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Long-term perspectives on world metal use – a model-based approach

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Abstract

In this report, a system dynamics model is described, which simulates long-term trends in the production and consumption of metals (i.e. iron/steel and an aggregate of metals of medium abundance) in relation to impacts such as ore-grade decline, capital and energy requirements and waste flows. This metal model can be of assistance in exploring the issue of sustainability of metal resource use. Application of the model to historical trends shows it to be fairly capable of reproducing the long-term trends in the 1900-1990 period, among others on the basis of two intensity of use curves applied to 13 world regions. For future trends, a set of perspective-based long-term scenarios has been constructed that represent the major paradigms in resource use. These scenarios highlight some of the uncertain factors in the relation between economic growth, metal resource exploitation and use, and energy and environmental consequences. They also indicate that apparently similar metal flows in society may be the result of quite different and sometimes contrary assumptions on metal demand, production patterns and resource base characteristics. Such analyses contribute to a more open and transparent discussion on the issue at hand by adding quantitative explications to qualitative views.

Preface

The text of this report has been submitted as an article to the journal Resources Policy. The article has been written as part of the IMAGE-PLUS project, which supports assessment of global change processes at the National Institute of Public Health and the Environment (RIVM). Within the context of the global assessment research, the model can be useful to study long-term changes in material flows, in relation to population and economic growth on the one hand and consequences for energy and capital requirements and waste flows on the other.

Contents

Summary

The world consumption of metals has sharply increased over the last 100 years, showing an average annual growth rate of about 3%. The resulting metal production and trade flows require sizeable global capital and energy inputs (more than 8% of total energy consumption) and cause a variety of environmental problems in mining, transport and upgrading. Moreover, several authors cited in the literature have pointed out the risks and consequences of depleting currently used high-grade resources.

In this report we describe a metal model which simulates several major long-term trends in production and consumption of metals: i.e. iron/steel and an aggregate of metals of medium abundance (copper, lead, zinc, nickel and tin). Integrating earlier models and assessments in this area, we focussed the model on long-term dynamics. It is primarily meant as a tool for analysis. Applying system dynamics and process analysis as methods, the model combines several types of analysis and theories into one integrated model, of which the most important elements are:

- Analysis of metal demand on the basis of intensity of use analysis;
- Interplay of technological development and ore-grade decline to describe (the impacts of) future primary production;
- Competition between primary and secondary production.

Application of the model to the 1900-1990 period
Our simulation experiments indicated the model to be fairly well able to reproduce the long-term trends in the 1900-1990 period.

With respect to metal demand, the model uses a relationship between metal-use intensity (defined as metal consumption per unit GDP) and per capita income. On the global scale, metal use intensity has declined for most metals over the last decades (while total consumption has increased). This is sometimes referred to as (relative) dematerialisation of the economy. The global trend, however, is dominated by high-income countries. A regional approach shows that while intensity has declined in high-income countries, material intensity has actually increased in low-income countries. The historical trend of 13 global regions was found to follow an inverted U-shaped curve reasonably well. This curve can be explained as a superposition of three different trends:

- The changes in metal requirements in different phases of the economic transition;
- The changes in metal requirements as a result of substitution;
- The changes in metal requirements as a result of technological development.

The effects of metal depletion on metal production is best described in terms of increased capital and energy demand due to ore-grade decline. The models show that global average ore grades have, over the last century, declined substantially by about 15% for iron and almost 70% for the group of metals of medium abundance (confirmed by regional empirical data). Technological development, however, has more than offset the potential increase in the use of production factors per unit of metal. As a result, metal prices decreased sharply over the first half of this century. In the last two decades, the decrease in metal prices seems to have leveled off. In the same period, energy efficiency improved by about 0.6% per year.

Perspective-based scenario analysis

There is a lot of controversy on future trends in metal resource use; in fact, the debate seems to be on a more fundamental level than that of technical uncertainties. Our model-based scenarios representing the major paradigms regarding – [un]sustainable - resource use (as based on several literature sources) allow a more quantitative interpretation of major controversies and risks in relation to metal resource depletion and use. The results suggest that apparently similar metal flows may correspond to rather divergent sets of assumptions on the metal resource base and its characteristics, and on developments in metal demand.

Although the model assumptions on future demand, supply and technology between the egalitarian, individualist and hierarchist 'utopian' scenarios differ significantly, the resulting impacts such as energy intensity and ore-grade decline are much more similar as a result of counteracting forces within the model. Some general conclusions:

- If industrialising countries follow the same pattern in terms of increasing IU as industrialised countries followed in the past, global metal demand could increase significantly in the next century by a factor of 3-6 and the declining trend in global IU may be temporarily reversed (occurs in all scenarios).
- Recycling is expected to increase continuously, reaching a level of about 50% of total metal production driven by technological development, increasing availability of scrap and the effect of declining resource quality. However, only in the egalitarian scenario is the high share of recycling (stimulated by taxes of primary resource extraction) able to prevent sharp increases in primary metal production.
- The relative abundance of iron/steel implies that trends in average declining energy intensity and production costs will continue in the scenarios. However, given the sharply increasing demand for iron/steel in industrialising countries, the share of iron and steel production in total energy consumption remains at a level of 5 to 10%.
- For the group of metals of medium abundance, historical decreases in energy and capital intensity for primary metals do not continue in the egalitarian scenario because technological innovations are offset by the relatively fast decline in ore grade.

For each scenario, risk factors can be identified. The clearest one is seen for the group of metals of medium abundance. Here, the combination of an unconcerned management style and a pessimistic assumption related to the availability of high-grade ore could lead to an enormous increase in energy requirements and waste flows.

We conclude the present model results to be capable of contributing to the existing understanding of trends in dematerialisation and resource degradation. In principle, the Metals Model can be integrated into the TARGETS and IMAGE/TIMER model to allow exploration of the following relationships: 1) metal production, energy consumption and energy prices, 2) investments (competition with other sectors) and 3) negative impacts of waste and mining in terms of land degradation.

1. Introduction

Over the last century, the exploitation of material resources has grown enormously, in parallel to the growth of economic activities. Currently, western economies use about 20 to 40 metric tons of raw materials per person per year (Adriaanse et al., 1997). Not only are human societies using materials more rapidly, there has also been a increasing diversity of materials (see e.g. Forester, 1988; Moll, 1989). While high material consumption rates certainly have contributed to the high living standards in large parts of the world, their enormous throughput has also raised questions with regard to the sustainability of current use (recently as part of the Factor 4 discussion – Weizsacker et al., 1998). Several authors have pointed out the risks of depleting limited reserves of high-grade resources[1]. In addition, exploitation of metals and other raw materials requires a sizeable amount of global capital and energy inputs and causes different sorts of environmental problems in mining, transport and upgrading. Finally, virtually all materials ultimately return to the environment, thus creating fluxes of substances that are potentially harmful to the environment. In this article, we will focus on an important type of material use, i.e. world-wide consumption and production of metals.

For some years sustainability-related questions with regard to metal production and consumption patterns have been analysed on the basis of material-flow type analyses (e.g. Moll, 1989; Jolly, 1993; Annema and Ros, 1994; Van der Voet, 1996). Attempts have also been made to analyse material resources in the broader context of economic growth and technological development (e.g. Suzuki and Shoji, 1977; Chapman and Roberts, 1983; Gordon et al., 1987; De Vries, 1989a and 1989b; Duchin and Lange, 1994; Ayres and Ayres, 1996; Mannaerts, 1997; Weston and Ruth, 1997). Building on such analyses, we have developed a metal model which simulates the long-term structural dynamics of metal resource exploitation and can be linked with the global, integrated assessment models TARGETS (Rotmans and De Vries, 1997) and IMAGE[2] (Alcamo et al., 1998). This Metal Model can be of assistance in exploring the issue of sustainability of metal resource use, especially in relation to population and economic growth on the one hand and consequences for energy and capital requirements and waste flows on the other. In the future, consequences in terms of environmental pollution may also be included (Verbruggen et al., 1997).

After describing the Metal Model and applying it to some important trends in metal resource use between 1900 and1990, we will use the model to explore possible futures. The expectation with regard to future natural resource use and its impacts is highly dependent on the world view of the person making the assessment, as has been discussed by Tilton (1996), for example. Here, the cultural-perspective based approach as developed within the TARGETS programme is used to deal with this type of uncertainty (Rotmans and De Vries, 1997).

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[1] Especially during the energy crises in the 1970s, predictions were made that the world would run out of some raw materials in 50 years (e.g. Meadows et al, 1972). Attention seems now to have shifted to the question on whether ore-grade depletion might aggravate the environmental problems mentioned in the main text (Tilton, 1997).

[2] TARGETS is an acronym for Tool to Assess Regional and Global Environmental and health Targets for Sustainability; IMAGE is an acronym for Integrated Model to Assess the Greenhouse Effect.

2. Description of the model and relevant theory

2.1 Introduction

Generally, three types of metals are distinguished on the basis of their resource availability: abundant metals (such as iron and aluminium), medium-scarce metals (such as copper and lead) and scarce metals (such as gold and platinum). Within the metals model, we have concentrated on the first two groups, aggregating them into two virtual 'metals', which we have called AbAlloy (Fe, Al, Cr, Ti) and MedAlloy (Cu, Pb, Zn, Sn, and Ni); see De Vries (1989b). Scarce metals, such as gold, silver and platinum, have not been included since their flows are relatively small, and in terms of energy requirement, scarce metals have no significant role. In the case of abundant metals, it was decided to focus solely on iron, since 1) the flows of other abundant metals are small compared to those of iron and since 2) the dynamics of iron and aluminium (the second most important metal in terms of production flows) differ significantly. A similar system dynamics model has been constructed for each 'metal', with the two models operating independently.

The general structure of the Metals Model is based on a simple flow diagram (**Figure 2.1**). Geological resources[3] are converted into reserves by exploration activities. Ore extracted from the reserves is used to produce refined metals or metal compounds (primary production), which are subsequently used to produce final consumption goods. These products remain in use for some time during or after which the metals they contain (i) slowly dissipate or (ii) are dumped in ways and places where they could constitute a secondary resource as long as they are not dissipated into the environment. Alternatively, materials can be recycled directly after their lifetime within the economy (secondary production). Consumption in the model is defined as primary production plus secondary production.

