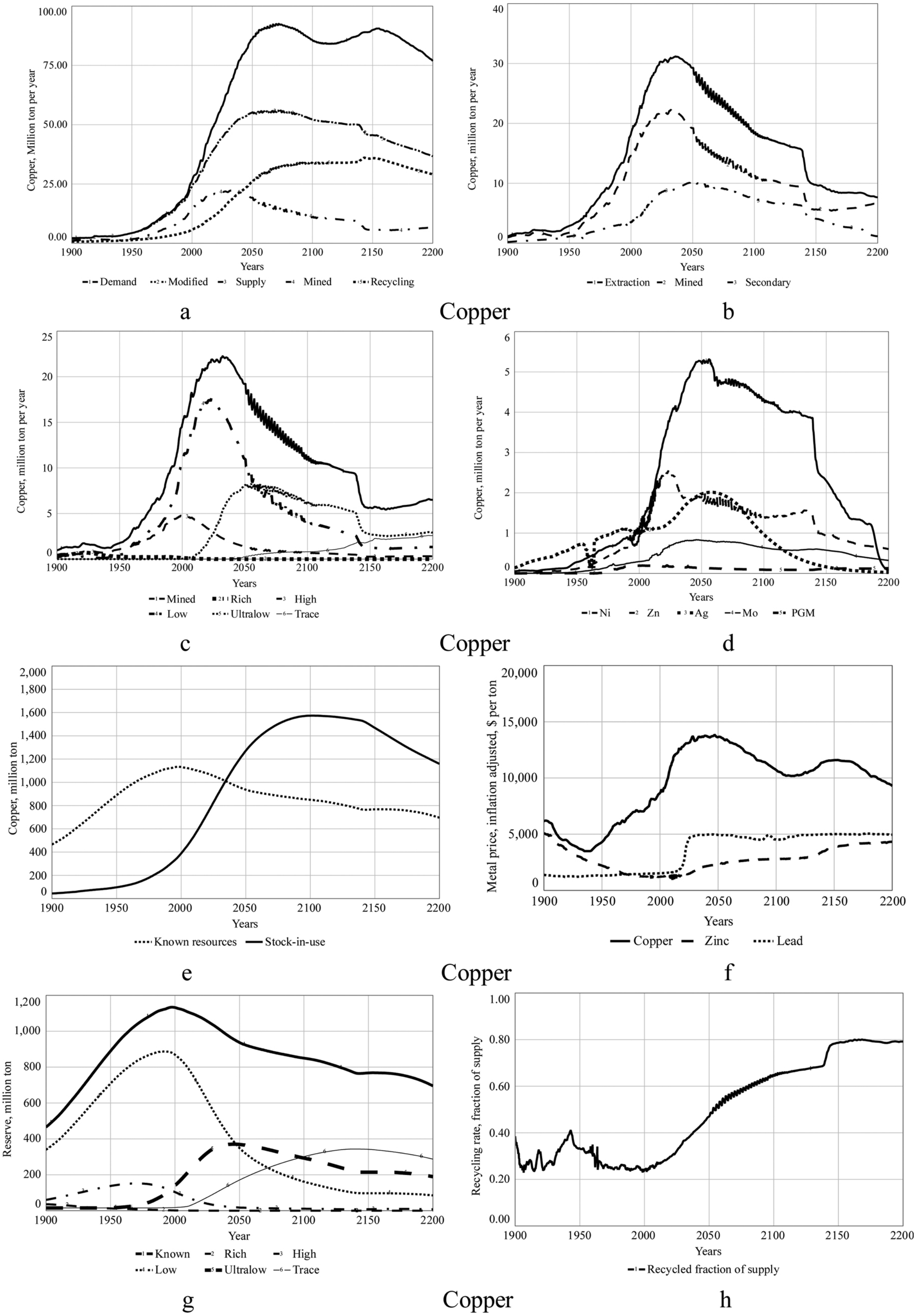


Fig. 6. Copper. (a); Demand, modified demand, mining, supply and recycling. (b): The extracted, primary mined, secondary mined and the observed rate of copper extraction. (c) copper mining and how this contributes from ore grade categories. (d) shows the secondary extraction. (e) shows the known reserves as compared to the stocks-in-use. (f) shows the copper price as compared to the metal price for zinc and lead. (g) shows the known reserves and (h) the recycled fraction.

Relating copper consumption to GDP makes good sense when a substantial part of the GDP expresses activities that increase investment in infrastructures and technology. The data come from Rio Tinto and Anglo America Annual Report (2013); Business Insider (2014); Kitco (2014) and Watari et al. (2018). Sometimes a decline in metal use beyond 40,000 $ per capita is seen. We interpret that decline to be caused by several phenomena: (1) That the society has reached a technological and infrastructural steady state, where metals is only used for maintenance and up-keeping (maintenance) of what is there. The provided structures are sufficient for the needs at hand. (2) Because of population decline, where the demand for consumption may be going down. (3) That the metal use has stagnated because of a broad neglect of maintenance of existing infrastructures in society. The neglect may be caused by true negligence (mismanagement) or economic shortcomings.

The demand is estimated in the model and adjusted when the price change. The demand function was determined with data from China, South Korea, Germany and the USA (Fig. 3). We get the equation:

$$\text{Demand} = \text{Need} * f(\text{GDP}) * \text{population} \tag{10}$$

And the demand is modified with the price, increased by low price, decreased by high price:

$$\text{Demand}_{\text{Modified}} = \text{Demand} * g(\text{Price}) \tag{11}$$

D_0 is the primary demand from needs before any feedbacks from price or scarcity. The function g(Price) is the demand modification function using market price as the input and expressed with a diagram inside the WORLD6 model. The diagrams have been found by comparing demands at different price levels. Demand_M is the demand D_0 after it has been adjusted by the feedback from price and GDP. For zinc and lead, the distribution of URR to ore grades was based on a best fit of the simulations to observations of ore grade development with time. The equations for f(GDP) for copper, zinc and lead derived when demand D_0 is expressed in kg per capita per year, are:

$$f(\text{GDP})_{\text{Cu}} = -0.0000000266 * \text{GDP}^2 + 0.00129 * \text{GDP} - 1.392 \tag{12}$$

$$f(\text{GDP})_{\text{Cu}} = -0.0000000177 * \text{GDP}^2 + 0.00087 * \text{GDP} - 0.928 \tag{13}$$

$$f(\text{GDP})_{\text{Cu}} = -0.0000000124 * \text{GDP}^2 + 0.00061 * \text{GDP} - 2.000 \tag{14}$$

5.7. Energy restrictions

Metal production is demanding energy. Copper, zinc and lead are among the large volume metals, and thus the energy used for their extraction in significant. The energy use for each metal is calculated for the extraction of the ore, the enrichment of the ore from raw rock to ore concentrate and smelting or refining to the final metal or alloying component is estimated in the model. For all the metals considered, the ore grade is declining, and the extraction energy use increase steadily. We have introduced that when the energy use for all the metals included in WORLD6 as a sum approach 65%, then the metal production is reduced as follows (curves can be found in the supplement document to this paper).

