Scarcity of Minerals and Metals: A Generic Exploratory System Dynamics Model

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Abstract

Possible short, medium and/or long term scarcity of minerals/metals may actually pose a threat to modern societies. Its potentially disruptive societal consequences qualify this issue for exploration from a world/regional security point of view. Hence, exploratory System Dynamics modelling and simulation is used in this paper to explore the dynamic complexity of potential mineral/metal scarcity under deep uncertainty and to create useful scenarios for risk management.

Keywords: Scarcity, Metals, Minerals, Exploratory System Dynamics

1 Introduction

1.1 The Issue: Scarcity of Minerals and Metals

Possible mineral/metal scarcity gets ever more attention as a potential security threat and a challenge for civil protection for many (Western) nations. Not only may shortening 'years of extraction until exhaustion' of high-volume minerals/metals pose a threat to the future way of living, potential strategic/speculative behaviour with regard to rare earth metals may also hinder or block the transition of modern societies towards more sustainable ones. These rare earth metals seem to be required in ever bigger quantities for many innovative –mostly 'greener'– technologies such as hybrid cars, flat screens, solar cells, led lamps, mobile phones. But these metals are quite dispersed, and their extraction/production expensive. Moreover, some countries, which already have quasi-monopolies on the extraction of specific rare earth metals, are believed/feared to constrain (future) exports. Hence, it is important to assess whether these natural and/or artificial constraints may actually lead to temporary and/or structural scarcity, which may, in turn, hinder the transition towards more sustainable societies.

1.2 The Method: Exploratory System Dynamics

Traditionally, System Dynamics (SD) (Forrester 1968)(Sterman 2000) is used for modelling and simulating dynamically complex issues and analysing their resulting non-linear behaviours over time in order to develop and test effectiveness and robustness of structural policies. The traditional approach may have to be used in a more exploratory way for issues that are characterised particularly by high degrees of dynamic complexity, very long time horizons, and deep uncertainty[1].

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[1]Lempert, Popper, and Bankes (2003) define deep uncertainty as situations 'where analysts do not know, or the parties to a decision cannot agree on: (i) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future [e.g. different drivers and underlying structures than

For such issues, improving models by increasing the level of detail or their size does not seem to help much. Instead of trying to develop ever more detailed models validated on past conditions, it may be more useful to focus on experimenting with *different* model formulations of the same issue, and exploring the influence of the full extent of a plethora of uncertainties on the robustness of policies, in other words, to explore long term policy effectiveness and robustness in the face of deep uncertainty.

1.3 The Paper: Goal and Organisation

The goal of this paper is to address the uncertain, dynamic complexity of mineral/metal availability and accessibility. As such, it may be a useful addition to historic, narrative, or short(er) term explorations of the issue (see (Kooroshy et al. 2010)). In its simple form, it may be used for exploring plausible developments, for selecting particularly interesting scenarios to be used for capability analyses, and for assessing a large range of plausible developments.

During the research, several models about mineral/metal scarcity were developed and used. Only one of these SD simulation models will be discussed here in order to keep the size of this paper within acceptable limits.

SD diagrammatic conventions are explained in section 2. The SD simulation model is presented in section 3. An illustration of behaviour generated with the model is provided in section 4. Traditional sensitivity analyses are reported on in section 5. The model is used to generate a worst credible scenario in section 6. Some policies to avoid or mitigate scarcity problems are briefly presented in section 7. Concluding remarks are presented in section 8. A 'hot testing & teaching case' corresponding to this issue –but based on one of the other models– is presented and discussed in (Pruyt 2010a).

2 System Dynamics and Diagrammatic Conventions

In the next section, a generic ESD simulation model is presented. But before presenting this model, it may be useful for readers without SD foreknowledge to get acquainted to SD and its diagrammatic conventions. Experienced System Dynamicists are advised to skip the remainder of this section and to continue with section 3.

SD models consist of specific structural elements causally linked into feedback loops. These models only contain *direct causal* relations (e.g. the blue links in Figures 1 and 2). For SD to be of any use, it is required that possible causal links can be perceived or hypothesised. Causal influences are either positive or negative. A *positive causal influence* –indicated by a blue arrow with a '+' sign in Figures 1 and 2– means that if the influencing variable increases (decreases), all things being equal, the influenced variable increases (decreases) too above (under) what would have been the case otherwise, or $A \underset{+}{\rightarrow} B \Rightarrow \frac{\partial B}{\partial A} > 0$. In other words, 'a positive arrow from A to B means that A adds to B, or, a change in A causes a change in B in the same direction' (Richardson 1997, p249). A *negative causal influence* –indicated by a blue arrow with a '-' sign in Figures 1 and 2– means that if the influencing variable increases (decreases), all things being equal, the influenced variable decreases (increases) under (above) what would have been the case otherwise, or $A \underset{-}{\rightarrow} B \Rightarrow \frac{\partial B}{\partial A} < 0$. In other words, '[f]or a negative link from A to B one says A subtracts from B, or a change in A causes a change in B in the opposite direction' (ibidem).

A *feedback loop* consists of two or more causal influences between elements that are connected in such a way that if one follows the causality starting at any element in the loop, one eventually returns to the first element. In other words, the variable feeds back –after some time– to itself, which makes that its behaviour is (partly) shaped by its own past behaviour. Feedback loops are

today], (ii) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (iii) how to value the desirability of alternative outcomes'.

either positive or negative. A feedback loop is called positive or reinforcing if an initial increase in a variable A leads after some time to an additional increase in A and so on, and that an initial decrease in A leads to an additional decrease in A and so on. Positive feedback loops in isolation generate exponential growth or decay. A feedback loop is called negative or balancing if an initial increase in variable A leads after some time to a decrease in A, and that an initial decrease in A leads to an increase in A. Negative feedback loops in isolation generate balancing or goal-seeking behaviour and can be used for automatic control/balancing.

Feedback loops give rise to nonlinear behaviour, even if all constitutive causal relationships are linear. Feedback loops almost never exist in isolation: several feedback loops are often strongly connected, and their respective strengths change over time. The feedback concept is a fundamentally important characteristic of SD.

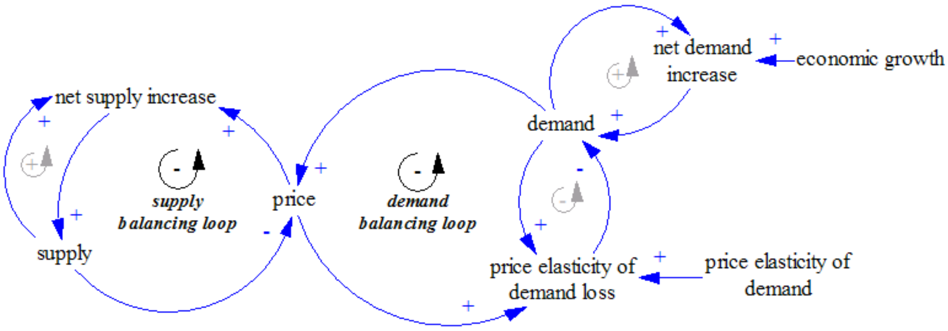


Figure 1: A detailed CLD

Causal Loop Diagrams (CLDs) are often used by System Dynamicists to map feedback loop structures. Figure 1 displays a detailed CLD of the simulation model displayed in Figure 3. Following symbols are used in a CLD: →+ represents a positive causal influence; →- represents a negative causal influence; →+ and →- represent a positive and a negative causal influence with a delay; ↺- and ↻- represent negative feedback loops; and ↺+ and ↻+ represent positive feedback loops.

A detailed CLD (as in Figure 1) can often be simplified and aggregated. The feedback loop structure is often easier to communicate by means of such aggregated diagrams (see Figure 2 for an aggregated CLD of the detailed CLD in Figure 1). This CLD reads as follows: an increase (decrease) of the *economic growth* leads to an increase (decrease) of the *demand* above what would have been the case without the increase (decrease) of the *economic growth*. This increase (decrease) of the *demand* causes –ceteris paribus[2]– the price to rise (fall), which leads to a delayed increase (decrease) of the *supply* and a delayed decrease (increase) of the demand. The increase (decrease) of the *supply* leads –ceteris paribus– to a decrease (increase) of the price.