The stocks and flows illustrated in **Figure 2.1** are governed by and associated with various information flows inside the model; **Figure 2.2** presents the most important ones. In the rest of this section, the main model parameters will be described in more detail, together with the actual trends found in global metal resource use. A more detailed description of the model can be found in other publications (Van Vuuren, 1995).

In terms of dynamics, the model combines several types of analysis and theories into one integrated model, of which the most important elements are:

- Analysis of metal demand on the basis of intensity of use analysis (earlier used in many energy models and by Tilton (1990), for instance, for metal demand);
- Interplay of technological development and ore-grade decline to describe (the impacts of) future primary production were used earlier by Chapman and Roberts (1983) and De Vries (1989b);
- Competition between primary and secondary production.

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[3] Geological resources refer to the total amount of a metal available in the earth's crust. Within the time-span of the model, geological resources can be considered as almost infinite. Depletion is modelled in terms of a decreasing ore-grade of reserves (see section 2.3).

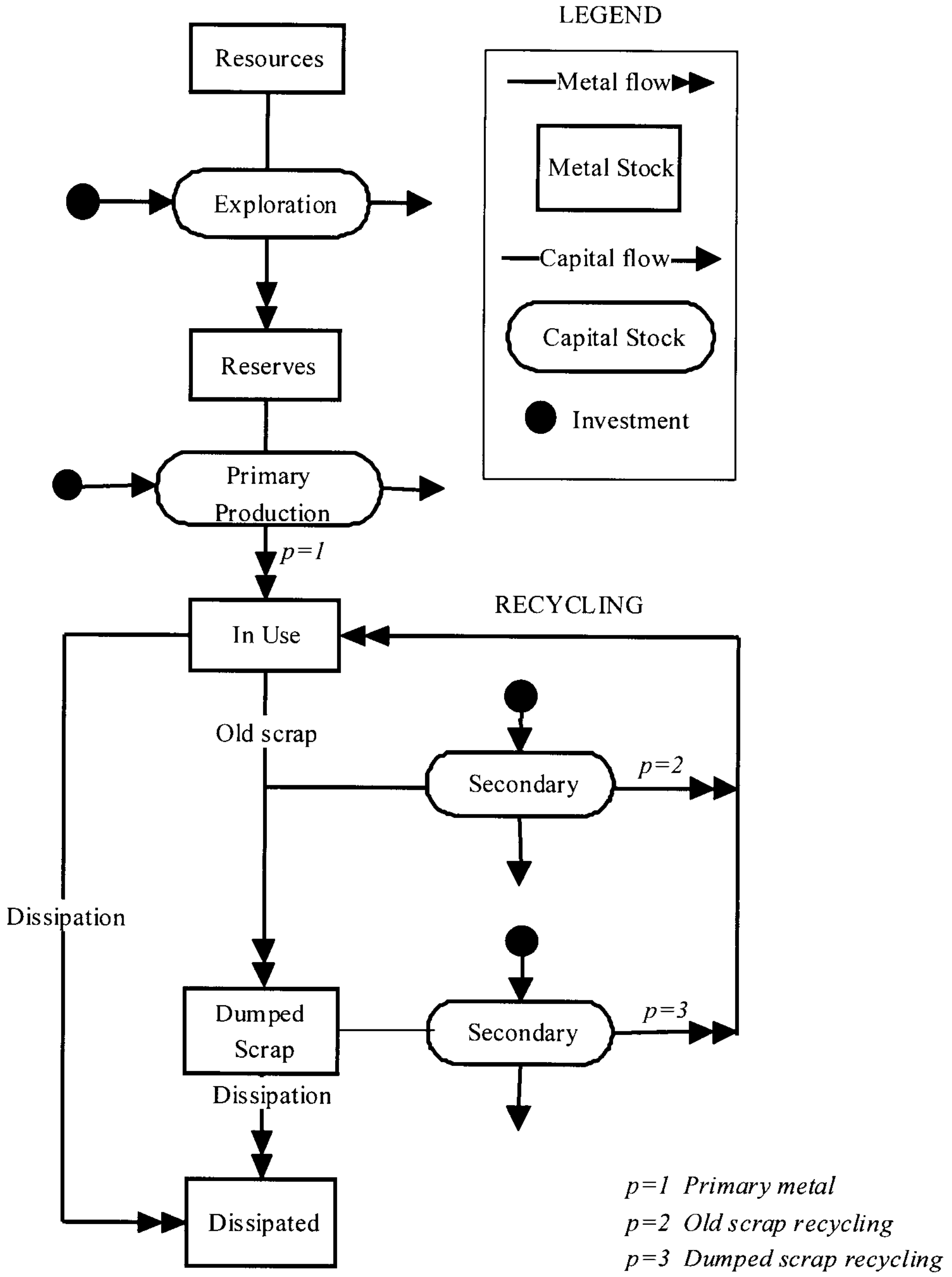

Figure 2.1: Stocks and flows in the metal model for iron/steel and MedAlloy.

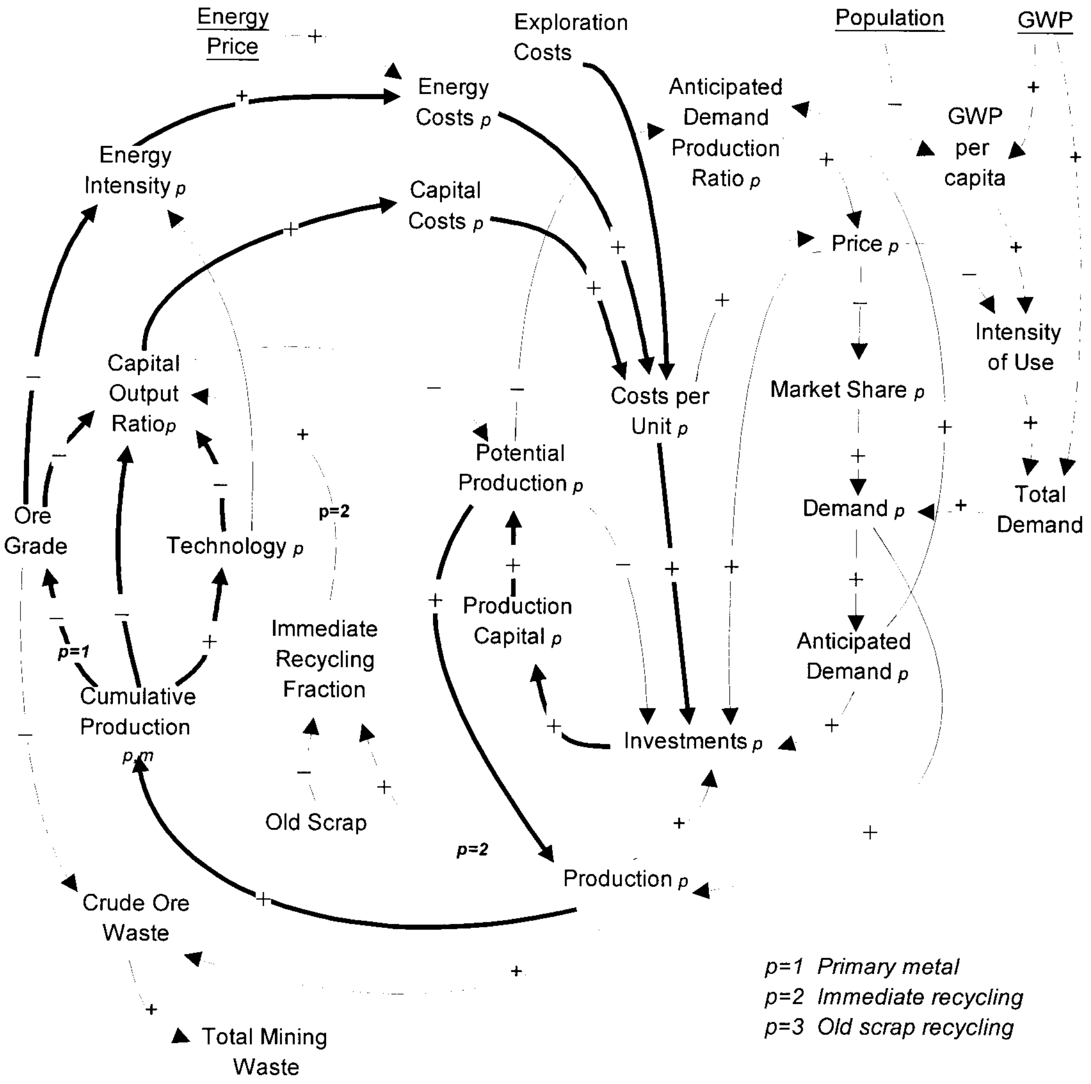

Figure 2.2: Model relationships within the metal model.

2.2 Metal demand

Over the last 100 years the global consumption of both iron and MedAlloy has sharply increased, with an average annual growth rate of 3.2% and 2.9%, respectively (**Figure 2.3**). Obviously, the building of cities, heavy industry and all kinds of machines and appliances have made a significant contribution to the growing use of metals. In 1992, about 50% of all iron and 70% of all copper was consumed in OECD countries; about 10% of both metals was consumed in Eastern Europe and the former Soviet Union, and 30% iron and 20% MedAlloy in the rest of the world (Klein Goldewijk and Battjes, 1997; IIIS, 1996). In most industrialised countries, demand for most metals in the last two decades has been showing slow growth or has even levelled off. In contrast, demand for iron and other metals has been growing sharply in many developing countries. Recently, Asia experienced an average annual growth in iron demand of about 8% per year. The per capita consumption of steel in developing countries is on average 51 kg per capita (1992) and in industrialised countries over 300 kg per capita – indicating that the still large potential for growth in the former.