5.8. Numerical integration of the WORLD6 model

The WORLD6 model is numerically integrated using a 1/365-year time-step in a 4-step Runge-Kutta numerical method for a standard run. However, the WORLD6 model will work well with a daily time-step. The key parameters are set according to best possible estimate from observation or independent assessments (resource size, intrinsic mining rate coefficient, extraction yields etc.) and then let to run in all modules. Thus, all validity checks will be checked for good fit throughout the whole model simultaneously. The development strategy for the model was to develop first standalone models for segments of the large model. First came the stand-alone module COPPER (Sverdrup et al., 2014a,b). Subsequently, the stand-alone model was then incorporated into the whole model. A reference run was made which can be described as a business-as-usual scenario. This is to what we will compare everything. This run is used for the model validation against the observations.

6. Results

6.1. Copper: Copper mining, extractable amounts and supply to society

The WORLD6 simulations results for copper are organized in a series of graphs, they all represent the scenario of business as usual.

Fig. 6a shows the supply to society, the mining rate and recycling. It can be seen that the supply is significantly larger than the primary production, and that is what counts for society. The difference is caused by recycling of copper which is a large source of the metal. With time, the simulations suggest that recycling will eventually become the largest source of the metal. Secondary extraction is also substantial, and it will also become larger than primary mining, but less than recycling. The supply is predicted to reach a level of about 45 million ton per year for copper. Whereas primary production peaks in 2035, the supply reaches the maximum level in about 2050–2060 with about 45 million ton of copper per year. Copper will be present in society long after the copper mines have run out, and it will be supplied from recycling and urban mining. It can be seen that copper supply to society peaks at about 60 million ton of copper per year in 2050 and stay at that level until about 2160, when the supply declines. Fig. 6b shows the extracted, mined, secondary extracted and the observed mined amounts of copper. Fig. 6c shows the simulated copper production, and the supply from the different ore grades. For copper, the willingness to pay is good because of the importance of copper for many essential functionalities of society.

The primary production is predicted to peak around 25 million ton of copper per year. Globally that corresponds to about 3 kg of copper per person and per year. The primary production is predicted to decline after 2045. Fig. 6d shows the secondary extraction and the contribution to the secondary extraction specified among different mother metals the secondary extraction takes place from.

The diagram show the copper contribution from mines being classified as nickel, zinc, silver, molybdenum or PGM mines. The contributions are significant, pointing out the fact that more and more primary mines are becoming multi-metal mines. Fig. 6e shows the development of known copper extractable amounts over time compared to stock-in-use. Supply to society is far larger than mining, because of recycling. It can be seen that whereas copper mining peaks in about 2040, copper supply to society does not peak until 2110 because of copper recycling from the stocks-in-use, about 70 years after the mining rate peaks. The stock-in-use in society reaches a maximum in 2090 at 1600 million ton of copper according to the calculations. Supply to society is larger than mining, because of effective recycling of copper. Copper has a high price, and copper recycling is helped by a cultural habit of copper being valuable that promote recycling by the population. After 2055, stock-in-society will be larger than known extractable amounts. Note how recycling will be the major source of copper after 2050. The known reserves for copper. They peak at about 1200 million ton and decline after 2200. Hidden resources are not included. Fig. 6f shows the simulated market price as compared to the observed. The fit to the observed data appears to be adequate. Note that the observed data line stops in 2017.

Fig. 6g shows the development of the known reserves of copper with time as simulated by the model. The known reserves simulated by the model approximately mirrors the observed data on known resources. Fig. 6h shows recycling fraction over time for copper. Estimates for copper recycling degree vary a lot and UNEP (2013) only gives a range for the period 2000–2010 at about 50%. There is a lot of industrial

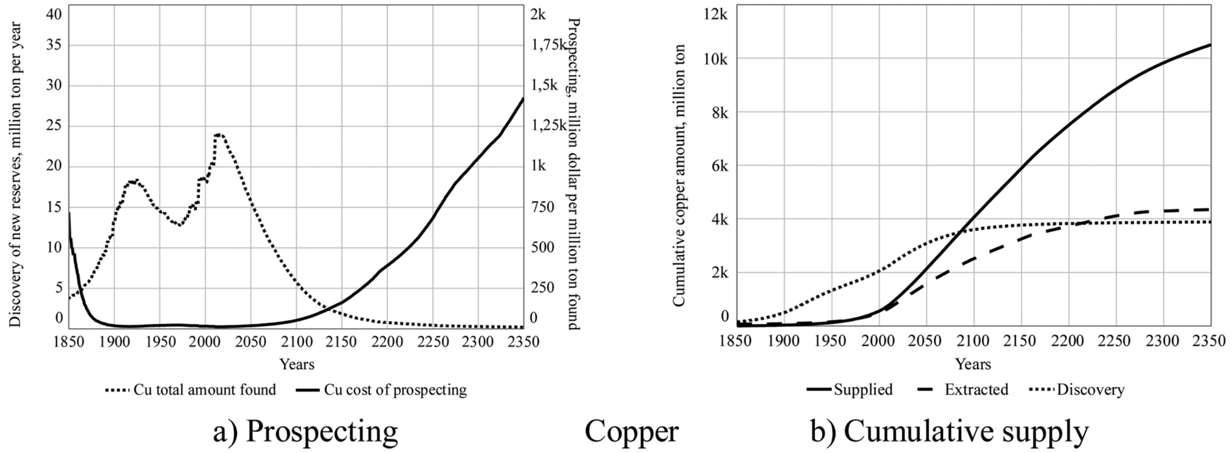


Fig. 7. Copper (a) Shows the cost of prospecting and the amounts found. (b) shows the cumulative amounts extracted, supplied and discovered from the simulations.

recycling internally to companies and industries that never gets reported. In many less developed countries, copper recycling is probably significant, but largely unrecorded. Be aware that there is a large delay effect in the recycling for copper. Copper goes into different types of mechanical commodities and into infrastructures like bridges, transmission lines, cables, train systems, cars, ships and housing. There the copper sits for 20–60 years before it is again released as waste or scrap and can be subjected to recovery and recycling. The copper we recycle today is normally many decades old.