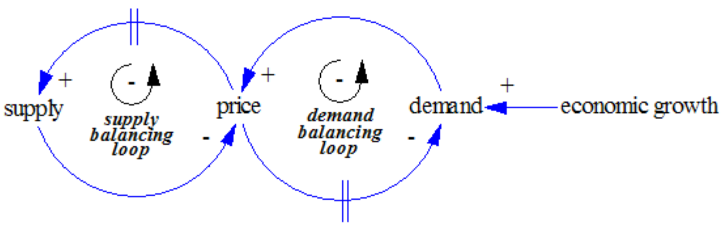


Figure 2: An aggregated CLD

SD models also contain *stock-flow structures*. Figure 3 shows a basic Stock-Flow Diagram

[2]Ceteris paribus is Latin for 'everything else being the same'.

(SFD), which graphically represents a SD simulation model, and more specifically, its stock variables (□), flow variables (⧗), auxiliary variables (◯ or no symbol), and constants (◇ or no symbol) and other direct causal influences between variables (the blue arrows). A stock variable –also called a level or a state variable– could be seen metaphorically as a 'bath tube' or 'reservoir'. During a simulation, stock variables can only be changed by flow variables (also known as rates). Every feedback loop contains at least one stock variable or memory (in order to avoid simulation problems caused by simultaneous equations).

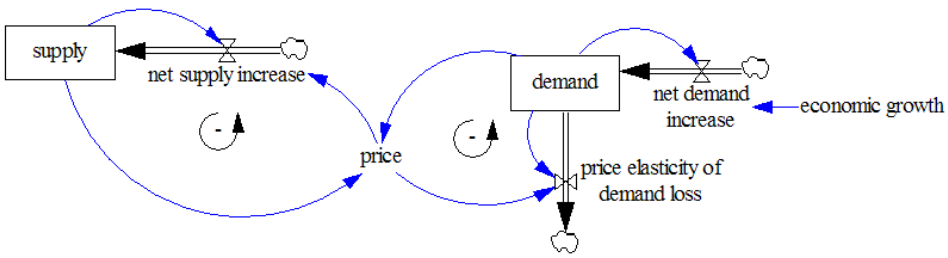


Figure 3: A SFD representing a SD simulation model

Positive inflows increase the contents of stock variables, and positive outflows decrease their contents: ingoing flows are, metaphorically speaking, taps or valves, and outgoing flows drains. Flow variables regulate the states of stock variables. Hence, flow variables are the variables that need to be targeted by strategies to improve the problematic condition/state of the more inert stock variables.

Mathematically speaking, the stock variable is the integral of the difference between the incoming flows and the outgoing flows over the time interval considered, plus the amount in the stock at the beginning of the period.

Time *delays* are also important elements of SD models. They are included in causal loop diagrams by means of slashed arrows (↛), and in stock/flow diagrams by different delay-type functions and/or stock flow structures, and slashed arrows (↛). *Nonlinear functions* may also be important in SD models. They are often included in computer models by means of (non-linear) table functions, also called lookup functions or graph functions.

The simulation over time of SD models of these structural elements gives what system dynamicists are really interested in: the overall modes of behaviour. System Dynamics is not to be used for exact point prediction or path prediction (Meadows and Robinson 1985, p34). One of the basic assumptions of SD is that the structure of a system (and model) drives its behaviour, and hence, that structural policies are needed to effectively and robustly change (possible) undesirable behaviours.

3 The ESD simulation model

The generic ESD simulation model comprises four major stock-flow structures outlined in the following subsections.

3.1 Demand and Supply

Figure 4 contains the demand, supply, and market price mechanisms of the ESD model.

The *Real Annual Demand* accumulates the net *economic demand growth* proportional to the *specific intensity* of that (set of) mineral(s)/metal(s) in the net economic growth. *Relative market price* increases (decreases) lead to *price elasticity of demand losses* (gains). And *substitution losses* occur when the *relative market price* rises above the price of a backstop *substitute*.

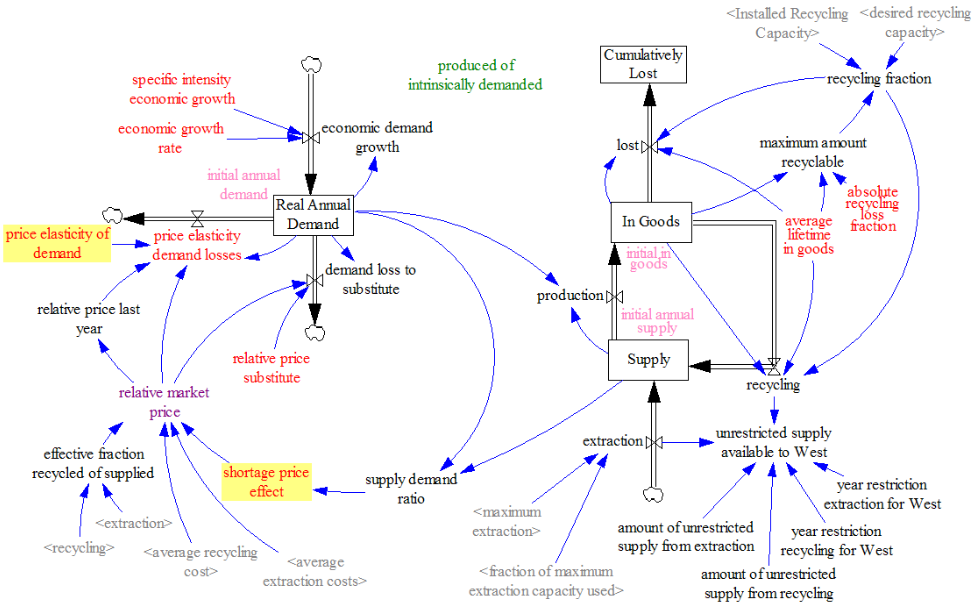


Figure 4: The 'demand and supply' view of the ESD simulation model

The critically important *shortage price effect* is modelled as a steeply declining logarithmic function of the *supply demand ratio* (see Table 2). In this model, this effect is multiplied by the average (extraction and recycling) cost and by the *normal profit margin* in order to calculate a *relative market price*.

The *Supply* stock variable increases both by means of the *extraction* flow and the *recycling* flow, both restricted by their respective *Installed Capacities*. Available *Supply* is subsequently used –in order to satisfy the *Real Annual Demand*– for the purpose of *production*, tying up minerals/metals *In Goods*. After an *average lifetime in goods*, some of the mineral/metal is lost, and some of it is recycled. The *recycling fraction* equals the minimum of either the *desired recycling* divided by the *maximum amount recyclable* or the *Installed Recycling Capacity* divided by the *maximum amount recyclable*. The *desired recycling* depends –in turn– on the *relative attractiveness of recycling* times the *Real Annual Demand* (see Figure 5(b)) plus the gap between *Real Annual Demand* and *Supply*.

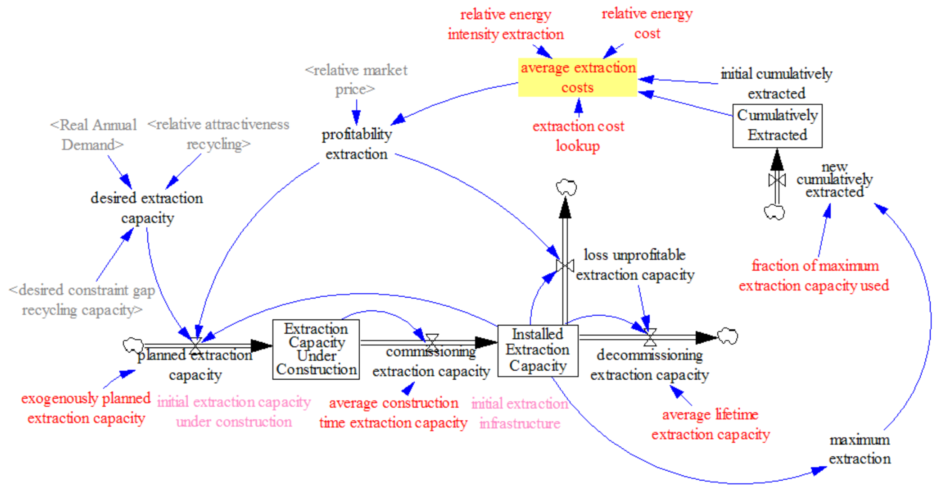
3.2 Extraction

Figure 5(a) contains the *extraction infrastructure* structure.