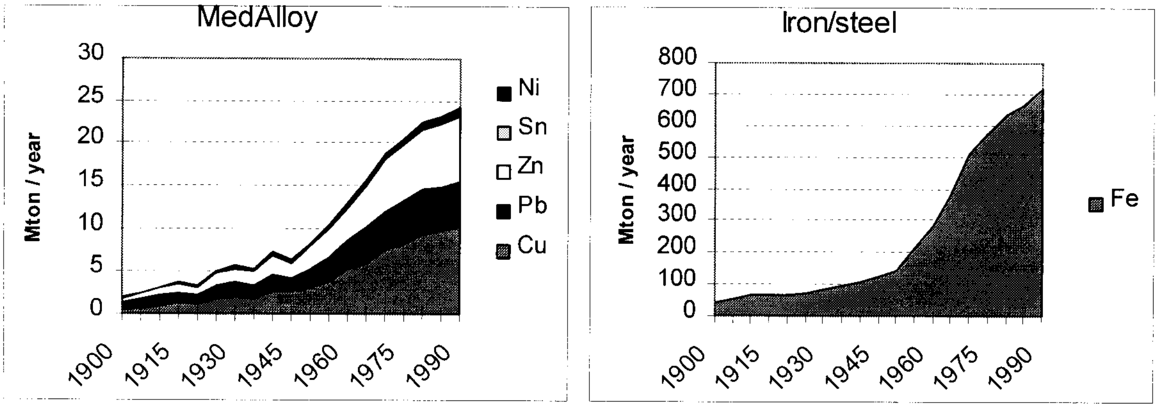

Figure 2.3: Global consumption (primary and secondary) of iron/steel and MedAlloy.
Source: Klein Goldewijk and Battjes, 1997

Empirical research in resource economics has found that metal use intensity (defined as metal consumption per unit GDP) can often be described as a function of per capita income. This function has been determined empirically and varies among countries and materials, but its general shape follows an inverse U-shaped curve (also called Intensity of Use hypothesis (see Malenbaum, 1975; Altenpohl, 1980; Tilton, 1990; Roberts, 1996)[4]. The inverted U shape can be explained in terms of superposition of three different trends:

- The changes in metal requirements in different phases of the **economic transition** from agriculture (low IU) to manufacturing and construction (high IU) and then to services (low IU) (see Tilton, 1986). The shift to a higher share of manufacturing and construction requires large (material) investments in building industrial infrastructure. For a wide range of countries, the size of the different sectors has been found to correlate (at least partly) with per capita income (see e.g. Maddison, 1989). It should also be noted that the imports and exports of metals embodied in final products (such as cars) are not recorded in metal trade statistics. Therefore re-allocation of final-product industries to countries with lower labour costs, and exports of final products to high-income countries, will tend to decrease the IU in industrial regions and increase the IU in developing regions.
- The changes in metal requirement as a result of **substitution**. The demand cycle of a material generally follows a pattern, in which the first stage of rapid growth after introduction is followed by a stabilisation phase and a final phase, in which the markets for the material become saturated. At the same time, cheaper or better materials (e.g. plastics) might penetrate the market and replace the original material. The reversal of growth can be so complete that even per capita or absolute consumption levels may begin to decline.
- The changes in metal requirement as a result of **technological development**, which leads to more efficient raw material use in the production of final goods or satisfaction of consumer functions (e.g. less metal use per car as described in Forester et al. (1988); Benardini and Galli (1993)).

The combination of these trends can result in the inverse U-shaped curve, as indicated in **Figure 2.4**. The three processes involved explain to a great extent the observed dematerialization in more advanced economies and will also be a key factor in understanding

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[4] Similar inverted U shaped functions are sometimes also found for environmental pressure (emissions or emissions divided by GDP), referred to as environmental Kutznetz curves (De Bruijn et al., 1998).

future resource use trends. The advantage of IU hypothesis is its simplicity; its most serious shortcoming is that neither new technology nor material substitution depends primarily on changes per capita income. Both factors have had a varying influence in the past, in particular, in response to prices. Obviously, the IU hypothesis is not able to deal with unexpected breaks from the past, e.g. sudden penetration of new materials or the consequences of an energy crisis.

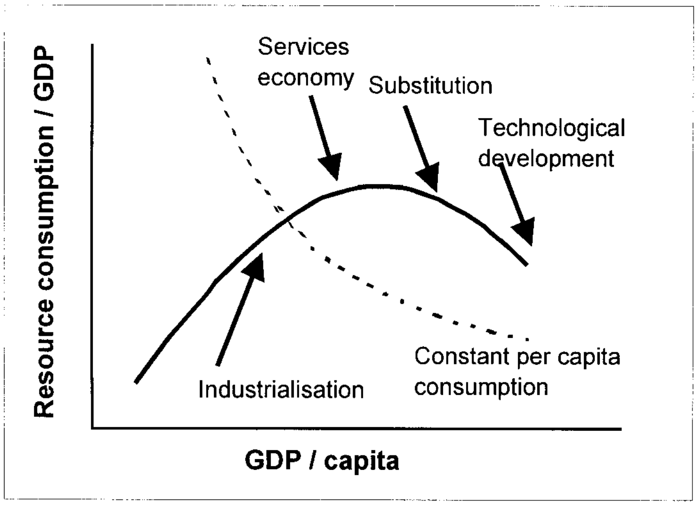

Figure 2.4: Intensity of Use hypothesis.

Figure 2.5 shows the IU for the consumption of steel and MedAlloy for 13 world regions. The data covers the 1970-1990 period[5] period for 12 regions; for the United States data are for the period 1900-1990 (Van Vuuren, 1995). It should be noted that particularly for the earlier period, both metal demand data and GDP data are relatively uncertain and often difficult to compare. Therefore, comparison of and trends in material intensity should be interpreted carefully.

The history of steel consumption in the United States is generally regarded as an excellent example of the IU hypothesis. Since about 1920, consumption per unit of GNP has decreased to 40% of the peak level. The dashed curves in **Figure 2.5** are isolines representing a constant per capita consumption of metals. Interestingly, the historical trend of the USA and the position and trend of the other regions follow an inverted U-shaped curve reasonably well. Four regions diverge sharply from this general pattern: the Former Soviet Union and Eastern Europe (relatively high use of metals in the past, corresponding to the importance of heavy industry during the centrally planned period, followed by a collapse of metal use during the economic restructuring process), Middle East (relatively high national income due to oil exports) and Latin America (monetary data might not directly correspond to changes in the physical economy due to high inflation rates; foreign debt and high capital charges might prevent development of basic industries). The great differences between the regions, their different directions of development and the position of the global average shown in **Figure 2.5** (indicated under 'World') all illustrate that it is impossible to determine long-term global

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[5] For GDP throughout this article, *real* per capita income is used on the basis of constant purchasing-power-parity corrected dollars (ppp$) of the year 1990 - taken from Summers and Heston (1991). Use of purchasing-power-parity corrected dollars instead of exchange-rate based dollars allows for better cross-regional comparison and significantly improves the capability to represent historical regional metal demand on the basis of trends in regional population and income.

trends directly from average global income and metal consumption. The global decreasing trend in IU is dominated by trends in high-income countries. Although it is possible to use a global average IU curve for specific period (e.g. 1950-1995 as shown by Roberts, 1996), economic growth in current low-income (and industrialising and materialising) regions could well cause the global average curve to diverge from its present dematerialising trend as shown in the scenario studies further in this article.

It should be noted that in **Figure 2.5**, technology transfer from high-income regions to low-income regions could be a fourth dynamic factor (next to economic transition and substitution, and technical development) determining the shape of the IU curve. Bernardini and Galli (1993) also suggested that on the basis of analyses for industrialised countries, the maximum intensity of the curve declines if reached later in time by a given economy. There are similar indications for industrial energy intensity where technology transfer is well-known and influential (De Vries et al., 1999).

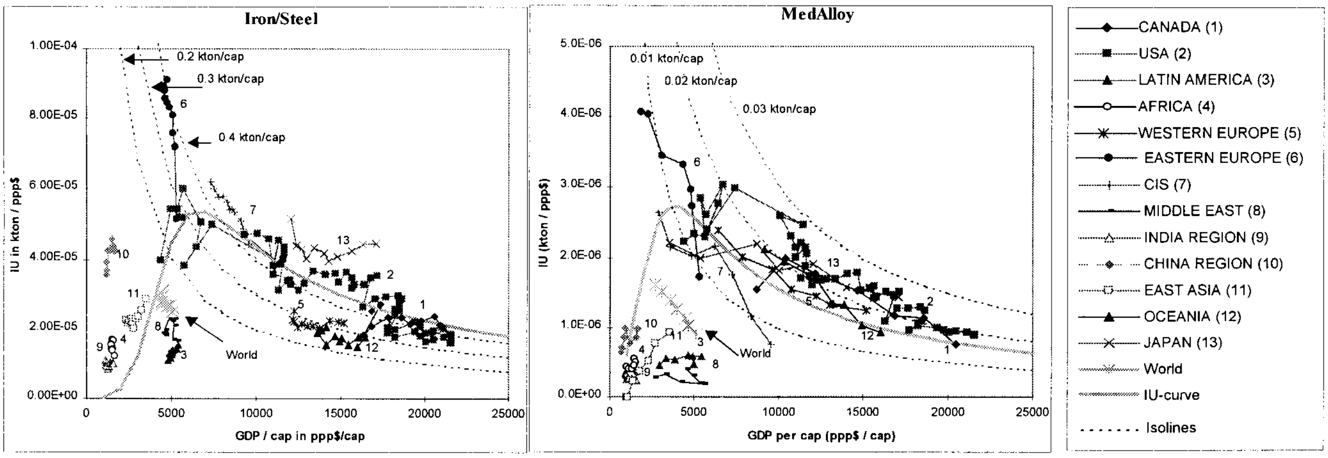

Figure 2.5: IU-curve for Iron/steel and MedAlloy use in 13 global regions.

For almost all individual metals included in MedAlloy and many other metals, a figure similar to that indicated for the aggregates is found. The most important exception is aluminium, for which the IU in high-income countries has not started to decline. Aluminium is in fact substituting other metals for various kinds of functional use (Moll, 1989).

In some cases, IU models have been constructed at country level on the basis on the sectoral composition of economies and metal use within these sectors. However, in view of limited data availability at the global level, we have focussed on metal use in the economy as a whole in reference to GDP, which has been shown to give good results (Roberts, 1996). On the basis of **Figure 2.5**, we decided to base the demand formulation for iron and MedAlloy on two single IU-functions in combination with regional income (in ppp$) and population development (**Eq. 2.1** in **Box 2.1**). This allows the model to deal with differences in per capita income and different growth rates in the different regions. The parameters x_1, x_2, and x_3 are constants, which determine the shape of the function and the level at which metal consumption is finally saturated ($=x_1$). F represents a factor between 0 - 1, allowing to scale down future metal demand from the IU curve. In the model, we use this factor to simulate the effect of technology transfer. E(p) describes the effect of metal prices on demand, for which we have used a simple elasticity function. The final set of the constants, based on the regional use trends have resulted in the IU curves as shown in **Figure 2.5**. This calibration resulted in a saturation level (parameter x1) of 450 kg per capita for iron/steel and 17 kg per capita for MedAlloy (vs. an actual level of 130 and 5 kg/capita in 1990 respectively).