Fig. 7a shows the simulated discovery of new reserves as a result of prospecting and the cost associated with that prospecting. After 2020, the success of prospecting will decline and at the same time as the costs for exploration goes up. This extraction cost increase has already been observed to start on a global scale for both copper and gold (Schodde, 2010). Fig. 7b shows the cumulative amounts supplied, extracted and discovered.

6.2. Zinc simulations: Zinc mining, reserves and supply to society

Fig. 8a shows the zinc demand, demand adjusted after feedback from price, supply into society, mined amount and the recycled amount according to the simulations. Note that supply and demand after price modification overlap perfectly. The implication of that is that there is no physical scarcity occurring throughout the period. There is a widening gap between the demand and the demand after price modification, showing the degree of soft scarcity in the system. This also is reflected in the increase in price with time (Fig. 8f). Fig. 8a also compares the amounts of zinc derived from copper and lead as compared to primary extraction. The primary mining is the most important source of zinc, followed by recycling. Supply to society is larger than mining, because of recycling. Fig. 8a shows that the zinc supply stop growing in 2070 and declines after that. Zinc supply to society peaks later than zinc supply from mining because of recycling from the zinc stock-in-use. The stock-in-use peaks at about 420 million ton of zinc. Fig. 8b shows the development of the known reserves of zinc with time, stratified down to ore grade categories. Fig. 8c show the mining rate and the origin from primary and contributions from different types of ore grades.

The best ore grades are extracted first, implying that only poor zinc ore grade amounts are available after 2015. Zinc mining reaches a maximum 2025 and declines steadily after that. Zinc mining is estimated to reach a maximum at a zinc production of about 16 million ton of zinc per year Fig. 8d shows the development of zinc stocks in society and in the known zinc reserves with time. The known extractable amounts peak about 2075. After 2050, stock-in-society will be larger than known extractable reserves. Note how recycling will be the major source of zinc after 2045. The zinc stocks-in-use peak around 2070. Zinc supply to society peaks later than zinc supply from mining because of recycling from the zinc stock-in-use. The stock-in-use peaks at about 450 million ton of zinc. Fig. 8d shows that after 2052, zinc in society will be a larger source of zinc than mining from ore deposits. Fig. 8e shows the recycling degree as fraction of supply. The recycling follows the price pattern, with high recycling at high price and little recycling at low price. Fig. 8f shows the simulated zinc price and the observed data. After 2030, the zinc price is predicted to increase because of decline in mining and continued increases in demands.

6.3. Lead simulations: Lead mining, reserves and supply to society

Fig. 9a shows the lead demand, demand after modification by price, the supply from mining and the amount of lead coming from copper and zinc mining compared to the observed mining rate. The demand after modification by price and supply to society overlap completely. This shows that there is no physical scarcity predicted in the whole period. Fig. 9a also shows that there is a small gap between demand and the demand modified by price. This shows that the degree of soft scarcity is limited, and that there will be no real shortage of lead. Fig. 9b shows the development of the known reserves over time. The known reserves are predicted to peak in 2020, and after that decrease slightly and slowly. The lead reserves and resources are very large, and there is no risk for any lead shortage because of resource limitations under the demand scenarios assumed. The curve for lead after 2020 depends to a large degree on the assumptions made for lead demand into the future. Fig. 9c shows the mining rate of lead and the contribution from different ore grade categories. The dotted line represents the recorded mining history to 2017 (Data from USGS website 2018). The supply of lead will reach a peak from mining in about 2030–2045 for copper, supply to society peaks later because of recycling from the stock-in-use, for lead supply to society, the total lead supply peaks at the latest in 2045. Because lead is being phased out from most of its uses, known extractable amounts stay high as extraction goes down due to lower demand. Lead is now banned in paints, colours, additive to vehicle petrol, in ammunitions for hunting and is being phased out from soldering alloys (UN/ECE LRTAP, 2019). All this because of its environmental and human toxicity. Lead is no more used in water pipes because of the toxicity risks. 80% of lead demand comes from car batteries and it is estimated that 85% of the batteries are recycled. That implies that about 85% of the lead in the batteries is recycled. That alone, accounts for about 60% of lead use is recycled (Rauch and Pacyna, 2009; UNEP, 2011a). Fig. 9d shows extraction rates, supply to the market and the amount from recycling. In 2014, primary and secondary mining of lead was 4.6 million ton, and 5.6 million ton was from recycling, a total supply of 10.2 million ton per year. That corresponds to recycling being about 55% of the supply. The cost of recycling is about 45–50% of the cost of primary production for lead. It is generally