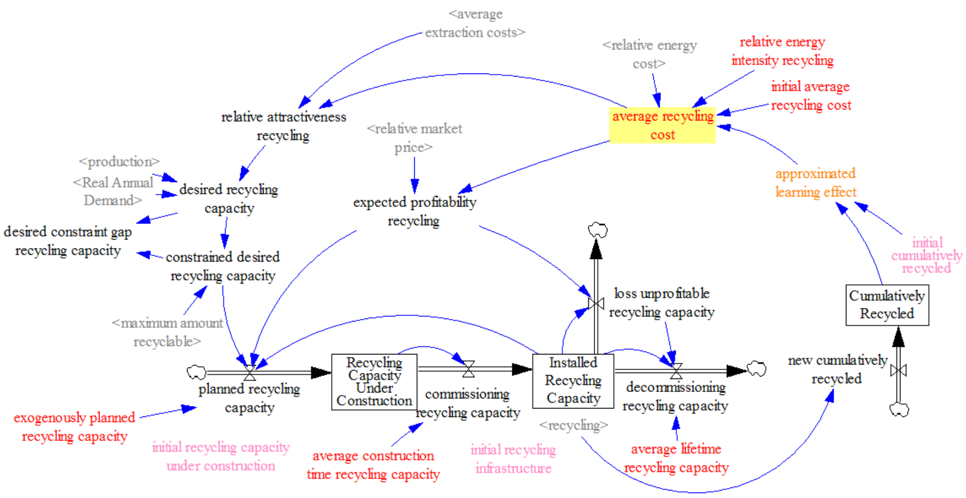
New *extraction capacity* is automatically planned for in the model if both the *profitability of extraction* and the gap between *desired extraction* and *Installed Extraction Capacity* are positive. The total *planned extraction capacity* then equals their product plus the *exogenously planned extraction capacity* (e.g. 'strategically' financed by governments). The *planned extraction capacity* flow lards the *Extraction Capacity Under Construction* stock, which, in turn, is gradually commissioned, increasing the fully operational *Installed Extraction Capacity*. The *Installed Extraction Capacity* is automatically and gradually *decommissioned*, after the *average lifetime of extraction capacity*. *Installed Extraction Capacity* may also be decommissioned before the end of its normal lifetime by the *loss of unprofitable extraction capacity* if extraction becomes loss-making.

The product of the full capacity *maximum extraction* and the *fraction of the maximum extraction capacity used* drives the net increase of the stock variable *Cumulatively Extracted*, which is used –by means of a very simple structure– to make sure that the *average extraction costs* increase.

In this model, the *average extraction costs* equal the product of the *extraction cost lookup*, the *relative energy cost* and the *relative energy intensity of extraction*. This *extraction cost lookup* is an exponential function of the difference between the *Cumulatively Extracted* and the *initial*



(a) The 'extraction capacity' view of the ESD simulation model



(b) The 'recycling capacity' view of the ESD simulation model

Figure 5: Submodels regarding installed extraction and recycling capacities

cumulative amount extracted (see Table 2 for its values). The *profitability of extraction* is then the difference between the *relative market price* and the *average extraction costs* divided by the *average extraction costs*.

3.3 Recycling

Figure 5(b) deals with the *recycling infrastructure* submodel, which is very similar to the *extraction infrastructure* submodel, with following four exceptions:

- In this model, the *average recycling cost* actually decreases because of the assumption that the recycling technology still has room to descend its learning curve. The simplified formulation assigns an inverse S-shape onto the *approximated learning effect lookup* function (see Table 2).
- Additionally, a 'returns to scale' effect was added to the recycling view during the scenario exercise. The *returns to scale* variable is an S-shaped lookup function of the *Installed Recy-*

cling Capacity. It generates the fractional cost reduction due to scale effects. This variable is not included here.

- The *desired recycling capacity* is *constrained* to the maximum recycling possible (given the *In Goods* stock). The resulting *gap between desired and constrained recycling capacity* is added to the *desired extraction* in Figure 5(a).
- The parameter values of the recycling submodel variables differ of course significantly from the parameter values of the extraction submodel (see section 4).

3.4 The Big Picture: Causal Loop Diagram with Major Feedback Loops

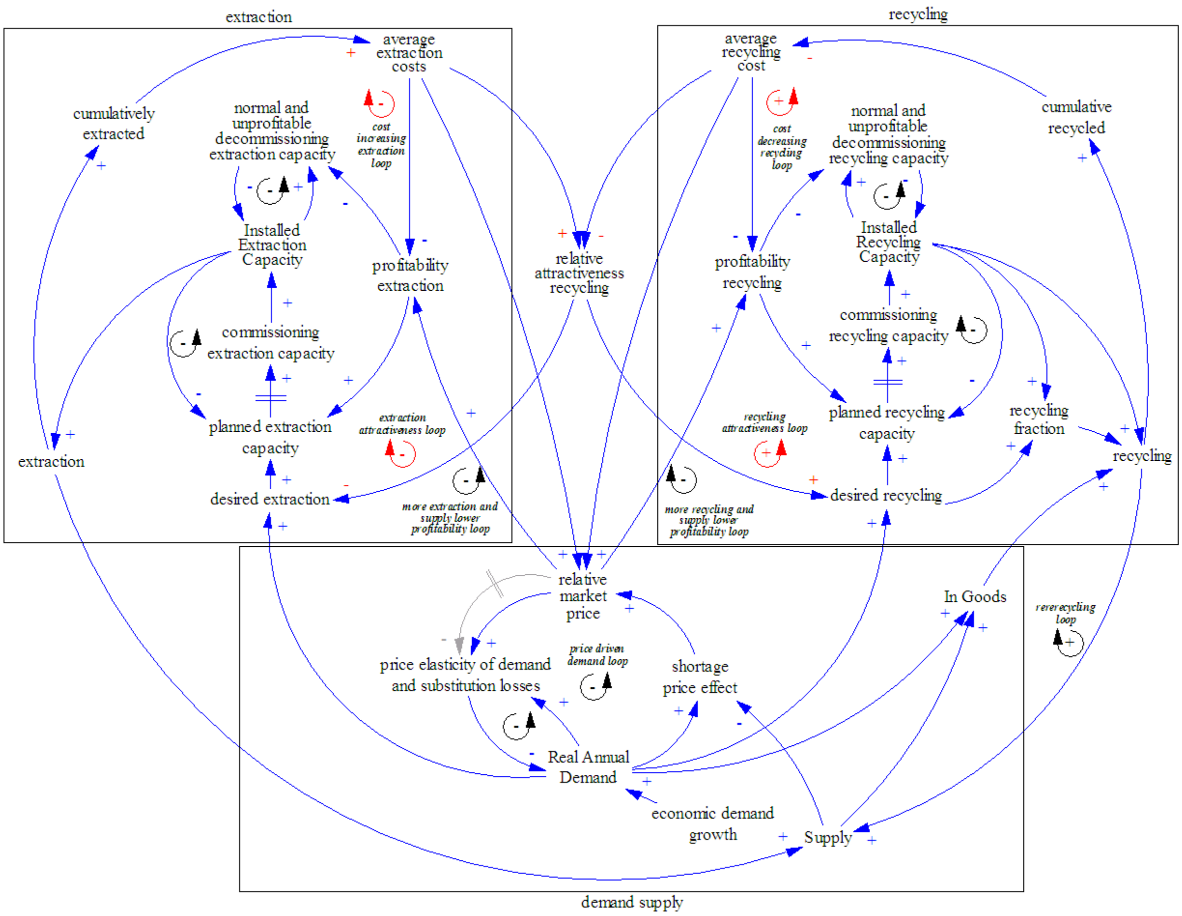


Figure 6: Main views and feedback loops of the SD simulation model

Figure 6 displays the main feedback loops of the simulation model. Differences in polarities between the extraction and recycling views are indicated in red: the two recycling sector feedback loops displayed in red are 'positive' (or reinforcing), but the linked extraction sector feedback loops are 'negative' (or controlling). Hence, although recycling may take off exponentially, it is intrinsically limited by the extraction loops. And these extraction loops are in turn limited by their steeply increasing extraction costs.