Box 2.1: Crucial model equations.

The Minerals Model is a system-dynamic model of which the most important material flows and information flows (including delays and anticipative behaviour) are indicated in Figures 1 and 2, respectively. The most crucial model equations are the following:

$$D_R = IU_R * GDP_R * E(price) = (\frac{x_1}{I_R + x_2 * I_R^{X_3}}) * F * I_R * Pop_R * E(price) \qquad (1)$$

(D_R = metal demand per region; IU_R = Intensity of Use; GDP_R = real regional Gross Domestic Product (ppp$), E(price) describes the effect of price on demand, x_1,x_2, and x_3 are empirically determined constants (for scenarios we will vary x_1), F = 1 for the historical models and can be slightly different from 1 for projections; I_R = real regional GDP per capita (ppp$); Pop_R = regional population).

$$Y_P = Y_{0,P} * Q_P^{-n} \qquad (2)$$

(Y : learning factor; Q : cumulative production; n : learning constant; p indicates the different types of production [primary / secondary]).

$$g_{P=1} = g_0 * Q_m^{-1/l} \qquad (3)$$

(g : ore grade; Q_m : cumulative mine production; l : depletion constant).

$$EI_{P=1} = \varepsilon_{0,SR} + \varepsilon_{0,MM} / g + ((\varepsilon_{SR} + \varepsilon_{MM} / g) * Y) \qquad (4)$$

(EI = energy intensity; in which ε_{SR} and ε_{MM} are the energy requirements for smelting and refining (SR) and mining and milling (MM). A distinction is made in a minimum energy requirement (ε_O) based on thermodynamics and a part depending on technological development).

$$COR_{p=1} = ((\gamma_1 + \gamma_2 * (g_0 / g) * Q_{p=1}^{-\alpha} + \gamma_3 * (g_0 / g)^{-\beta})) * Y \qquad (5)$$

(α, β, γ_1, γ_2, γ_3 are constants representing the effects of economics of scale and ore-grade decline on the Capital Output Ratio. Based on De Vries, 1989a).

$$costs_P = C_{en,P} + C_{cap,P} + C_{expl,P=1} = price_{en} * EI_P + COR_P * Ann + C_{expl,P=1} \qquad (6)$$

(costs : costs per tonne produced; C_{en} : energy production costs; C_{cap} : capital production costs; C_{expl} : exploration costs; $price_{en}$: the average price of energy; COR : capital-output-ratio; Ann : annuity factor).

$$prod_p \approx IMS_p * D = (price_p^{\lambda} / \sum_p price_p^{\lambda}) * D \qquad (7)$$

($prod_p$: production per production category p (primary or secondary); IMS : indicated market share; $price_p$: price of metal produced by production category p (more or less equal to costs); λ : logit parameter). If capacity is insufficient, the real market share of category p can be lower than suggested by IMS.

2.3 Metal production

The model distinguishes between primary production and recycling (see **Figure 2.1**). Historically, the processing of metals has been subject to steady progress in energy efficiency, and the share of recycled metals, which may require substantially lower energy inputs than the use of virgin metals, is growing. In the model, market shares of primary production and recycling are calculated from the relative costs of their outputs using a multinomial logit function: i.e. if costs are equal, market shares are also equal; if relative costs rise, the market share declines, depending on a cross-price elasticity (For more details, see De Vries and Van den Wijngaart, 1995). In contrast to the demand formulation, the rest of the model assumes a one-region world[6]. The following sections will discuss the major model assumptions for these production types.

2.3.1. Primary production

Primary production in the model encompasses all processes from mining and milling to smelting and refining. With respect to primary production (indicated as p = 1 in **Figure 2.2**), two main loops can be distinguished: 1) the long-term loop describing the trade-off between depletion and learning dynamics, and 2) the short-term demand-investment-production-price loop. Here, we focus on the long-term loop, since it is much more relevant given our model objective.

Long-term loop: learning and depletion

Within the model, we have defined the issue of (potential) depletion of resources completely in terms of quality, i.e. ore grade. Assuming that resources of the highest quality are exploited first, further exploitation might lead to quality decline. Next, the effects of quality decline are calculated in terms of the energy requirement and production costs per unit of primary metal. Production costs in the model are a sum of energy costs, capital costs and exploration costs; the latter two derived from the Capital Output Ratio (COR) (**Eq. 2.6** and **Figure 2.2**). All other costs, such as labour costs, are not accounted for separately. Both capital costs and energy costs[7] are assumed to result from an interplay between technological development of exploitation technology (i.e. 'learning-by-doing') and ore-grade decline (i.e. depletion).

The first factor, technological development, has been extremely important for production costs so-far. Considering steel, for instance, in this century we have seen the introduction of the Bessemer production process, open-hearth steel production, oxygen steel production, continuous casting processing and electric-arc steel production – reducing energy requirement and production costs. Several authors have found a log-linear relationship between

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[6] As discussed in the previous section, it is impossible to model long-term trends in global metal demand on the basis of a one-region world. For production, at this moment we are not able to describe the complex dynamics of regional metal production and trade (depending, for instance, on availability of capital, low-cost labour force, low-cost energy resources, metal resources, productivity and transport costs). We have assumed that - since metal ores and commodities are traded globally - most of the production dynamics included in the model can adequately be described at the one-world level.

[7] Energy costs are equal to the product of energy intensity and energy prices. Currently, energy prices are an exogenous model input (based on Rotmans and De Vries, 1997).

cumulative production and the efficiency of the process for different types of engineering applications. The more frequently a process (here, exploitation and production of iron/steel and MedAlloy) has been performed, the more knowledge has accumulated to improve its efficiency. The progress ratio of such curves generally varies between 0.65-0.95[8] (Chapman and Roberts, 1983; Argote and Epple, 1990; De Vries and van den Wijngaart, 1995; Weston and Ruth, 1997; Neij, 1998). Based on historical data, a log-linear relationship with a progress ratio of 0.8 is used in the Metals Model (**Eq. 2.2**; Chapman and Roberts, 1983).

The impacts of ore grade decline or depletion has been the subject of long debate. Geologists have devoted considerable attention to assessing resource availability at various grades (quantity-quality relationships). Empirically derived Lasky-type relationships describe (the logarithm of) ore grade as a function of the logarithm of cumulative tonnage of ore produced[9]. Deffeyes and MacGregor (1980) have derived depletion constants for several metals on the basis of such a Lasky-relationship; these have been used in the Metals Model (**Eq. 2.3**). **Eq. 2.4** describes the energy intensity as a function of ore grade decline and technological development. A similar formula is used for capital intensity (COR). The actual choice of parameters for the COR equations is based on the work of De Vries (1989a) and for energy intensity on the work of Chapman and Roberts (1983).

Short-term loop

A second loop, operating in the shorter term, describes investments in primary production, or mining and producing capital in response to (1) imminent market shortages, i.e. if potential production capacity is lower than anticipated demand, or (2) expected profits, i.e. the extent to which prices exceed production costs (see **Figure 2.2**). To model the behaviour of investors we have included an anticipated demand, which is based on a linear extrapolation of total demand trends five years into the future.

2.3.2 Secondary production

Materials recycling is often mentioned as an important factor to a more efficient use of resources. In principle, recycling limits waste flows to the environment and reduces energy requirements since the energy-intensive mining and concentration stages are avoided. Post-consumer recycling rates have increased over time. The main factors influencing the recycling rates are: (1) scrap availability compared to consumption, (2) relative processing costs of scrap and virgin metals and (3) possibility of cost-effective scrap collection (Duchin and Lange, 1994).

With a view to the different dynamics we distinguish between two types of recycling in the model: (i) old scrap recycling, i.e. direct recycling of metal products after their use (p=2 in **Figures 2.1** and **2.2**), and (ii) dumped scrap recycling, i.e. recycling of metal products after disposal (p=3 in **Figures 2.1** and **2.2**)[10]. Dumped scrap recycling has been negligible in the

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[8] The progress ratio is defined as 1 minus the factor with which production per unit of capital or energy improves on a doubling of cumulative output.

[9] In fact, this empirical relationship can be looked upon as the high-grade end of a log-normal distribution. Log-normal distribution of elements is often assumed to be a fundamental law of geochemistry. Lasky-type relationships should be used with care – more elaborated models exist and other geologist have questioned the underlying log-normal distribution of elements (Brinck, 1979; Singer and Mosier, 1981).

[10] Secondary production in the literature sometimes also includes 'home scrap' and 'process scrap' recycling, which refers to recycling within the metal industry. These types of recycling have not been modelled explicitly;

past due to a lack of infrastructure and incentives and to the high (labour) costs[11]. We have, however, included this type of recycling, since some consider it to be an attractive form of production in the long-term as depletion of high grade primary resources continues – a factor which could significantly reduce the amount of waste.

Dynamics of secondary production

The model dynamics for recycling are comparable to those for primary production. The main difference is that the COR for old scrap recycling (p=2) depends on the quality of the material to be recycled. Since it is assumed that easily recyclable fractions of depreciated products will be recycled first, recycling will - in general - become more expensive if a higher fraction of old scrap is recycled (Gordon et al., 1987). The energy intensity of old scrap recycling of the metals included in this study is currently, on average, about one-fourth till one-third of primary production in 1980 (Chapman and Roberts, 1983; Frosch et al., 1997). Both the COR and the energy intensity of old scrap recycling are assumed to increase with the fraction of scrap recycled. The relationship of Gordon et al. (1987) between the fraction recycled and capital requirements has been used in the model both for capital and energy requirements.

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they are considered as part of the primary production process.

[11] This may not be a valid observation for the less developed regions, in which collecting dumped scrap is often a source of income; the relevant data are lacking, however.