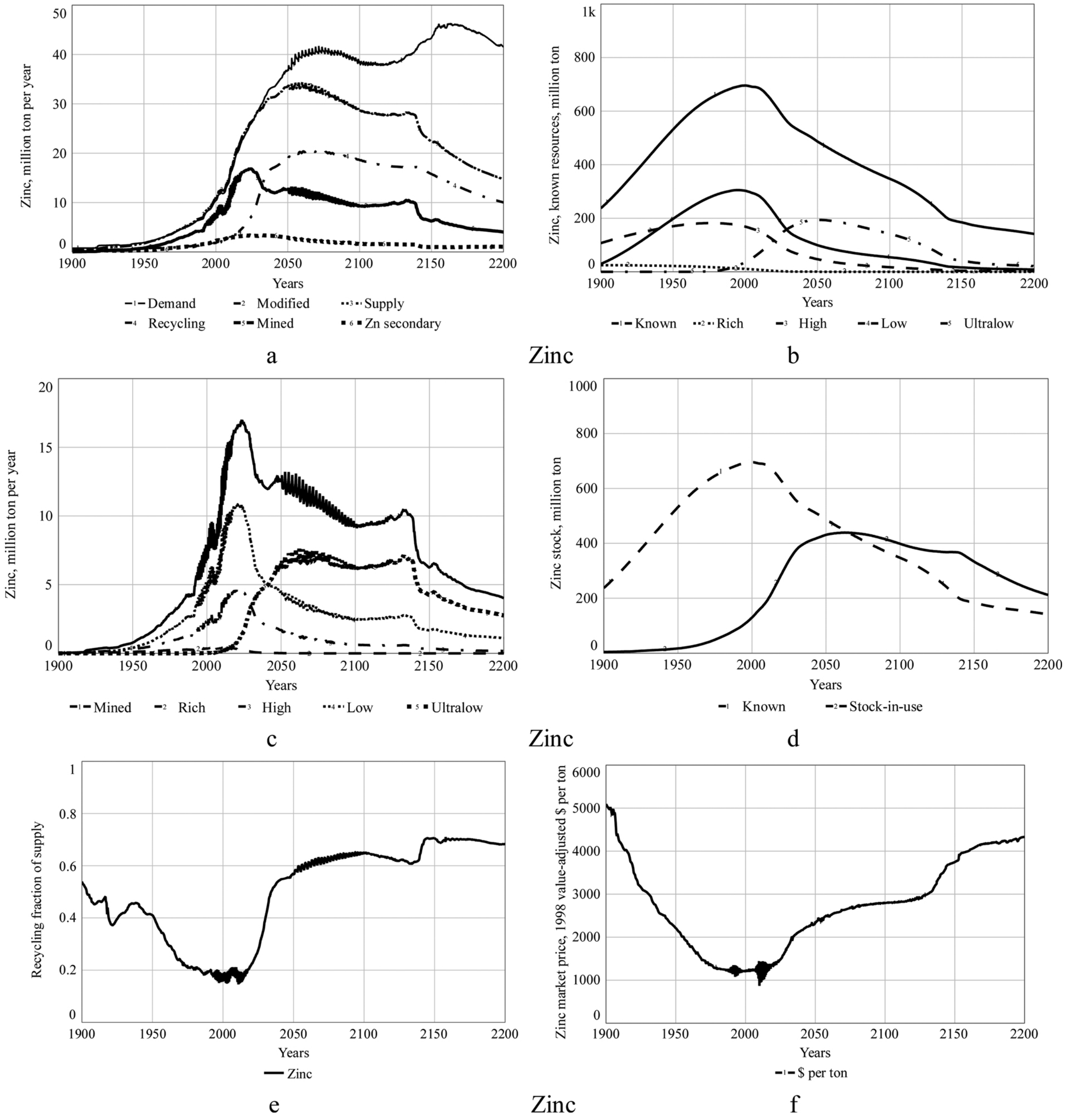


Fig. 8. Zinc (a) shows mining, demand, modified demand by price, supply to society and recycling. (b) shows known extractable amounts distributed to the different ore grade categories used in the model. (c) shows the zinc mining rate and contribution from different ore qualities. (d) shows the stocks-in-use and the known resources. (e) shows the recycling fraction, no data is available for comparison. (f) shows the market price compared to the observed price. The dotted line represents the observed data (until 2017).

agreed that about 80–85% of all lead batteries from cars are recycled (UNEP, 2011a). Fig. 9e shows the recycling degree for lead. Fig. 9f shows the simulated lead price with time as compared to the observed data up until 2017.

6.4. Testing the model

The WORLD6 model has been tested against the recorded mining data derived from the USGS (2013) databases. The WORLD6 model does reproduce the observed mining rates satisfactory when the model is driven by market demand and price dynamics. The WORLD6 model uses the extraction cost stratified ore grades for lead and that results in about the double reserve estimate of what gets actually extracted as compared to the USGS 2014 estimates. Fig. 10a shows the cumulated amount of copper, zinc and lead mined from 1870 to 2017, the dots are the line based on the integration of observed mining data. Fig. 10b shows the long term fit between the observed data for copper mining and the simulation output for copper mining. The fit shows that there is no systematic bias in the model since the fit is excellent (Fig. 10a, $r^2 = 0.986$). Fig. 10c and d show the same for zinc and lead.

6.5. Cu, Zn and Pb ore grades 1800-2200

The model suggests the ore grades of copper, zinc and lead will continue to decline. The ore grade of all the base metals modelled go down with time, the large transition occurs between 1900 and 1960 for copper, and 1960 and 2015 for zinc and lead (Fig. 11d). The trend is irreversible, and the strongest indicator that these metals will one day