3.5 Assumptions and Simplifications

Although resources are not assumed to be limited physically in this model, they are seriously constrained by the exponentially increasing extraction costs.

The market for these elements is seriously simplified in this model. In the model, it is a rather transparent and efficient market based on an average cost-plus price times a normal profit margin and a shortage premium. The real market for these elements is, contrary to this modelling assumption, far from transparent and efficient.

Another important assumption of this generic ESD model is the assumed existence of a backstop substitute. If the model is used to study the ensemble of minerals/metals, then there is –as far as we know– no substitute. And if the model is used to study a particular mineral/metal for which there is no substitute, then the same point can be made. In that case, the substitute could be priced such that it does simply not become an option.

The current form of the model does not consider part of the *Cumulatively Lost* stock as a recycling resource. This criticism could be dealt with by small adaptations of the current model (see section 8).

If the *profitability of extraction* is positive, then it influences the *planned extraction capacity*, else it influences the *loss of unprofitable extraction capacity*. This 'binary' decision structure for either additional planning or additional decommissioning may be an artificial cause for cyclic behaviour generated by the model itself.

4 The Base Case

4.1 Parameter Values and Lookup Functions

The first three columns of Table 1 contain the names, units and parameter values and Table 2 the lookup functions that are used in the BaseCase run (and thereafter unless specified differently). The last four columns of Table 1 deal with the sensitivity of the model to small changes, which are discussed in section 5.

variable name	unit	value	name	low	high	sensitive
initial annual demand	10^5 t	1.0	UVS1	0.9	1.1	num0
price elasticity of demand	dmnl	0.2	UVS2	0.05	0.4	num+
relative price substitute	dmnl	5.0	UVS3	2.0	7.0	beh-
initial annual supply	10^5 t	1.1	UVS4	1.0	1.2	num+
initial in goods	10^5 t	20	UVS5	15	25	num-
average lifetime in goods	yr	15	UVS6	10	20	num0
initial extraction infrastructure	10^5 t/yr	1.1	UVS7	1.0	1.2	num0
average lifetime extraction capacity	yr	30	UVS8	25	35	num-
initial extraction capacity under construction	10^5 t/yr	0.1	UVS9	0.08	0.12	num-
average construction time extraction capacity	yr	5	UVS10	2	7	num-
fraction of maximum extraction capacity used	dmnl	1	UVS11	0.8	1.1	num+beh-
relative energy intensity extraction	dmnl	1	UVS12	0.8	1.2	num0
exogenously planned extraction capacity	t/yr/yr	0	UVS13	1000	10000	beh-
initial recycling infrastructure	10^5 t/yr	0.1	UVS14	0.08	0.12	num-
average lifetime recycling capacity	yr	30	UVS15	25	35	num-
initial recycling capacity under construction	10^5 t/yr	0.1	UVS16	0.08	0.12	num-
average construction time recycling capacity	yr	5	UVS17	2	8	num0
initial average recycling cost	dmnl	2	UVS18	1.5	2.5	num+beh-
relative energy intensity recycling	dmnl	1	UVS19	0.8	1.2	num+
absolute recycling loss fraction	%	30	UVS20	20	40	num+
exogenously planned recycling capacity	t/yr/yr	0	UVS21	1000	5000	num0
normal profit margin	%	10	UVS22	0	20	num+

Table 1: Parameter values used unless specified differently (dmnl = dimensionless)

Note that the model presented here is a generic model and that the values in the first three columns of Table 1 and Table 2 are just a set of generic values. The resulting behaviour is not the 'most likely' or the 'expected' behaviour, and is most certainly not to be interpreted as a

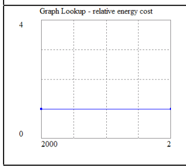
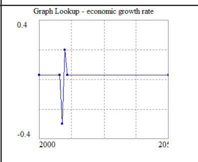
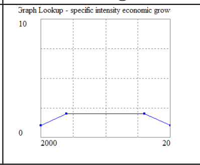
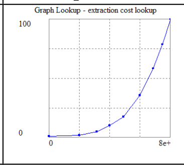
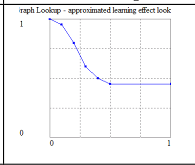
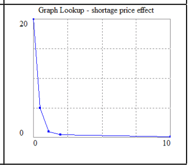
relative energy cost	economic growth rate	specific intensity economic growth	extraction cost lookup	app. learning effect lookup	shortage price effect
					
dmnl	1/yr	dmnl	dmnl	dmnl	dmnl
(2000,1), (2050,1)	(2000,0.03), (2008,0.03), (2009,-0.3), (2010,0.2), (2011,0.03), (2050,0.03)	(2000,1), (2010,2), (2040,2), (2050,1)	(0,1), (2M,2), (4M,10), (8M,100)	(0,1), (1M,0.95), (2M,0.8), (3M,0.6), (4M,0.5), (5M,0.45), (10M,0.45)	(0,20) (0.5,5) (1.1,1) (2,0.5) (10,0.1)

Table 2: Lookup functions (names, corresponding graphs, dimensions, and couples) used unless specified differently (dmnl = dimensionless)

forecast or a foresight. It is –at most– an illustrative model behaviour, in other words, just one out of many scenarios generated by the generic model. Although this is not pursued in this paper, specific scenarios could also be developed by means of (slightly adapted versions of) this model.

4.2 Base Case Behaviour

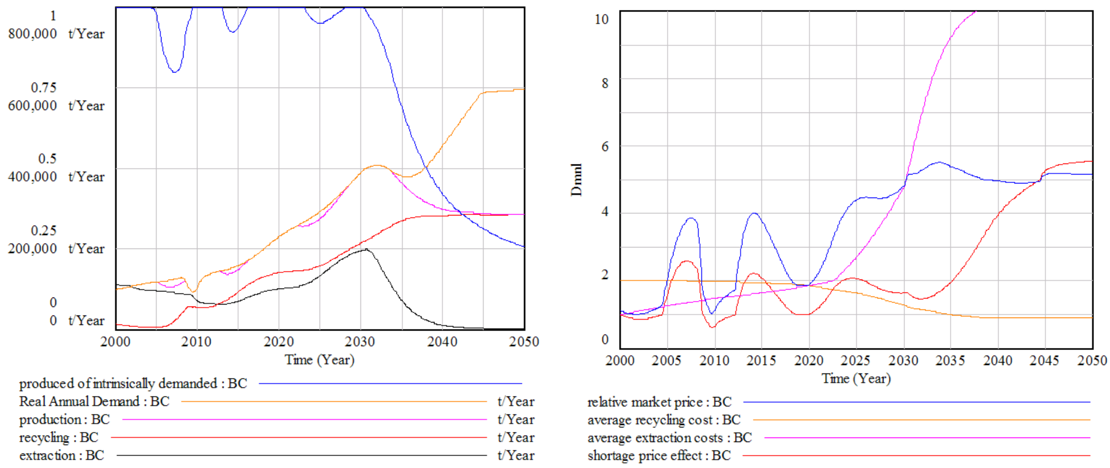


Figure 7: **Left:** Base case behaviour of the variables *produced of intrinsically demanded*, *Real Annual Demand*, *production*, *recycling*, and *extraction*. **Right:** Base case behaviour of the variables *relative market price*, *average recycling cost*, *average extraction cost*, *shortage price effect*.