3. Model calibration based on the 1900-1990 period

In order to show the relevance of the model and to find estimates for some of the model parameters, the model has been calibrated by comparing simulation results to historical data from 1900 to 1990. Because this is done by adjusting a set of model parameters to give the best possible match, we refer to this process as model calibration and not model validation. As previously stated, some of the historical data is uncertain. However, our objective with the model is not the exact reproduction of past trends; rather, we will concentrate on the long-term trends. The Metals Model has over 50 input variables (i.e. constants, multipliers and time series). This article will not describe the data collection and calibration efforts in detail (see Van Vuuren (1995) for a detailed calibration of the USA-model), but instead, will be devoted to the most relevant results.

Figure 3.1a shows both historical and simulated iron/steel and MedAlloy consumption for the 1900-1990 period. On the basis of the historical regional GDP and population data taken from Klein-Goldewijk and Battjes (1997), as well as the historical consumption data from USBM, MetallGesellschaft (various years) and IIIS, the model reproduces past consumption on the scale of **Figure 3.1a** fairly well. A closer look reveals some discrepancy for iron/steel, where the simulated values are too high for the period up to 1960 and slightly too low after 1960 as a result of several regions, in particular Eastern Europe and the former Soviet Union, diverging from the general global IU curve used in the model. For MedAlloy, simulated demand is a bit too low after 1990. Further improvement is only possible by introducing region-specific IU curves. **Figure 3.1b** shows that simulated secondary production rates as a fraction of total production also follow the historical estimates fairly well.

The simulated ore grade depends primarily on the initial ore grade and the depletion factor. Throughout this century the ore grade for several metals has decreased considerably. At the start of the century, iron ore was generally mined at an ore grade over 60%, while nowadays even ore grades of 20% are common in the United States. High iron contents are still common, for instance, in South America and Africa. For copper ore, one of the most important constituents of MedAlloy, the average ore grade in the United States was about 3% at the beginning of the 20th century while the current grade is on average about 0.9% (USBM, 1993). Average global grades are often considerably higher than the United States grades and the spread of grades around the world is substantial. It should be noted that decreasing grades are only partly caused by depletion; they are also a result of a transition to cheaper open-pit mining, for example.

In the model, we have used empirically derived relationships between ore grade and cumulative production. This has led to a steadily declining ore grade (see **Figure 3.1d**). For MedAlloy, the model indicates a trend from a 7% average ore grade in 1900 to a 2% grade in 1990. For iron/steel the trend is from 64% to 55%. The amount of waste produced is also highly dependent on the mining method. Open-pit mining produces large amounts of overburden. Over the last few decades, the trend has been to open-pit mining – with lower ore grades but also lower production costs due to economies of scale –which has led to an increasing amount of mining waste.

Due to lack of data on world average metal costs and prices, calibration of the model is done mainly on the basis of historical prices in the U.S.A. (USBM, 1992), except for steel for which after 1960 we averaged the West European and U.S.A. steel price[12]. Metal prices in London show, in general, a similar trend as in the U.S.A, consistent with the conclusion of Mannaerts (1997) on the basis of historical European and U.S.A. prices that divergent steel prices cannot last long across different parts of the world. Nevertheless between 1975 and 1990, U.S.A. steel prices show a sharper increase than European prices, mainly caused by economic instability (exchange rate fluctuations) and major shifts in U.S.A. steel production (ore and steel products are increasingly imported). The main long-term trends in metal prices are reasonably well reproduced by the model, in particular, the overall decline in metal prices during this century as a whole, the sharp price decline before 1960 and the slow price decline in the 1970-1990 period (historically prices sometimes even rose in this period), see further **Figure 3.1c**. Historical price shocks are obviously not reproduced, since they are related to short-term dynamics which are not the focus of our model (such as speculation and events such as wars, large new discoveries of metal deposits and the longer term impacts of the energy crises in the 1970s). The model is not able to reproduce the short period of low (U.S.A.) MedAlloy price at the beginning of this century and the price increases in the 1975-1985 period.

Finally, the model reproduces both overall energy use of the iron and steel sector (IEA, 1998) and energy intensity very well (Worell et al., 1997; Hendricks et al., 1998). Historical energy intensity for various countries between 1980 and 1991 was between 20 and 50 GJ/tonne crude steel – while rates of efficiency improvement varied between 0.0% and 1.8% per year. The model results in a global energy intensity of 20-30 GJ in the same period (including recycling) and an annual improvement of 0.6%.

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[12] For steel, we have used hot-rol steel prices (see USBM (1992) for a discussion on the most useful indicator).

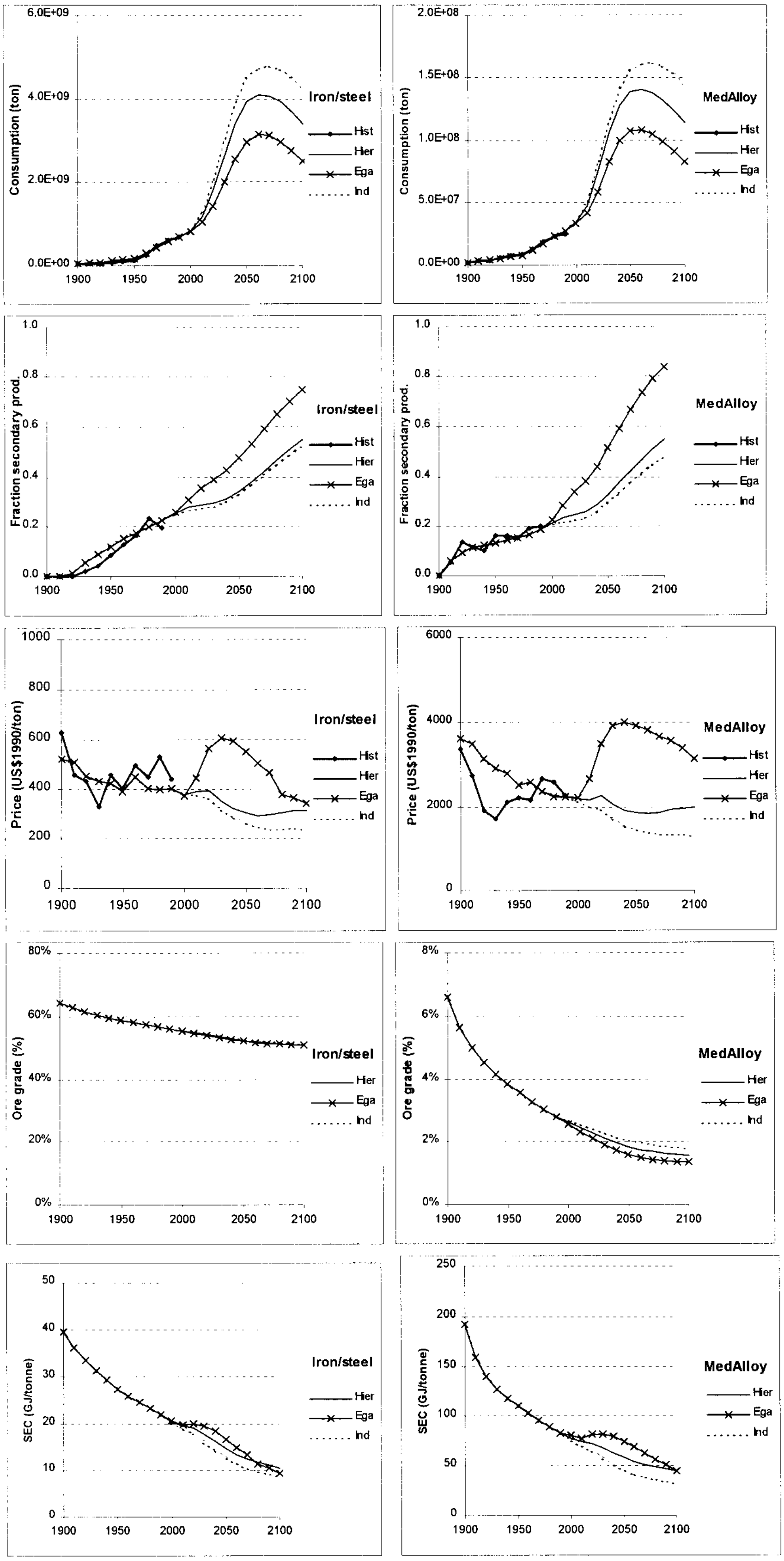

Figure 3.1: Model results 1900-2100.

Ega = Egalitarian, Hie = Hierarchist, Ind = Individualist. Hist = Historical data, (a)Demand, (b) Share of secondary production (=old scrap + dumped scrap recycling), (c) Average Metal Price, (d) Ore grade, (e) Average Energy Intensity.

4. Looking to the future: a perspectives approach

As described in the preceding section, the Metal Model can reproduce the past reasonably well for a set of key variables like metal demand and secondary metal production. Since the model was designed to examine long-term dynamics, we could simulate future trends based on model parameters derived from the calibration using 'best estimate' scenarios for population and economic growth. Uncertainties could be handled by calculating an uncertainty range around a central projection. However, the debate on future metal exploration, exploitation and recycling takes place on a much more fundamental level than this (compare Latesteijn, 1994; Tilton, 1996). Or as Tilton (1996) concludes: *'that intelligent and informed scientists remain so divided on such important issues for the future of humanity after years of debate is surprising. The explanation, at least in part, appears to lie with the different paradigms adopted by [...] different groups coupled with quite contrasting views on the beneficence of technology, public policy and the marketplace'*.

Therefore, it is more helpful to develop scenarios that reflect the main positions in the ongoing debate. Such model-designed scenarios might contribute to the discussion as they force the debaters to provide a quantitative, internally consistent, foundation for their opinions and expectations; one cannot suffice with a qualitative or semi-quantitative analysis as often happens in so-called 'story telling'. As such the model can help in making the main controversies explicit and offering the possibility to zoom in on those parameters making the largest contribution to the differences in outcomes. We have used the cultural theory of Thompson et. al. (1990) as heuristic for developing consistent scenarios following the TARGETS approach (Rotmans and De Vries (1997). We have used the work of Tilton (1996) to elaborate the perspectives in the Metal Model. Reasons for using the cultural theory instead of other social theories as a rationale in exploring possible futures are based on the following criteria: an empirical basis, universality in time and space, comprehensiveness (does the theory cover both lifestyles and world views), elaborateness and applicability to the subject (Hoekstra, 1998).