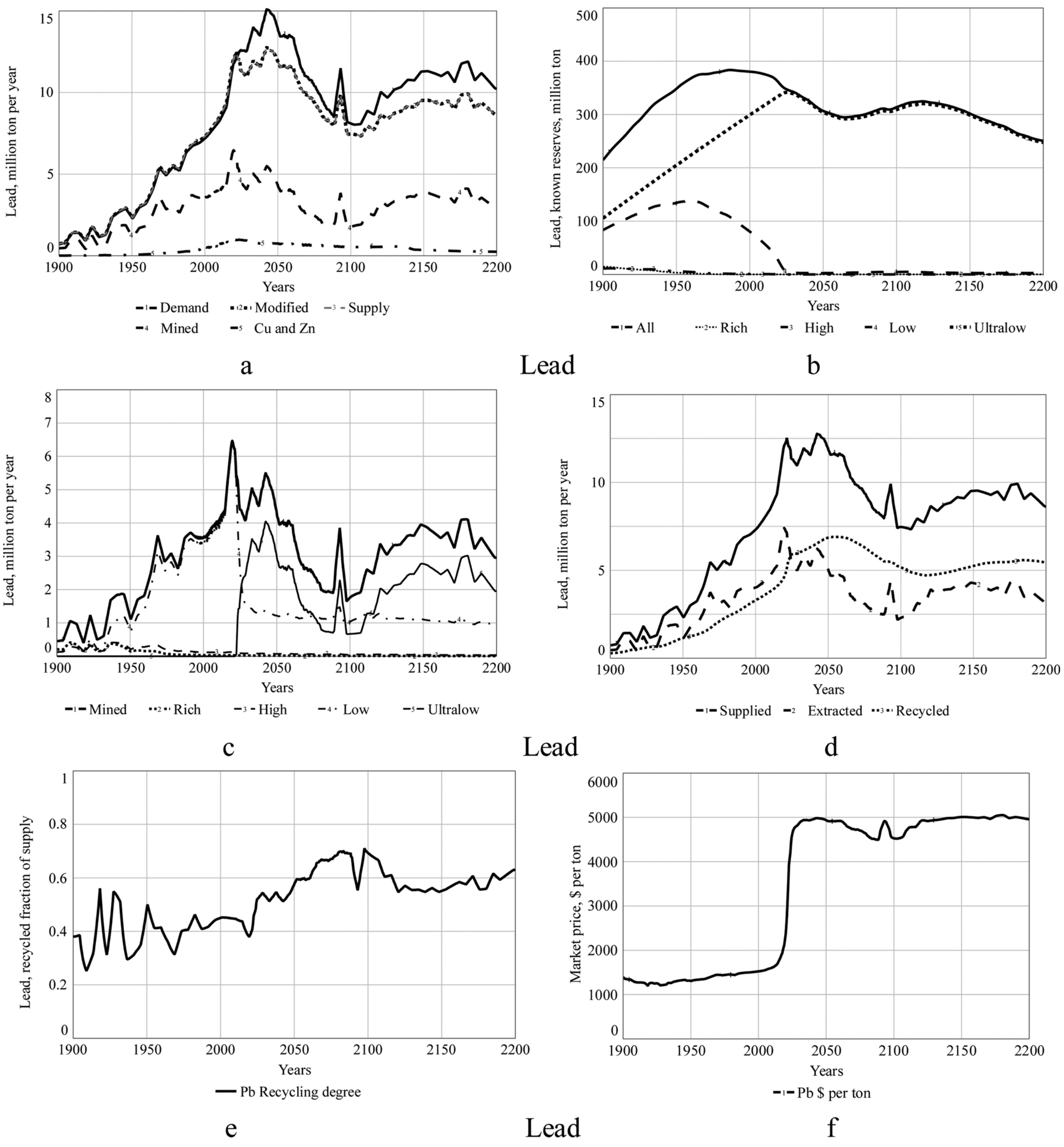
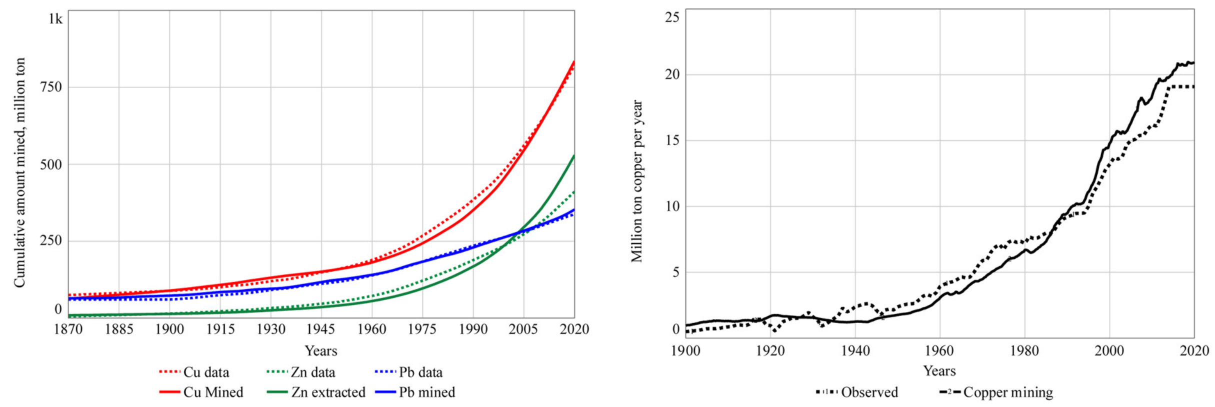


Fig. 9. Lead: (a) lead demand, demand after modification by price, the supply from mining and the amount of lead coming from copper and zinc mining compared to the observed mining rate. (b) shows the development of the known reserves over time. (c) shows lead mining rates, contribution from different ore grades and data on mining. (d) shows the extraction rate, supply to the market and the amount from recycling. (e) shows the recycling degree for lead. (g) shows the market price compared to the observed price, no data after 2017.

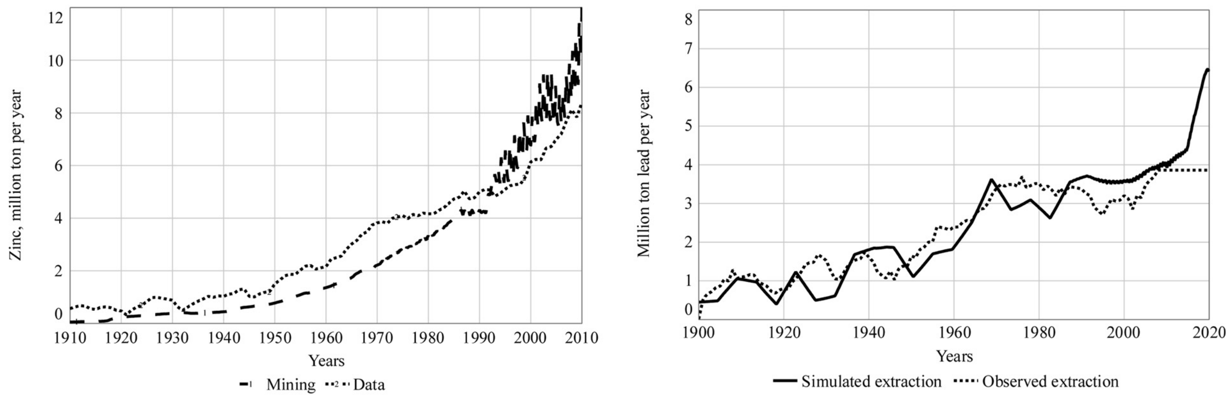
become scarce. The declining ore grade implies that more effort is needed to extract metal, as every ton or ore contains less metal. The result is that energy use and work input increases steadily. Almost all metal mines have consistently declining ore grades (silver, gold, uranium, zinc, lead, tin, gold, copper, nickel, platinum, palladium, niobium, tantalum), ranging from a reduction in ore grade by a factor of 5 (palladium), a factor of 10 (uranium) to a factor of 40 (lead, gold, silver), it is a consistent global pattern (Mudd, 2007, 2009, 2010a,b, Mudd et al., 2013a,b, Mudd and Jowitt, 2014). Table 4 shows an overview of amounts of copper, zinc and lead extracted supplied to society.

The metal market price is well simulated for copper (Fig. 11a), zinc (Fig. 11b) and lead (Fig. 11c). Copper and lead supply to society is far larger than primary mining, because of effective recycling of copper. Copper has a high price, and copper recycling profits from a cultural habit promoting recycling. Zinc has a lower recycling rate, and this is caused by zinc being used for purposes where it is not possible to recycle it. One of the most important uses of zinc, galvanization of iron for rust protection, works by sacrificing the zinc, thus losing it. Similarly, anodic corrosion protection, implies zinc being sacrificed to corrosion to protect another metal. After 2055, stock-in-society will be larger than known extractable amounts. Note how recycling will be the major source of copper after 2050.



a) Cumulative

b) Copper



c) Zinc

d) Lead

Fig. 10. Cumulative shows the cumulative amounts mined for copper, zinc and lead as compared to the observations. The cumulative amounts show that errors are not building up in the model. The simulations show very little bias from the data and systematic errors are not building up.