The behaviour of the BaseCase scenario behaviour is displayed in Figure 7. In the left hand side graph, it can be seen that in the short to medium-term *production* is not able to satisfy the *Real Annual Demand* at some points in time and that this gap becomes a structural gap in the longer term. The resulting short to medium term price spikes only marginally damp the rise of the *Real Annual Demand* which is rather inelastic (0.1). However, the structural increase of the *average extraction costs* favors the development of recycling and –at a later stage– the gradual replacement of *extraction* by a backstop *substitute*. The latter effect causes the main indicator (*produced of intrinsically demanded*) to drop substantially.

5 Traditional Sensitivity Analyses

5.1 Univariate Sensitivity Analyses

The right hand side of Table 1 shows the manual univariate sensitivity analyses performed on the model parameters and the results of these analyses (in terms of their degree of numerical sensitivity (num-, num0, num+) and behavioural sensitivity (beh-, beh0, beh+)). It is important to know that, in SD, behavioural sensitivity matters much more than numerical sensitivity.
In short, the model seems to be somewhat sensitive to small changes in individual parameters, especially in the four following ones: the *relative price of the backstop substitute*, the *fraction of the maximum extraction capacity used*, the *exogenously planned extraction capacity*, and the *initial average recycling cost*.

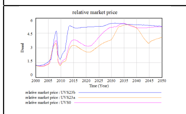
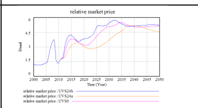
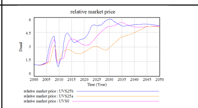
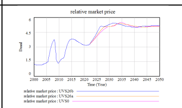
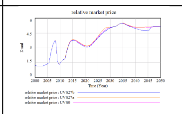
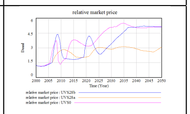
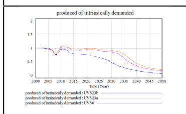
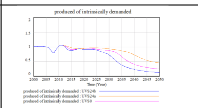
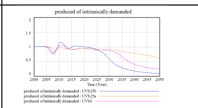
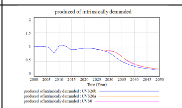
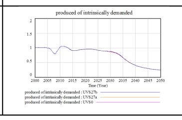
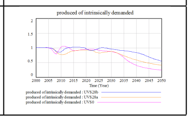
relative energy cost	economic growth rate	specific intensity economic growth	extraction cost lookup	app. learning effect lookup	shortage price effect
UVS23	UVS24	UVS25	UVS26	UVS27	UVS28
behavioural	behavioural	behavioural	numerical-	numerical-	behavioural
					
					

Table 3: Sensitivity of the model to small changes in the lookup functions (relative market price in row 4 and the indicator in row 5)

However, the model is much more sensitive to changes in the lookup functions (see Table 3), especially to changes in the *relative energy cost* lookup function, the *economic growth rate* lookup function, the *specific intensity* lookup function, and the *shortage price effect* lookup function.

5.2 Multivariate Sensitivity Analyses

Several Multivariate Sensitivity Analyses (MSAs) are discussed in this subsection. In a MSA, probability distributions are defined for uncertain variables, parameter values are sampled from these distributions, and many (e.g. thousands of) sets of parameter values are simulated instead of just one.

Some of the lookup functions are included as parameters for which a probability distribution is defined and sampled, namely the *specific intensity* lookup function, the *relative energy cost* lookup function, and the *economic growth rate* lookup function.

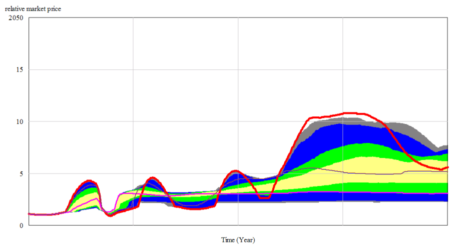
These simulations are somewhat simplistic because: (i) parameter values sampled from the probability distributions do not change during a run, and (ii) it is assumed here that the different distributions are independent.

5.2.1 MC2: *price elasticity of demand* and *relative price substitute*

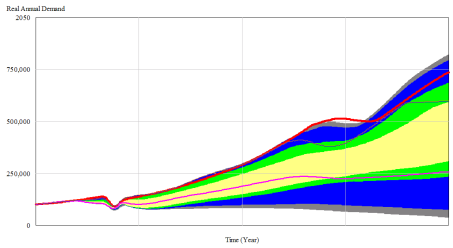
In the MC2 MSA, two parameters are distributed uniformly (*price elasticity of demand* $\sim U[0,1]$; *relative price substitute* $\sim U[2,10]$), 1000 parameter sets are sampled using Latin Hypercube sampling, and simulated. The results are displayed in Figure 8.

Combinations of a low *price elasticity of demand* and a high *relative price substitute* lead to a high Real Annual Demand, serious price spikes followed by structurally high long-term prices, much extraction and especially recycling.

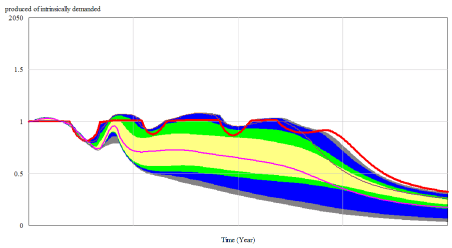
Combinations of a high *price elasticity of demand* and a low *relative price* of the backstop *substitute* lead to a low Real Annual Demand, minor price movements followed by structurally low long-term prices, and not much extraction but a reasonable amount of recycling.



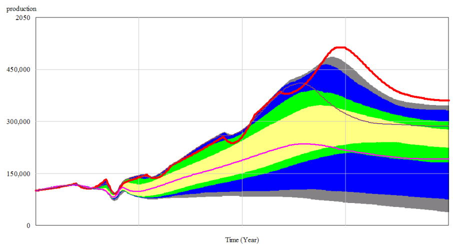
(b) MC2 relative market price



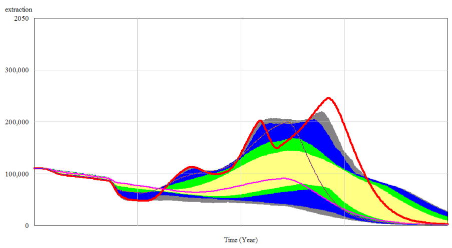
(c) MC2 real annual demand



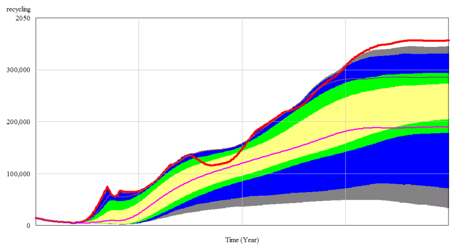
(d) MC2 produced of intrinsically demanded



(e) MC2 production



(f) MC2 extraction



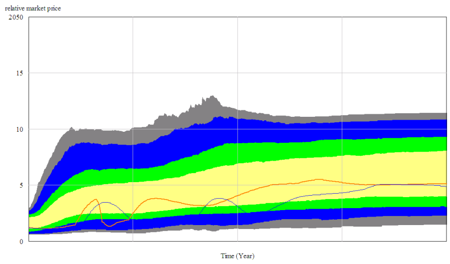
(g) MC2 recycling

Figure 8: MC2: LH1000; price elasticity of demand [0 , 1]; relative price substitute = [2, 10].

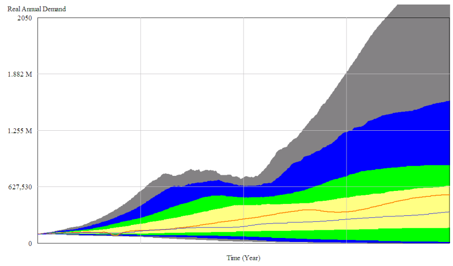
5.2.2 MVS4: Latin Hypercube on 8 variables

MVS4 consists of 1000 Latin Hypercube samples from the following distributions:
price elasticity of demand = RANDUNIFORM[0, 0.5];
relative price substitute = RANDUNIFORM[2, 10];
specific intensity economic growth = RANDUNIFORM[0.5, 4];
fraction of maximum extraction capacity used = RANDUNIFORM[0.8, 1];
initial average recycling cost = RANDUNIFORM[1; 4];
relative energy cost = RANDUNIFORM[0.5; 4];
economic growth rate = RANDNORMAL(0.01, 0.03);
exogenously planned extraction capacity = RANDTRIANGULAR[0, 0, 5000];
exogenously planned recycling capacity = RANDTRIANGULAR[0, 0, 5000].