Using the cultural theory, three 'active' perspectives can be formulated for sustainable development: the individualist, hierarchist and the egalitarian. The individualist emphasises the opportunities of development based on technological development and human creativeness. Nature is considered benign. The hierarchist tries to maintain a social order by means of a competent-authority structure. Within limits, nature is considered to be able to resist human interference. The limits are based on scientific expertise and must be enforced by the government using bureaucratic procedures. The egalitarian emphasises the importance of strong group structures having common targets and values, but without authority structures. Nature is seen as vulnerable. Some key characteristics are summarised in **Table 4.1**.

Table 4.1. General characteristics of the perspectives.

	Hierarchist	Egalitarian	Individualist
General characteristics			
Myth of nature	Perverse, tolerant	Ephemeral	Benign
Concept of human nature	Sinful	Born good, malleable	Self-seeking
Management style	Control, regulatory	Preventive	Laissez-faire, adaptive
Desired system properties	Controllability	Sustainability	Exploitability
Ideal scale	Large	Small	Appropriate
Economic growth	Desirable with conditions	Not a primary goal	Unconditionally desirable
Salient risks	Loss of control	Catastrophes	Threats to free market
Risk-handling style	Institutionalisation	Reduction	Risk-seeking
Attitude to needs/resources	Expanding resource base	Needs-reducing strategy	Rational allocation of resources

For each of these perspectives one can distinguish between world view and corresponding management style. The former includes assumptions about how the world operates, based on interpretation of historical trends and speculations about the future. The latter describes which policy measures are thought to be necessary from a certain perspective. The combination of world view and corresponding management style results in certain consistent expectations of future developments and human responses. In the next section, we will discuss potential developments in line with these consistent scenarios or paradigms.

5. Perspectives in the Metals Model

Tilton (1997) describes two different schools of thought with respect to depletion of exhaustible resources: the concerned and the unconcerned; these are linked with egalitarian and individualist perspectives, respectively. We used the main arguments of these schools of thought to formulate our scenarios[13]. The main assumptions with regard to model parameters are shown in **Table A.1 (Appendix A)**. Despite these differences, all three scenarios have also some basic assumptions in common:

- All three scenarios assume moderate to strong economic growth of 2.3-3 % per year in all parts of the world; all assume that global population stabilises around 2060 at 8.8 billion and starts to decline to a final level of 7.1 billion in 2100 (compare De Vries et al., 1999).
- In all three scenarios, it is assumed that current low-income regions will follow a more-or-less similar path in terms of IU to what high-income regions followed earlier. Because almost 80% of the global population live in these low-income regions, this assumption creates a potentially great demand for metals.
- All scenarios assume rising prices for energy carriers by about a factor of 4 over the next century (from 1990 US$4 to 15-16 per GJ). The rationale for this is, however, different: whereas energy prices could be high in the egalitarian world due to taxes; for instance motivated by impending climate change, they increase in the individualist world mainly because of a higher use rate and hence faster depletion (Rotmans and De Vries, 1997).

5.1 The concerned egalitarians

The egalitarians adhere to the so-called fixed stock paradigm. Although, they are (now) well aware that new discoveries and technology have increased mineral reserves in the past and are likely to do so in the future, they regard resources as limited, based on social impacts and environmental damage associated with resource production (Friends of the Earth, 1998; WWF/IUCN, 1999). Several case studies, for instance, indicate that metal mining is both a direct and an underlying cause of forest loss and degradation – and that mineral wealth can actually depress social conditions in developing countries (WWF/IUCN, 1999). As society resorts to lower grades and to more remote deposits, natural areas will be more heavily disturbed (e.g. by large open-pit mines and mining accidents, as witnessed recently in Spain), more energy will be needed and increasing amounts of environmental wastes generated. Because population growth, economic growth and spread of material-intensive lifestyles, in particular, could potentially increase demand by order of magnitude, major policy initiatives are needed to reverse current trends in resource use and material-intensive lifestyles.

To reflect this, we have used the recently developed IPCC B1 scenario (IPCC, 1999), representing moderate population growth and relatively low, but more equally distributed, economic growth (see **Table A.1**). This has been combined with a relatively pessimistic view of the rate at which ore grades decline as production continues[14] (see **Table A.1**). We have

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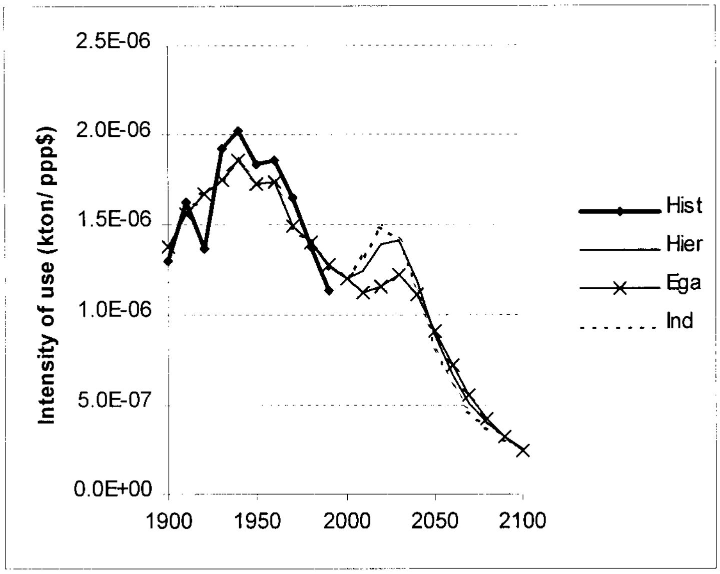
[1313] It should be noted that the past is as well amenable to divergent interpretations, since the available information does not allow for a single, unambiguous explanation. However, we do not pursue such a perspective-based interpretation of past developments.

[14] One might think here of the existence of a bimodal distribution of metal ores as hypothesised by Skinner (1979), which could significantly limit the availability of high-quality ores.

also assumed that a high tax on primary production will be introduced to internalise environmental costs and accelerate recycling (as for instance proposed in Ayres, 1997). Finally, we have assumed that egalitarian policies such as the promotion of technology transfer, will lower the top of the IU curve for currently developing regions. Nevertheless, even in the egalitarian scenario strong growth outside the OECD region results in a temporary rise of the metal-intensity world average, as shown for MedAlloy in **Figure 5.1**.

Figure 5.1: Global IU curves for MedAlloy according to the different scenarios.



Compared to the other scenarios, metal demand in the egalitarian scenario is relatively low and a high fraction of demand is covered by secondary production (see **Figure 3.1a** and **3.1b**). In a world governed by egalitarian policies, recycling is expectedly one of the ways in which the negative consequences in terms of energy and waste flows from low-grade ore mining can be mitigated (**Figure 3.1b-3.1d** and **Table 3.2**).

Table 3.2: Model variables in 2100 - the three scenarios and the egalitarian nightmare.

	MedAlloy				Iron/steel			
	hier.	ega.	ind.	night mare	hier.	ega.	ind.	night mare
	1990 = 1.0				1990 = 1.0			
Absolute indicators								
demand	4.2	3.0	5.2	10.0	5.0	3.7	6.2	12.4
energy consumption	2.2	1.6	2.0	8.8	2.4	1.5	2.4	7.1
waste	4.1	1.3	5.2	17.4	3.6	1.6	4.6	10.6
ore grade	0.6	0.5	0.6	0.3	0.9	0.9	0.9	0.9
price	0.9	1.4	0.6	1.6	0.8	0.9	0.6	1.0
Relative indicators								
IU	0.20	0.19	0.20	0.18	0.24	0.23	0.23	0.23
fraction recycling	2.9	4.5	2.6	2.8	2.4	3.3	2.3	2.0
total energy eff.	0.5	0.5	0.4	0.9	0.5	0.4	0.4	0.6
waste efficiency	1.0	0.4	1.0	1.7	0.7	0.4	0.7	0.9

Hier. : Hierarchist, Ega. : Egalitarian; Ind. : Individualist; Nightmare : Egalitarian Nightmare. Waste is the sum of mining waste and depreciation flows. Prices, energy efficiency and waste efficiency are the average value for all processes (primary and secondary).

The moderate increase in metal prices (**Figure 3.1d** and **Table 3.2**) until 2050 is mostly the result of the tax on primary production and the subsequent fall in secondary production costs resulting from economies-of-scale and learning-by-doing. In the egalitarian world view, only currently identified technical resources (5600 Gtonnes and 9 Gtonnes for Iron/steel and MedAlloy, respectively) can be used without generating an unacceptable environmental effect; hence 50% of these resources are still unexploited by the end of the next century.

5.2 The unconcerned individualists

The individualists point out that any appropriate estimate of the ultimate stock of metals shows an exceedingly long lifetime at current rates of consumption. For example, 1.5×10^{15} tonnes of copper thought to be present in the earth's crust would last for some 160 million years at recent rates of world consumption and, in fact, metals are not even destroyed when consumed (Simon, 1980). Furthermore, although population growth accelerates demand and thus depletion, it also increases the stock of human capital. The latter generates the new technologies that keep the costs of exhaustible resources falling. If resource allocation is left to the marketplace, the price system will foster exploration of new resources, material substitution or even recycling. For these reasons they adhere to the opportunity-cost paradigm, emphasising that cost-reducing effects of new technology and other developments have in the past easily off set the cost, increasing effects of depletion, even if energy and environmental costs are included (Barnett and Morse, 1963).

The optimism of the individualist world view is implemented in the model in the low estimates for the depletion parameters and relatively rapid technological change (see **Table A.1**). High economic growth is assumed, as in the IPCC A1 scenario (IPCC, 1999) and taxes are not raised. The saturation level of the IU curve is put at a slightly higher level to reflect material-intensive lifestyles, which results in a relatively high metal demand (see **Figure 3.1a**). Despite high metal consumption, the optimistic assumptions regarding technology and depletion result in: 1) a relatively low-energy intensity (see **Figure 3.1e**), 2) slow ore-grade decline despite the high level of primary production (see **Figure 3.1d**), 3) low metal prices (see **Figure 3.1c**) and 4) little environmental waste generated per unit of primary metal produced (see **Table 3.2**). Still, secondary production becomes sufficiently competitive to supply more than 50% of demand for both groups of metals in 2100 (see **Figure 3.1b**).

5.3 The 'business-as-usual' hierarchists

The hierarchist world view and management style have been implemented as a middle position, except for technological progress, for which hierarchist institutions tend to have a more cautious view (see **Table 3.1**). Hierarchists do not see any reason why technological change will be faster than it has been in the past. From the viewpoints of both the egalitarian and the individualist, the hierarchist choices are considered as 'muddling-through' because no clear choices are, or for that matter, can be made.