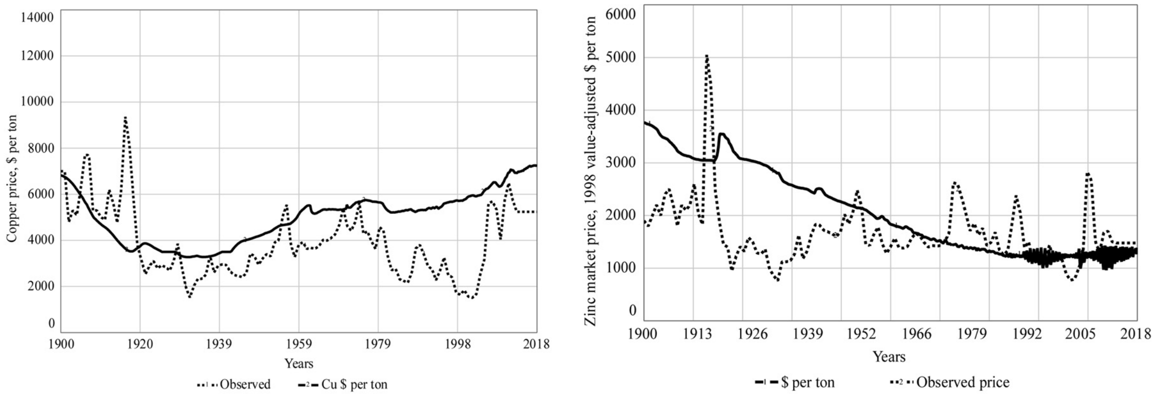
7. Discussion

7.1. On the adequacy of the way prices and supply are modelled

The WORLD6 model seems to be able to reconstruct observed data reasonably well. The Mass Flow Analysis performed by Northey et al. (2014) reach the same conclusions concerning need for future policies as we do. The consistently declining ore grades are matched by the model (Fig. 11d), is a strong indication of the coming scarcity and increased price for copper, zinc and lead. We are able to reconstruct the past history of copper, zinc and lead mining rates and ore grade decline and approximate metal price levels for all three (Fig. 11). The market mechanism and how well the prices can be modelled for metals, materials and commodities has been described, shown and discussed in a related but separate study by the authors (Sverdrup and Olafsdottir, 2019a,b,c and Olafsdottir and Sverdrup forthcoming, 2019). Fig. 11d is an empirical proof that copper, zinc and lead are becoming more scarce metals, showing that the copper, zinc and lead reserves and resources are becoming depleted. The pattern is accurately reconstructed by the model. The depletion is first manifested as a quality decline, and as well as showing that we are on the road to scarcity. For copper, zinc and lead all the higher grades are exhausted, and all mines are working on ore grades from 1/10th to 1/40th of what they were 150 years ago.

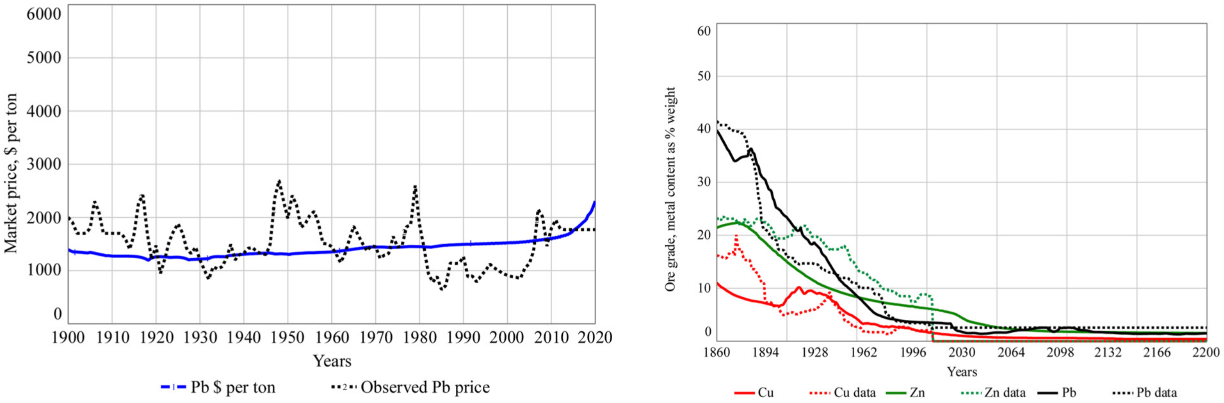
We need to carefully distinguish between the primary production from mines and total supply to the market. Long after primary copper, zinc and lead mining has been reduced to insignificant levels, supply may be kept up by efficient recycling. The time after 2050 will be the age of urban mining, where more copper, zinc and lead metal is supplied from recycling that from primary extraction from mines. That assumes that recycling stays efficient or improves. It appears as the method to use an extraction cost-ore quality stratified approach gives a better estimate for extraction calculations and a model that will respond better when put inside an economic model. Such a price model is able to respond to changing economic conditions, which is preferable for the WORLD6 model. In the model, the demand is taken from the market, and when the market amount decrease, then the prices increase. The higher prices push mining, causing the price to decrease. The model becomes self-regulating. Thus, the market dynamics are fully expressed in the present WORLD6 model.

In the discussion of sustainability, we should note that recycling can delay symptoms of scarcity for a significant time even after the production from mines has stopped. The recycled copper, zinc and lead have nothing of the dependent metals preserved and this must be considered in a future strategy for how they are to be sourced. The dependent metals may fast run into physical scarcity because the price has no feedback on the extraction rate of the mother metals copper, zinc or lead. It is important to consider that when the commodity is still relatively cheap, it may for that reason be unnecessarily wasted, when it would in retrospect have been relatively easy to induce better use efficiency and recycling. To wait until there is severe scarcity would be too late for optimal mitigation as unnecessary resources would already have been wasted by then. Others have proposed deep ocean mining (Scott, 2001) but efficient and affordable technology for this has failed to surface so far (See below). Different authors point to future risks and possibilities and mainly focus on issues of short-term market conditions, better technologies and new markets. The future will show how these issues will really work out under a different set of conditions with potential scarcity and additional challenges of climate change (Wagner and Fettweis, 2001; Ghose, 2009; Eliott et al., 2014; Morrigan, 2010). In the model, different efficiencies in extraction, mining, costs are



(a) Copper price

(b) Zinc price



(c) Lead price

(d) Ore grade

Fig. 11. The diagrams show further detail in the test of the models ability to reconstruct the price as compared to the data. (d) The simulated ore grades as compared to the observed data. The solid lines are the simulations, the dotted lines are annual data on approximate global average ore grades. The picture of drastically declining ore grades globally, points towards resource exhaustion and increasing prices.