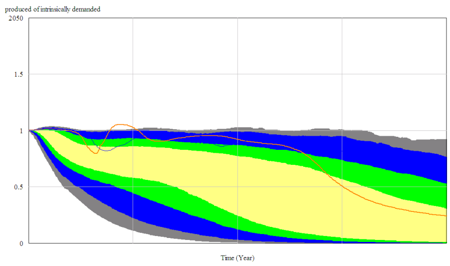
Figure 9 shows the aggregate results of MVS4. It only shows the envelops of values at each moment of time and does not trace the individual trajectories. The individual traces show rather spiky trajectories.



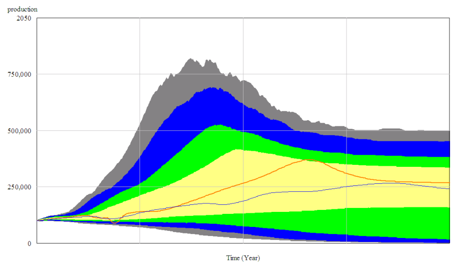
(b) MC4 relative market price



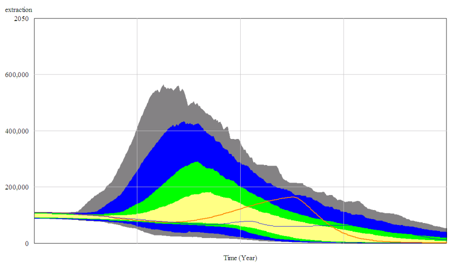
(c) MC real annual demand



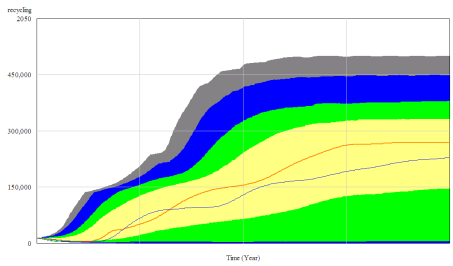
(d) MC4 produced of intrinsically demanded



(e) MC4 production



(f) MC4 extraction



(g) MC4 recycling

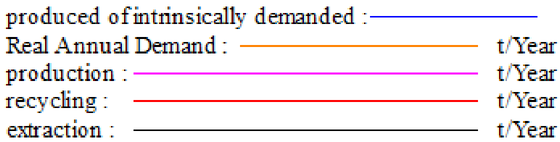
Figure 9: MC4: LH1000 on 8 variables

6 The Construction of a Worst Credible Scenario

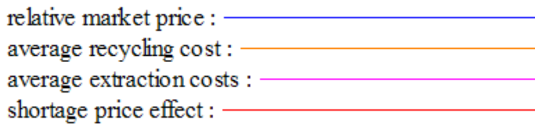
In this section, the sequence of changes made to create a worst credible scenario is reproduced here. This model-supported dialogue between modeller and client allowed to exchange information, discuss (modelling) assumptions, explain the dynamic consequences of changes made, and gradually develop a useful scenario. The scenarios discussed in this section are still generic scenarios. The scenarios and corresponding graphs are not to be interpreted as 'predictions' about the size and timing of the shortages and price spikes, etc.

Figures 10(c) and 10(d) show the behaviour of the first scenario, which is –starting from the BaseCase scenario– characterised by a rather low *economic growth rate* of 1% per year from 2011 on. Even in that case, there may be short-term price rises due to temporary shortages as well as a structural price rise due to rising extraction costs and a growing gap between demand and supply. Although supply increases due to the expansion of the recycling sector, it falls short of rising demand because of a shrinking extraction sector.

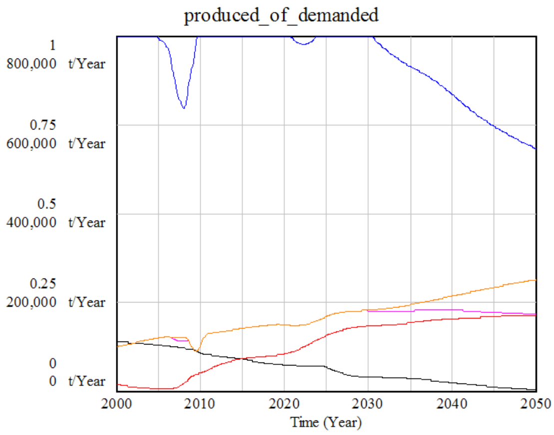
Figures 10(e) and 10(f) show that the behaviour of the second scenario –which is characterised