5.4 Risks for these perspectives

The scenarios discussed so far are based on coherent sets of world-view and human responses, and neither of them seem to result in clearly undesirable effects in terms of resource price and degradation, energy consumption or environmental consequences. In this sense, each of these futures can be labelled as 'utopian' and have even some common characteristics, though for different reasons. Some general conclusions can be drawn:

- if industrialising countries follow the same pattern in terms of an increasing IU, global metal demand could increase significantly in the next century (a factor of 2-4) and the declining trend in global IU may be temporarily reversed;
- the relative abundance of iron/steel metal implies that trends in declining energy intensity and production costs simply continue in the scenarios. The share of iron and steel production in total energy consumption (i.e. following the A1 and B1 scenarios; IPCC, 1999) remains at a level of between 5-10%. In 1995 this level was 7.4 % (IEA, 1998).
- For MedAlloy, historical decreases in energy and capital intensity for primary metals do not continue in the egalitarian scenario because technological innovations are offset by the relatively fast decline in ore grade.

Each of the perspectives can be criticised, in particular, in terms of the risks involved. What happens if the world does not turn out as expected in the perspective in question? Obviously, the individualist scenario is considered to be risky adventure from an egalitarian perspective, as it assumes that depletion occurs only very slowly, technology changes fast, relatively large amounts of waste can be generated without major environmental repercussions and large differences in wealth can be sustained. On the other hand, the egalitarian scenario from the individualist perspective is based on a lack of courage – resulting in more poverty and fewer opportunities. The main risk in this scenario concerns the question whether the human population is willing or able to change its lifestyle. Clearly, the 'government' in this scenario will lose its support if there are signs that the natural system is more robust – and economic sacrifices are perceived as unnecessary. **Table 3.3** provides for each perspective an indication of the main risks, turning it from a 'utopia' into a 'dystopia', with undesirable and sustainable aspects.

Table 3.3: Sensitivity of each scenario to discrepancies between world view and management style.

	Egalitarian scenario	Individualistic scenario	Hierarchist scenario
Overestimating the resilience of the natural system with regard to impacts of mining and pollution.	--	++	++
Overestimating the presence of high-grade ore.	-	++	0
Overestimating the rate of technology development	+	++	0
Overestimating the ability of humans to change their life-style	++	--	0

++ Very sensitive to such risks; 0 : Not very sensitive to such risk; -- : Completely unsensitive to such risks.

The most obvious risk scenario is that of the 'egalitarian nightmare': economic growth and management belonging to the unconcerned individualist, with ore-grade decline and technological development expected in the egalitarian scenario. **Table 3.2** shows the results of the 'egalitarian nightmare' vis-à-vis other model results. In this scenario we have used the population growth of the IPCC A2-scenario (IPCC, 1999) to implement the egalitarian fear that population growth could reach a level of 14 billion people if no additional measures are taken. The 'egalitarian nightmare' results in **Table 3.2** picture a world in which metal use generates large and increasing energy use, which in turn aggravates the impending threat of climate change; rising metal prices keep less industrialised regions in a poverty trap and enormous fluxes of mining waste put an ever-increasing stress on ecosystems, resulting in loss of biodiversity.

It should be noted here that most environmental consequences are outside the scope of our model. Nevertheless, environmental pressures in terms of waste generated and energy consumed increase sharply in this scenario to levels that will be considered totally unacceptable by the egalitarians (for MedAlloy waste generation and energy consumption increase to 17 times and 8 times above their 1990 levels, respectively)[15]. Such increases also seriously increase the expanse of natural areas disturbed by mining. For MedAlloy, strong signs of resource degradation are observed, i.e. rising energy intensity for production of primary metal and rising average prices (**Table 3.3**). In fact, in the case of MedAlloy, all presently identified technical resources will be consumed before 2060. For iron/steel, the consequences are slightly less obvious, but here too, due to sheer growth in demand, energy consumption and waste production increase to levels several times higher than current ones.

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[15] Adriaanse et al. (1997) proposed using material flows as an indication of total environmental pressure. These waste flows constitute a very large share of the total material flows.

6. Conclusions

In this paper, we have described the metal model, which simulates some major long-term trends in production and consumption of metals (i.e. iron/steel and an aggregate of metals of medium abundance). Integrating earlier models and assessments in this area, the model's focus is on long-term dynamics and is primarily meant as a tool for analysis, and clearly not for predictions. It aims to fill at least partly a gap in understanding the 'material' economy, which has been less thoroughly analysed than energy and fuel fluxes.

Our simulation experiments indicate the model to be fairly well able to reproduce the long-term trends in the 1900-1990 period; however, regional economic and demographic trends have to be taken into account to give an adequate picture of developments in demand. It would be interesting to analyse the regional differences in IU and to develop IU curves on the basis of such an analysis so as to shed more light on the long-term relationship between economic growth and material flows.

A perspective-based construction of long-term scenarios has been shown here to reveal some interesting insights about several controversies in this field of resource economics. Our model-based scenarios representing the major paradigms towards – [un]sustainable - resource use, based on Tilton (1996) and Thompson et al. (1990), allow a more quantitative interpretation of major controversies and risks in relation to metal resource depletion and use. The results suggest that apparently similar metal flows may correspond to rather divergent sets of assumptions on the metal resource base and its characteristics, and on metal demand developments. We hope that such analyses will contribute to a more open and transparent discussion on the issue at hand, thus avoiding a post-modern 'anything goes' adagium.

Because coupling with environmental and ecosystems (e.g. via pollution, land degradation or mining accidents) is not part of our model and because resource depletion is modelled in terms of declining resource quality and not outright depletion, none of the scenarios presented cause a system collapse. The effect on economic growth has not been included either. In future activities, we hope to integrate the metal model into the IMAGE modelling framework, presently being used to construct some of the new IPCC scenarios (De Vries et al. 1999).

Although the model assumptions, and type of production and consumption, between the egalitarian, individualist and hierarchist 'utopian' scenarios differ significantly, resulting impacts such as energy intensity and ore-grade decline are much more similar as a result of counteracting forces within the model. In all modelled scenarios, industrialisation and economic growth in current low-income regions leads to a strong growth in metal demand – and even a temporary rise in global intensity of use. For abundant metals, resource quality decline is, in all cases, expected to be limited. For the less abundant metals, however, assumptions with regard to depletion and technology development can result in significant impacts of resource degradation on energy consumption and waste – in particular, in combination with an unconcerned management style and a pessimistic assumption about the availability of high-grade ore. The differences between the scenarios (certainly in a broader perspective of resource management) are important for future policies. Obviously, not all world views and management styles can be right, but at the moment there is no evidence to rule out any of the scenarios: there is no proof that the world will soon run out of cheap metals or suffer from intolerable environmental side-effects. Neither is there support for the complacent view that everything will sort itself out in the marketplace. Further research should be directed to resolving, as far as possible, the existing controversies.

The present model result can contribute to existing knowledge on trends in dematerialization and resource degradation. Moreover, this information can also be used in the context of energy demand models, since the metal industries consume between 5 and 10% of global primary energy. In principle, the Metals Model can be integrated into the TARGETS and IMAGE/TIMER model. In this way, the following linkages might be explored: 1) energy consumption and energy prices, 2) investments (competition with other sectors), and 3) negative impacts of waste and mining (land degradation).

The current model also still has serious shortcomings. First of all, trends of IU should be analysed in view of the underlying trends, such as substitution (in particular, with plastics and aluminium) and economic trends (sectoral composition of economies). This requires more integration of technical knowledge (e.g. from Life Cycle Analysis) and existing economic models. The model could also be improved by including more detail on the production side – distinguishing important production processes (such as open hearth versus electric arc production for steel) and including regional production curves.

References

Adriaanse, A., S. Bingezu, A. Hammond, Y. Moriguchi, E. Rodenburg, D. Rogich and H. Schütz (1997). *Resource Flows, The material basis of industrial economies.* World Resources Institute, Washington DC.

Alcamo, J., E. Kreileman and R. Leemans (Eds.) (1998). Global change scenarios of the 21st century. Results from the IMAGE 2.1 model. Elsevier Science. London.

Altenpohl, D. G. (1980). *Materials in World Perspective. Assessment of Resources, Technologies and Trends for Key Materials Industries.* Springer-Verlag, Berlin.

Annema, J. A. and J. Ros (1994). Management of the zinc chain. *Resources, conservation and recycling.* **12**. 209-219.

Argote, L. and D. Epple (1990). Learning curves in manufacturing. *Science.* **247**. 920-924.

Ayres, R.U. and L.W. Ayres (1996). *Industrial Ecology – Towards closing the material cycle.* Edward Elgar, Cheltenham, UK.

Ayres, R.U. (1997). Metal recycling: economic and environmental implications. *Resources, Conservation and Recycling.* **21.** 145-173.

Barnett, H.J. and C. Morse (1963). *Scarcity and growth.* John Hopkins. Baltimore.

Benardini, O. and R. Galli (1993). Dematerialisation: Long-term Trends in the Intensity of Use of Materials and Energy. *Futures.* **25.** 431-447.

Brinck, J.W. (1979). *Long term raw materials prospects.* Brinck International Resources Consultants B.V., Alkmaar, The Netherlands.

Chapman, P.F. and F. Roberts (1983). *Metal Resources and Energy.* Butterworths, London.

De Bruijn, S.M., J.C.J.M. Van den Bergh and J.B. Opschoor (1998). Economic growth and emissions: reconsidering the emperical basis of the environmental Kuznets curves.*Ecological Economics.* **25.** 161-175.

Deffeyes, K.S. and D. MacGregor (1980). World Uranium Resources. *Scientific American.* **242** (1). 50.

De Vries, H.J.M. (1989a). Effects of resource assessments on optimal depletion estimates. Resources Policy. *Resources Policy.* September.

De Vries, H.J.M. (1989b). *Sustainable Resource Use - Optimal depletion within a geostatistical framework.* Institute for Energy and the Environment (IVEM), University of Groningen, The Netherlands.

De Vries, H.J.M. and R. van den Wijngaart (1995). *The Targets/IMage Energy (TIME) 1.0 Model.* National Institute of Public Health and the Environment, Bilthoven, The Netherlands.