Table 4
Overview of amounts metal extracted from mines and supplied to society to 2400. Million ton.

Item	Copper	Zinc	Lead
Primary URR, million ton	4,030	2,676	3,015
Secondary URR, metal in other mother metals, million ton	770	594	398
Total URR	4,800	3,270	3,413
Overall extraction yield	87%	87%	85%
The part of URR being extractable, million ton	3,510	3,076	2,563
Supplied to mined ratio, Factor X	2.6	3.4	1.8

improving with time and as a function of the metal price. This is further described in the supplement (Figures 3, 4 and 5 in the supplement).

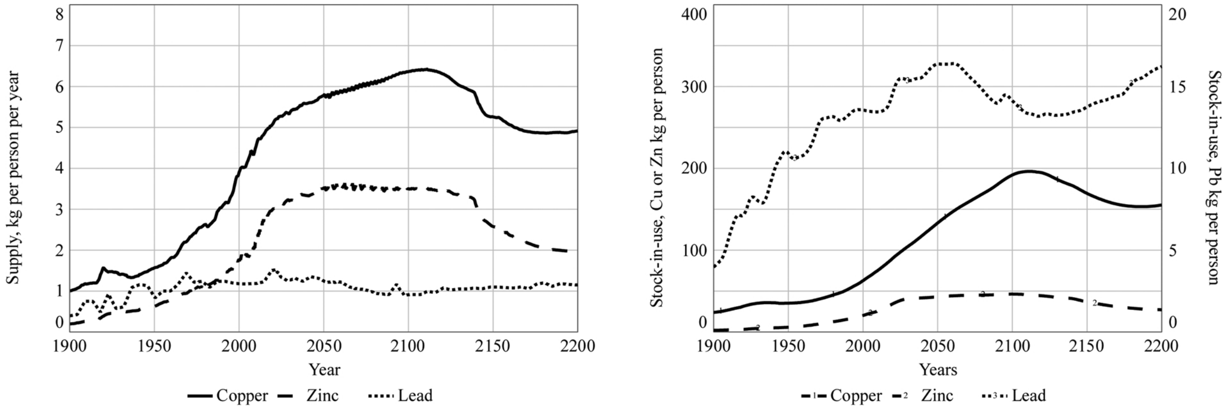
7.2. The risk for scarcity and the importance of using a useful metric

The declining ore grade is a clear indication that the resource has been depleted. For some time, this was offset by improvements in efficiency and lowering of wages, but that has recently come to an end. The differences in metal production amounts, and the fact that significant amounts already are booked for important purposes in society, makes substitution a significantly limited option for coping with larger scarcity issues. Fig. 12a shows the supply in kg per person and year and Fig. 12b the stock-in-use, kg per capita, for copper, zinc, lead and nickel as calculated using the WORLD6 model. The stock-in-use indicates the amount of utility that we have from each metal, whereas the supply per person, suggests how much we have available for maintenance, to replace losses and if possible, for growth. The model suggests that volume growth for copper use stops about 2030, for zinc it is around 2140 and for lead it stopped already around 1980.

The observed data are extracted from diagrams in the publications of Mudd (2009, 2010a,b, Mudd et al., 2013a,2013b) as well as single values picked throughout very many publications. The utility of copper peaks in society in 2120, for zinc in 2090, for lead in 2070. The supply level stays above the 2017 level to after 2400 for copper and declines to the 2017 level in 2350 for zinc. The stock-in-use stays above the 2017 level beyond 2400 for both copper and zinc but falls below that in 2260 for lead. In many of its uses, zinc is not recycled in a way that gets it back into the system. Use of zinc in pigments or in galvanization imply a complete loss of the material.

Based on the simulation outputs, it looks like there will not be any acute levels of physical scarcity in the next century. The main reason for this will be the increasing price and the retarding effect this has on demand. A main driver for price increases will be increasing extraction costs. The main reason for the increasing extraction costs will be the decline in ore grade and the increasing energy costs during the period. The WORLD6 model simulations imply a Factor X of 2.6 for copper, 3.4 for zinc and 1.8 for lead for the period 1850–2350 (Table 4). Factor X is the ratio of supplied to mined, showing how many times each kg is used before it is lost.

For zinc and lead, there is a reason for concern, that the simulations here may give a too optimistic picture. Our own estimates based on geological literature and surveys done by geological surveys (Burrows and Lesher, 2012; Cooke, 2013; Cossette et al., 2014; Cox et al., 2003; Crane and Kavalieris, 2012; Cunningham et al., 2008; Ehrig et al., 2012; Gray et al., 2014; Hehnke et al., 2012; Hertzman et al., 2012; Lang and



(a) Supply per person per year (b) Stock-in-use per person

Fig. 12. The supply in kg per person and year (a) and the stock-in-use (b) kg per capita, for copper (-1-), zinc (-2-), and lead (-3-) as calculated using the WORLD6 model.

Gregory, 2012; Leveille and Stegen, 2012; Ludington et al., 2012; Mihalasky et al., 2011, 2015a,b, Taylor et al., 2012, 2013a,b, Xavier et al., 2012; Yakubchuk et al., 2012; Zientek et al., 2014a,2014b, 2015, Zürcher et al., 2015) sums up to very much larger reserves and resources that some studies by Mudd et al. (2017a,2017b). They went through a large number of mines being operated at present and prospecting literature, and their estimates were about ¼ of the other estimates. We have been in contact with our Australian colleagues, but it has been difficult to resolve what is the real reason for the large discrepancy. At present, this adds an uncertainty to the results for zinc and lead. Using ¼ of the resource size implies severe zinc and lead scarcity within the next 50 years.

For copper, the estimates of Mudd and his colleagues and the other studies are fully consistent. For copper, zinc and lead there are few options for substitution beyond a very limited scale. For some applications, lithium may be a technical substitute for lead. But lithium is produced in 250,000 ton per year whereas the demand for lead is 2.5 million to per year. Thus, lithium is not a realistic alternative for large scale substitution. Large scale substitution can only take place with a metal that is produced in larger amounts than the one it should substitute for. For copper, that can only be iron and aluminium. For zinc, it can only be copper, aluminium, manganese or iron. For lead, it can only be iron, manganese, chromium, aluminium, zinc or copper. The best bet is that aluminium may substitute for a significant amount, but far from all. Thus, we cannot count on substitution to prevent a situation of scarcity in these metals. Using less, and using less, to do more service may be a way.