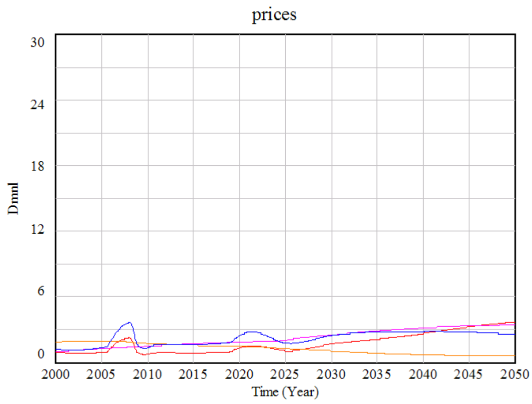
(a) Legend left hand side graphs



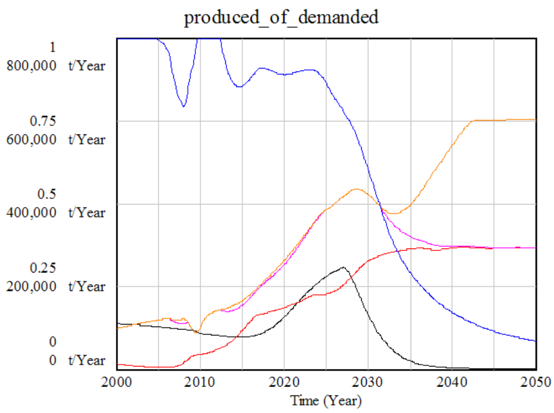
(b) Legend right hand side graphs



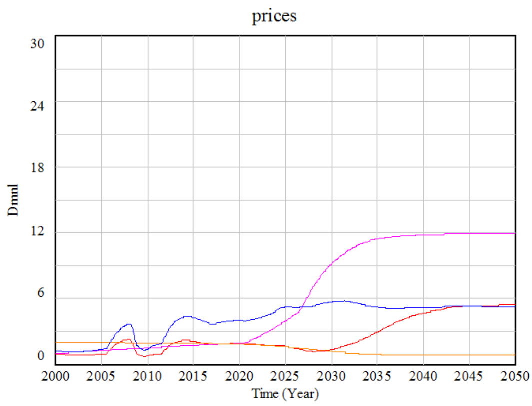
(c) Scenario 1: low growth scenario



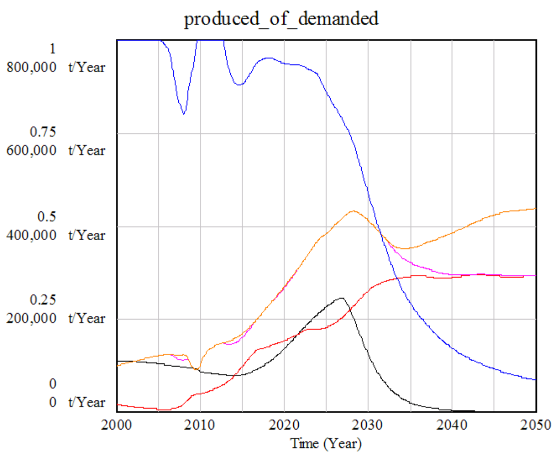
(d) Scenario 1: low growth scenario



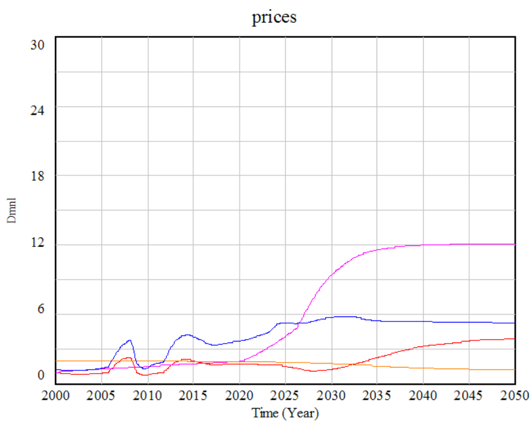
(e) Scenario 2: high growth scenario



(f) Scenario 2: high growth scenario



(g) Scenario 3: scenario 2 + low recycling



(h) Scenario 3: scenario 2 + low recycling

Figure 10: Scenario 1, scenario 2, and scenario 3

by a rather high *economic growth rate* of 4.5% per year from 2011 on– strongly differs from the behaviour of the low growth scenario. In case of scenario 2, the price spikes are slightly larger, but more importantly, the price becomes structurally higher in the medium to long run, due to the medium-term increase of the extraction costs and –at a later stage– the shortage price effect. The rise of the extraction costs –far above the price of the backstop substitute (5 times the initial normal price)– leads to a collapse of the extraction sector and a reduction of demand (compared to what would have been the case without price-related influences).

Figures 10(g) and 10(h) show the effects –in addition to the high growth rate of scenario 2– of less favorable conditions for development of the recycling sector: a higher *absolute recycling loss fraction* (40% instead of 30%), a lower *approximated learning effect* (40% instead of 60% by 2050), and a lower *returns to scale* effect (50% instead of 70% by 2050). The results only slightly differ from those of scenario 2: the higher recycling costs further suppress demand, even at a lower price shortage effect.

Scenario 4 is an underinvestment scenario: only 80% of *extraction capacity* as planned under normal conditions is planned for in scenario 4. Figures 11(c) and 11(d) show nevertheless that the resulting behaviour is almost exactly the same as without underinvestment.

In scenario 5, the *relative energy intensity of extraction* rises exponentially to 5 times its initial value. This corresponds to mining at increasing geographic and geological distances. It does not lead to a different system behaviour (see Figures 11(e) and 11(f)) because it only pushes the *average extraction costs* –already above the cost of the backstop substitute– further up.

Figures 11(g) and 11(h) show the behaviour of scenario 6 which equals scenario 5 but then with a low(er) *price elasticity of demand* of 5% (instead of 20%) and with a *relative price substitute* of 20 times (instead of 5 times) the initial price of the mineral(s)/metal(s) of interest. These two changes lead to a much higher *Real Annual Demand*, disastrous cycles of the *relative market price* after which the *relative market price* rises above the price of the substitute and remains at a high level. In this case, there will be more (expensive) extraction, as well as more recycling.

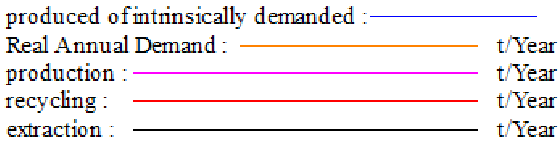
Energy prices quadruple in scenario 7 compared to scenario 6, raising average recycling costs. The resulting price spikes become even more extreme (see Figure 12(d)), further suppressing the demand (see Figure 12(c)).

In scenario 8, the *economic demand growth* and the *relative energy cost* are multiplied by sinusoid functions. Figures 12(e) and 12(f) show that these sinusoid inputs have an impact, but do not fundamentally change the previous results.

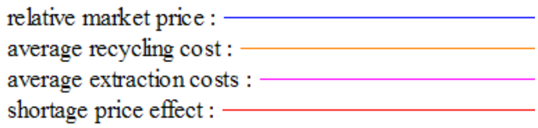
The latter scenario(s) may well be a '*worst credible*[3] mineral/metal scenario' because:

- the spectacular price falls are disruptive for extraction and recycling industries;
- the spectacular price rises are disruptive for mineral/metal-dependent industries (the sequence of price spikes may force them into bankruptcy or to move strategically);
- the long-term mineral/metal scarcity may lead to serious geopolitical problems;
- the potential of the recycling industry is limited by the extraction industry, and the full recycling potential is not reaped;
- and if this scenario is about a necessary mineral/metal without a decent substitute (or about all metals/minerals), then future welfare will be seriously jeopardised.

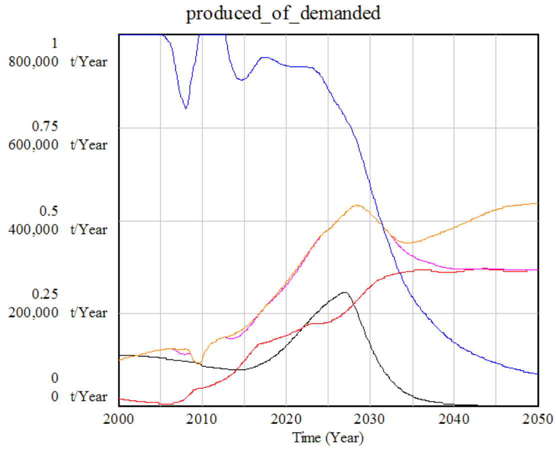
[3]Most National Risk Assessment approaches require worst credible scenarios.



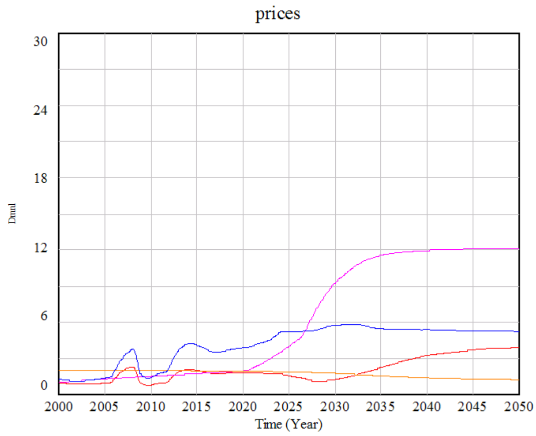
(a) Legend left hand side graphs



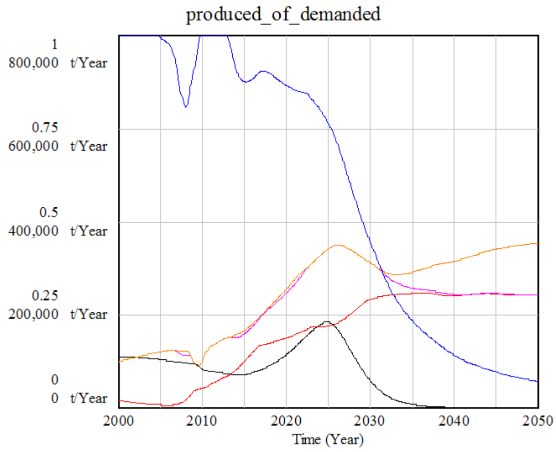
(b) Legend right hand side graphs



(c) Scenario 4: scenario 3 + 20% underinvestment

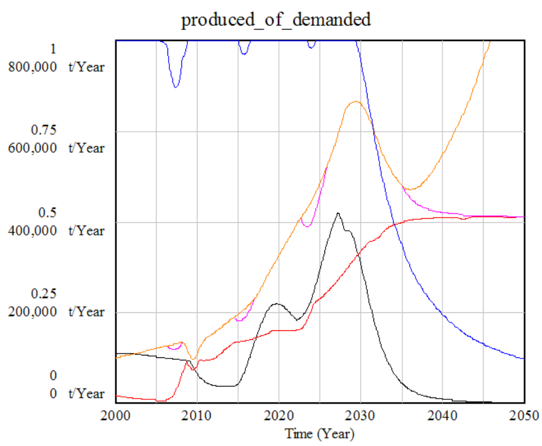


(d) Scenario 4: scenario 3 + 20% underinvestment



(e) Scenario 5: scenario 4 + increasing energy intensity

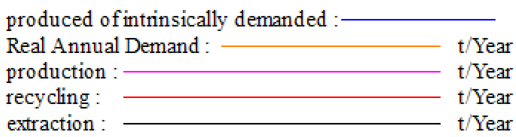
(f) Scenario 5: scenario 4 + increasing energy intensity