De Vries, H.J.M., J. Bollen, L. Bouwman, M. den Elzen, M. Janssen, E. Kreileman and R. Leemans (1999). Greenhouse gases in an equity, environment and service-oriented world: an IMAGE-based scenario for the next century. (submitted for publication in *Technological Forecasting and Social Change*).

Duchin F. and G.M. Lange (1994). *The Future of the Environment. Ecological Economics and Technology Change.* Oxford University Press, New York.

Friends of the Earth (1998). *Uit balans. Sociale en ecologische gevolgen van de Nederlandse consumptie van metalen.* Milieudefensie, Amsterdam, The Netherlands.

Forester, T. (Ed.) (1988) *The Materials Revolution - Super conductors, new materials and the Japanese challenge.* The MIT Press, Cambridge, U.S.A.

Frosch, R.A., W.C. Clark, J. Crawford, A. Sagar, F.T. Tschang and A. Webber (1997). The industrial ecology of metals. A reconnaissance. *Phil. Trans. R. Soc. Lond. A.* **355.** 1335-1347.

Gordon, R.B., T.C. Koopmans, W.D. Nordhaus and B.J. Skinner (1987). *Towards a New Iron Age ? Quantitative Modelling of Resource Exhaustion.* Harvard University Press, Cambridge, U.S.A.

Hendricks, C. H.M. Aichinger, M. Joksch and H.P. Domels (1998). Energieaspekte und gegenwärtige Verbrauch an Energierohstoffen der Weltstahlerzeugung. *Stahl und Eisen.* **118**. 39-48.

Hoekstra A.Y. (1998). Perspectives on water : an integrated model-based exploration of the future. PhD thesis, Delft University of Technology, The Netherlands.

IEA (1998). *IEA Database Beyond 20/20. Version 4.1.* International Energy Agency, Paris.

IIIS (1996). *Steel Statistical Yearbook 1995.* International Institute for Iron and Steel, Brussels.

IPCC (1999). *Special Report on Emission Scenarios.* Intergovernmental Panel on Climate Change. Draft version March 1999.

Jolly, J. H. (1993), Material flow of zinc in the United States 1850-1990. *Resources, conservation and recycling.* **9**. 1-30.

Klein Goldewijk, C.G.M. and J.J. Battjes (1997). *A Hundred Year (1890-1990) Database for Intergrated Environmental Assessments (HYDE, version 1.1).* National Institute of Public Health and the Environment, Bilthoven, The Netherlands.

Latesteijn, H.C., D. Scheele, D. and J.J. Schoonenboom (1994). Paradigms of sustainability and perspectives of environmental utilisation space. *Milieu.* **5**. 244-251.

Maddison, A. (1989). *The World Economy in the 20th Century.* Organisation for Economic Co-operation and Development, Paris.

Malenbaum. W. (1995). *World Demand for Raw Materials in 1985 and 2000.* McGraw-Hill, New York.

Mannaerts, H. (1997). Stream – Economic acticity and physical flows in an open economy. *Current Research.* Central Planning Bureau. The Hague.

Meadows, D.H., D.L. Meadows, J. Randers and W.W. Behrens (1972). *Limits to Growth.* Universe Books, New York.

Metallgesellschaft (various years). *Metallstatistik.* C. Adelmann. Frankfurt am Main.

Moll, H.C. (1989). *Aanbod van en vraag naar metalen; ontwikkelingen, implicaties en relaties; een methodische assessment omtrent subsitutie van materialen.* Institute for Energy and Environment (IVEM). Working report no. 9. University of Groningen, The Netherlands.

Neij, L. (1998). The use of Experience Curves to Analyse Cost Reductions in Renewable Energy Technologies. *Technological Innovations, Sustainable Development and the Kyoto Conference.* ENER Bulletin. 22.98, Roskilde, Denmark.

Roberts, M.C. (1996). Metal use and the world economy. *Resources Policy.* **22**. 183-196.

Rotmans, J. and B. de Vries (1997). *Perspectives on Global Change - The TARGETS Approach.* Cambridge University Press, Cambridge, U.K.

Schmitz, C.J. (1979). *World non-ferrous metal production and prices 1700-1976.* Frank Cass and Company Ltd., London.

Simon, J.L. (1980). Resources, Population, Environment: An oversupply of False Bad News. *Nature.* **208**. 1431-1437.

Singer, D.A. and D.L Mosier (1981). A review of regional mineral resource assessment methods. *Economic Geology.* **76.** 1006-1015.

Skinner B.J. (1979). The frequency of mineral deposits. Alex. L. Du Toit Memorial Lectures. Geological Society of South Africa.

Summers, R. and A. Heston (1991). The Penn World Table (Mark 5): An expanded set of international comparisons, 1950-1988. *The Quaterly Journal of Economics.* May. 327-368.

Suzuki, Y. and K. Shoji (1977). Global Metallic Resource Model in Kaya, Y. et al., Future of Global Interdependence (FUGI project). Presented at the 5th IIASA Global Modelling Conference, Laxenbourg, Austria.

Thompson, M., R. Ellis and A. Wildavsky (1990). *Cultural theory.* Westview Press, Boulder, U.S.A.

Tilton, J.E. (1986). Atrophy in Metal Demand. *Materials and Society.* **10.** 241-243.

Tilton, J.E. (Ed.) (1990). *World Metal Demand.* Resources for the Future, Washington DC.

Tilton, J. E. (1996). Exhaustible resources and sustainable development. Two different paradigms. *Resources Policy.* **22** **(1-2)**. 91-97.

USBM (1993). *Statistical Compendium* (CD-ROM). U.S. Bureau of Mines, Washington DC.

USBM (various years). *Mineral Yearbook - Volume 1: Metals and Minerals.* U.S. Government Printing Office, Washington DC.

USBM (1992). *Metal Prices in the United States through 1991.* U.S. Bureau of Mines, Washington DC.

Van der Voet, E. (1996). *Substances from cradle to grave.* Ph.D. thesis, Centre for Environmental Science, University of Leiden, The Netherlands.

Van Vuuren, D. P. (1995). *Modelling Metal Resource Use - Documentation, Calibration and Extension of the TARGETS Minerals Model.* Department of Science, Technology and Society, Utrecht University, The Netherlands.

Verbruggen, E., D. Van der Meent, A.H.W. Beusen, and A. den Hollander (1997). *GLOBETOX - Modelling the global fate of micropollutants.* National Institute of Public Health and the Environment, Bilthoven, The Netherlands.

Weizsacker E. , A.B. Lovins and L.H. Lovins (1998). *Factor four: doubling wealth, halving resource use.* Earthscan, London.

Weston, R.F. and M. Ruth (1997). A dynamic, hierarchical approach to understanding and managing natural economic systems. *Ecological Economics.* **21**. 1-17.

Worell, E., L. Price, N. Martin, J. Farla, and R. Schaeffer (1997). Energy intensity in the iron and steel industry: A comparison of physical and economic indicators. *Energy Policy.* **25** (7-8). 727-744.

WWF/IUCN (1999). *Metals from the forest. Mining and forest degradation.* World Wide Fund for Nature/World Conservation Union, Gland, Switzerland.

Appendix A Implementation of the perspectives

Table A.1: Implementation of the perspectives

	Egalitarian (Concerned)	**Hierarchist**	**Individualist (Unconcerned)**
Demand[a]			
Max. Population Size[b]	As hierarchist	8.8×10^9 in 2050	As hierarchist
GWP/cap in 2100[b]	47,500 $\$_{1990}$	65,000 $\$_{1990}$	80,000 $\$_{1990}$
Future Saturation level[c]			
Iron/steel	As hierarchist	0.45	Hierarchist + 20 %
MedAlloy	As hierarchist	0.017	Hierarchist + 20 %
Reduction of IU curve[d]	0.25% per year	-	-
Depletion[e]			
Ore grade decline			
Past			
Iron/steel	As hierarchist	25	As hierarchist
MedAlloy	As hierarchist	3.9	As hierarchist
Future			
Iron/steel	20	25	30
MedAlloy	2.4	3.9	5.5
Technological change[f]			
Past			
Prim. prod. Iron/steel	As hierarchist	0.80	As hierarchist
Prim. prod. MedAlloy	As hierarchist	0.80	As hierarchist
Sec. prod. Iron/steel	As hierarchist	0.90	As hierarchist
Sec. prod. MedAlloy	As hierarchist	0.90	As hierarchist
Future			
Prim. prod. Iron/steel	0.85	0.80	0.80
Prim. prod. MedAlloy	0.85	0.80	0.80
Sec. prod. Iron/steel	0.75	0.90	0.80
Sec. prod. MedAlloy	0.75	0.90	0.80
Energy Prices[g]	Egalitarian utopia TARGETS 1.0 (ca. 16 US$/GJ in 2100)	Hierarchist utopia TARGETS 1.0 (ca. 16 US$/GJ in 2100)	Individualist utopia TARGETS 1.0 (ca. 15 US$/GJ in 2100)
Tax on primary production	10% in 2000[h] 50% in 2050 100% in 2100	5% in 2000[i] 10% in 2050 20% in 2100	None

[a] Demand is determined for 13 regions (see **Figure 2.4**), based on the regional populatioin and economic growth.

[b] Scenarios taken from IPCC (1999). Egalitarian = B1-scenario. Individualist = A1-scenario.

[c] Parameter x_1 in **Eq. 2.1** (Box 2.1).

[d] Parameter F in **Eq. 2.1** (Box 2.1).

[e] Ore grade decline is expressed in terms of a percentual decrease of ore grades for each doubling of accumulated production (= determines depletion constant in **Eq. 2.3** (Box 2.1)). Values are based on weighted averages from Deffeyes and MacGregor (1980), low and high estimates.

[f] The decrease of the capital output ratio (COR) and energy intensity for each doubling of accumulated production (see **Eq. 2.4 and 2.5**)

[g] Energy price is based on the average of electricity and fuel prices, taken from utopias in TARGETS 1.0 (Rotmans and de Vries, 1997). The prices are mentioned in constant dollars of 1990. The 1990 energy price is 4 US$/GJ.

[h] Egalitarian taxes on primary metal prices are used to subsidise secondary production.

[i] Hierarchist taxes on primary metal prices are used to reduce overall capital costs in the industry sector.

Appendix B Mailing list

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