7.3. The circular economy and copper

Copper zinc and lead are key metal is changing society towards a circular economy. They are the main source of the technology metals that are required for all new technologies. The supply of these depend on the hydrometallurgical extraction from ore concentrates, and the turn towards cheaper heap leaching type of extraction, is a real concern for technology metals supply sustainability. Copper is used in large amounts for new technologies and new energy generation technologies, and potentially the demand may grow more that foresee and more than the industry can supply. Under such a scenario, the only extra amount will be from recycling. Fig. 13 shows the simulated ratio between amount supplied in total and the amount primary extraction from ores in the ground. This is sometimes called Factor X. A Factor X value below 2 implies a poor metal use efficiency, a value above 5 is very good. In simplified terms, Factor X expresses how many time the metal is used before it is lost. For all three metals, there are room for great improvements.

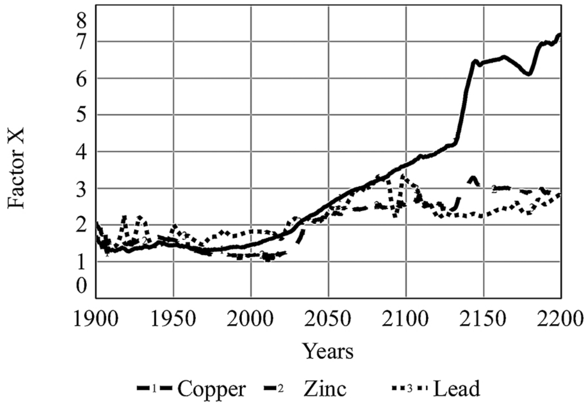


Fig. 13. The simulated Factor X for copper, zinc and lead.

7.4. Model limitations and strengths

The main limitations for this model lies in the parameterization of the model. In this model, very many assumptions were made, and there was not always information available to check them all. It is a global model and many parameter settings are global averages, where fully representative global surveys for the particular aspects are not available, but rather a number of snapshots. Then we have made generalizations and assumptions that have been described in the supporting material.

The major strength of the model is that it is mass and energy balance consistent, and requires very little adjustment and calibration. It is not driven by fitting it to timeseries, but based on underlying fundamental systems properties and mechanisms. This allows the model to have larger generic validity, but it definitely takes more time and effort to develop and parameterize. It is a major strength that it simulates all the resources simultaneously, that the outputs are both linked and mutually consistent and successfully verifies against observations.

The WORLD6 model consists of very many simple sub-modules which interact through very many coupled feedbacks, generating a very flexible and dynamic system. The long-term experience is that making the complex model from simple component helps keep the whole system numerically stable.

The main limitation of any deterministic model is that whatever is not represented in the model, has no effect on the simulated outputs. It means that when the model recreates what is observed, that can be interpreted to imply that the necessary and essential parts of the system has been captured. When the outputs does not recreate what is known to have happened in the past, that indicates that some essential component of the system has not been represented in the model. That is an important message to get, in order to make a better model. We have chosen to create a deterministic model, as we would like to use the system to explain what passed in the past, based on the system understanding. When we can explain the past from understanding, then the probability of making good predictions for the future will be better.

In modelling a system, a choice must be made: what to include in the model and represent well and what to park in the assumptions. A simple model is easy to operate, but it has limited content and flexible dynamics. A simple model can only answer simple questions. As a result, the assumptions are very complex with complex ramifications. The complexity of the system is inherent to the system and cannot be changed, and ignoring them, does not make them go away. A complex model considers more aspects and will have more dynamics and feedbacks. It can be used to answer more complex questions, and the assumptions will be simpler, as complexity is moved from the assumptions and represented in the model. The philosophy of the WORLD6 model is a balance between these aspects outlined above. Each module is constructed to a certain point as a relatively simple sub-module. Each module should be reasonably well representing the system, but without going to excessive details, demanding inputs that gets difficult to get operationally. Adding more detail, demand more parameterization information to be collected, which is time-consuming and costly, and when the resources are not present there for doing that, then assumptions must be made instead.

8. Conclusion

The conclusion is that there is not any immediate crisis risk for copper, zinc and lead supply in the short term, but that in the long run (after 2030), soft scarcity manifested as rising metal prices. This is under the assumption that copper demand increases dramatically more than what we have assumed. If new technologies would result in sharply increased copper demand, then a scarcity situation before 2200 would be possible. This implies that it becomes an economical prioritization about what is important to use copper for and what is not. There is no room for any substantial increase in copper or zinc supply per person after 2025.

A Copper:
  a The copper provision per capita per year and as stock-in-use per capita in the future goes through a maximum and stays level with a slight decline for copper.
  b There will not be a copper crisis with a physical shortage. There will be a soft scarcity where the price goes up enough to reduce demand. The price goes up modestly, mostly because of declining ore grade and increasing cost of extraction, as well as demand being much larger than what the system can supply. The supply per capita and year will stay at or above the supply level of 2010 beyond 2250.
  c Copper becomes expensive in the future, and the global society will have to live with copper being valuable and more expensive. This will make mass use in poorly recycled products problematic
  d In the future, there will be a no-growth, tight market, but no physical scarcity or supply collapse.

B Zinc
  a Provision per capita per year goes through a maximum and declines.
  b The price goes up modestly, mostly because of declining ore grade and increasing cost of extraction.
  c Recycling of zinc is not likely to improve as many applications are based on losing the metal or used dissipatedly in a way that makes recycling problematic (Galvanizing against rust or as sacrificial anti-corrosion anodes on ships are some examples).
  d In the future, there will be a no-growth, tight market, but no physical scarcity or supply collapse.

C Lead
  a Declines slowly for zinc and for lead it declines by policy design. Lead resources will be sufficient at all times.
  b The price will increase because of declining ore grades causing increasing extraction costs.
  c Demand will stagnant because or legislative restrictions on lead use and increasing concerns about its long-term health effects on humans It will probably only remain for limited niche applications.
  d In the future, there will be a stagnating market, but with no real physical scarcity.

D For all the metals, an end-of-growth type of result is clearly visible in all outputs. Similar patterns can be seen in other assessment (silver, gold, lithium, wolfram, molybdenum, tantalum, rhenium, niobium, tin, nickel or rare earths). The low global population scenario (Global population peaks at 9 billion and declines to levels between 2 and 4 billion people) shows a long term stabilizing steady state market for copper and zinc. This occurs in 2030 for copper, in 2050 for zinc and has already happened for lead (2010).

Declaration of interests

The authors declare that they have no known competing inancial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.rcrx.2019.100007.

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