(g) Scenario 6: scenario 5 + high substitute price and low price elasticity of demand

(h) Scenario 6: scenario 5 + high substitute price and low price elasticity of demand

Figure 11: Scenario 4, scenario 5, and scenario 6



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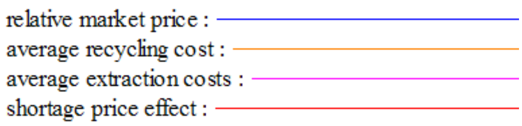

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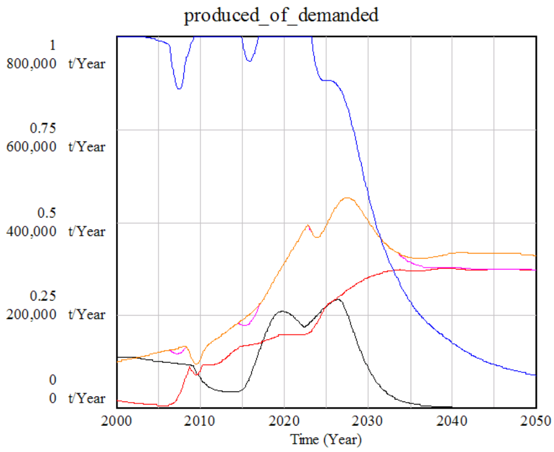
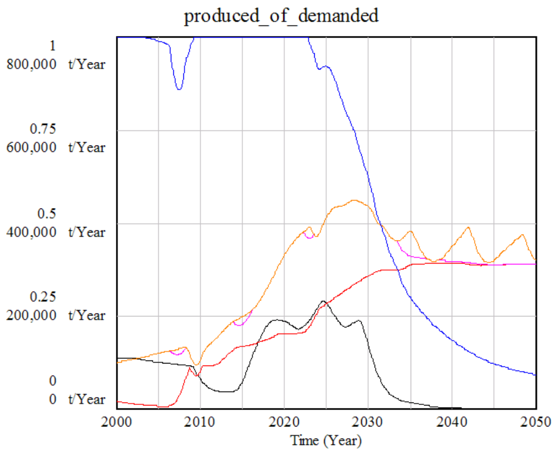


(c) Scenario 7: scenario 6 + quadrupling energy prices

(d) Scenario 7: scenario 6 + quadrupling energy prices



(e) Scenario 8: scenario 7 + sinus on demand growth and energy costs

(f) Scenario 8: scenario 7 + sinus on demand growth and energy costs

Figure 12: Scenario 7 and scenario 8

7 Dealing with these Scenarios?

Simulation models can be used to develop scenarios. They can also be used to test the effectiveness and robustness of potential policies to deal with all sorts of scenarios. Potential policies that may be required for the worst credible scenario developed in the previous section include:

- strategic[4] investments in extraction capacity and recycling capacity;
- *strategic reserves* to smooth cyclic price movements, solve temporary scarcity problems, and increasing the sum of extraction and recycling capacities;
- expansion of the recycling resource base (i) by early consideration and reorganisation of the non-recycled *lost* outflow (e.g. stockpiling potentially valuable waste), and (ii) by recycling part of the historically *Cumulatively Lost* metals/minerals;
- reduction of the dependency on particular minerals/metals, e.g. by developing substitutes through R&D;
- protection of the recycling industry against short-term and long-term energy price rises, e.g. by early investment in renewables.

8 Concluding Remarks and Future Work

8.1 Concluding Remarks

Potential scarcity of metals / minerals is dynamically complex and systemic. Hence the choice for the System Dynamics method. The main (hypothesised) feedback effects, mechanisms and delays were therefore included in a SD simulation model dealing with this issue.

An exploratory SD approach was opted for given the fact that the dynamics depend to a large extent on the assumptions (formulations) and values used, and exact formulations and (future) parameter values are uncertain.

The generic model presented in this paper was used to (i) facilitate general and detailed discussions (i.e. about hypotheses), (ii) visualise possible behaviours over time, (iii) gradually develop a worst credible scenario.

Some applied conclusions can be derived in spite of the fact that the model presented here is still very generic.

Particularly important (for the dynamic behaviour of the model/issue) are the price elasticity of demand and the existence of substitutes, the development of the extraction and recycling costs, the decision rules for planning and decommissioning installed capacities, and last but not least, the mechanism that determines the (shortage) price.

The current formulation of the model leads to endogenous cyclic behaviour of the market price. However, the latter effect may be caused –to some extent– by the formulation of the model. The formulation of the recycling resource base (only the flow) may also negatively influence the outcomes.

The worst credible scenario is most of all driven by the growth rate (high), the price of the substitute (high), the price elasticity of demand (low), and energy prices (high).

[4](read: exogenous additions, hence, not strictly following the endogenous economic rationale)

8.2 Future Work

Future work related to mineral/metal scarcity includes:

- adapting this and other models to the context/characteristics of specific metals/minerals;
- adapting this and other models to a set of possible substitute metals/minerals, mapping possible dependencies between them;
- extending the model to explore possible geopolitical issues and/or extending the current model with artificial/strategic behaviours;
- performing Exploratory Modelling and Analysis (deep uncertainty analysis) to this and other models (see (Pruyt 2010b), (Pruyt and Hamarat 2010a), and (Pruyt and Hamarat 2010b)).

References

Forrester, J. (1968). *Principles of Systems.* Cambridge, MA: Wright-Allen Press, Inc. 1

Kooroshy, J. et al. (2010, January). Scarcity of minerals: A strategic security issue. Technical Report 02/01/20, The Hague Center for Strategic Studies, The Hague. http://hcss.nl/en/news/1286/Scarcity-of-Minerals.html. 2

Lempert, R., S. Popper, and S. Bankes (2003). Shaping the next one hundred years: New methods for quantitative, long-term policy analysis. RAND report MR-1626, The RAND Pardee Center, Santa Monica, CA. http://www.rand.org/pubs/monograph_reports/2007/MR1626.pdf. 1

Meadows, D. and J. Robinson (1985). *The Electronic Oracle. Computer Models and Social Decisions.* Chichester: John Wiley & Sons. 4

Pruyt, E. (2010a, July). Making System Dynamics Cool II: New hot testing and teaching cases of increasing complexity. In *Proceedings of the 28th International Conference of the System Dynamics Society*, Seoul, Korea. System Dynamics Society. http://www.systemdynamics.org/cgi-bin/sdsweb?P1026+0. 2

Pruyt, E. (2010b, July). Using Small Models for Big Issues: Exploratory System Dynamics for Insightful Crisis Management. In *Proceedings of the 28th International Conference of the System Dynamics Society*, Seoul, Korea. System Dynamics Society. http://www.systemdynamics.org/cgi-bin/sdsweb?P1266+0. 18

Pruyt, E. and C. Hamarat (2010a). The concerted run on the DSB Bank: An Exploratory System Dynamics Approach. In *Proceedings of the 28th International Conference of the System Dynamics Society*, Seoul, Korea. System Dynamics Society. http://www.systemdynamics.org/cgi-bin/sdsweb?P1027+0. 18

Pruyt, E. and C. Hamarat (2010b). The Influenza A(H1N1)v Pandemic: An Exploratory System Dynamics Approach. In *Proceedings of the 28th International Conference of the System Dynamics Society*, Seoul, Korea. System Dynamics Society. http://www.systemdynamics.org/cgi-bin/sdsweb?P1389+0. 18

Richardson, G. (1997). Problems in causal loop diagrams revisited. *System Dynamics Review 13*(3), 247–252. 2

Sterman, J. (2000). *Business dynamics: systems thinking and modeling for a complex world.* Irwin/McGraw-Hill: Boston. 1