# Anthropogenic Metabolism and Environmental Legacies

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# Anthropogenic Metabolism and Environmental Legacies

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*For prehistoric Man, the total metabolism (input, output and stock of materials and energy to satisfy all human needs for provisions, housing, transportation, etc.,) was mainly determined by the physiological need for food, for air to breathe, and for shelter. The material turnover of modern Man is 10–20 times larger. The fraction that is used for food and breathing is small. The so-called anthropogenic metabolism covers not only the physiological metabolism but includes also the thousands of goods and substances necessary to sustain modern life. "Anthropogenic" stands for man-made. The Anthroposphere is the sphere in which human activities take place, sometimes called technosphere or biosphere. Today, the most important man-made material flows are due to activities such as cleaning, transporting, residing and communicating. These activities were of little metabolic significance in prehistoric times.*

*Even more astonishing than the increase in the material flows is the tremendous material stock, which mankind has been accumulating, and which continues to grow faster than ever. This stock is found everywhere. It begins with mining residues left behind as tailings. It goes on with the material stocks of industry, trade and agriculture, and culminates in the urban stock of private households and of the infrastructure for transport, communication, business and administration. It ends with the comparatively small but growing material wastes in landfills.*

*The difference in stock accumulation between prehistoric and modern times is striking. Present-day material stocks amount to about 3–400 tons per urban citizen. We have to manage and maintain this stock. Today's societies have to make far-reaching decisions about the constant renewal of the urban stocks, such as buildings, roads, communication systems, etc. The residence time of materials in the stock ranges up to 100 years. This means that once a material is consolidated into the stock, it will probably not show up quickly in the output of the stock, namely in waste management.*

*The presence of this large and growing stock has many implications:*

1. *as an important reservoir of valuable resources, it holds a tremendous potential for future recycling;*
2. *as a mostly unknown source of materials, the importance of which is not yet in focus, which awaits assessment with respect to its significance as a resource and as a threat to the environment;*
3. *as a long-term source of severe pollutant flows to the environment. An assessment has been made that urban stocks contain more hazardous materials than so-called hazardous waste landfills, which are a focus of environmental protection;*
4. *as a challenge for future planners and engineers to design new urban systems. In the future, the location and amount of materials in city stocks should be known. Materials should be incorporated into the stock in a way which allows easy reuse and environmental control;*
5. *as an economic challenge to maintain high growth rates, building up even larger stocks, and setting aside sufficient resources to maintain this stock properly over long periods of time.*
6. *as a challenge to simulation modelers, who must deal with the complexities of the many processes contributing to urban metabolism, including the influence of long-term global, regional and local environmental, socioeconomic and cultural changes (*see ***Contaminated Lands and Sediments: Chemical Time Bombs?****, Volume 3).*

## METABOLISM OF THE ANTHROPOSPHERE

### Phenomenology: Growing Stocks and Flows Surpassing those of Nature

The following phenomena are typical for the metabolism of today's affluent societies:

- rates of material consumption and stock accumulation are high and growing;
- for many materials, man-induced material flows exceed natural flows;
- consumption emissions are surpassing production emissions;
- the metabolism of cities is mainly linear (throughput economy), thus cities are heavily dependent on their hinterland as a source for raw materials, as a partner for trade of manufactured goods, and as a sink for dissipation.

#### *High Growth Rates of Material Flows and Stocks in Affluent Societies*

As presented in Figure 1 and Table 1, the household consumption of goods has increased from prehistoric to modern times by more than an order of magnitude. The term *good* is used for products with a positive or negative economic value. A good is made from substances, which are defined as chemical elements or compounds consisting of uniform units such as atoms (element) or molecules (compound). The term materials stands for both goods and substances. This growth is even larger if all of the materials used in mining, agriculture, forestry, manufacturing, distribution and consumption are included. The main target of these large material flows is the consumer. With his/her

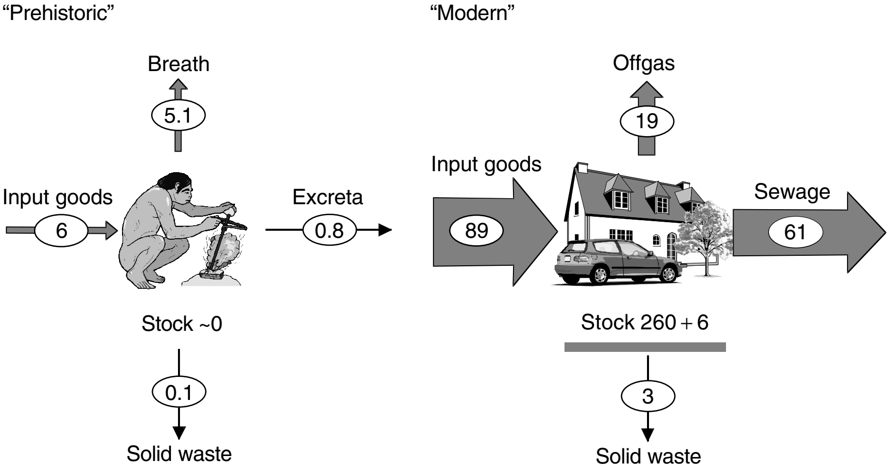

**Figure 1** Material turnover of prehistoric and modern Man, in tons per capita per year. Included are all materials used in private households to satisfy the needs for food, shelter, hygiene, transportation, communication, etc., (for details, see Baccini and Brunner, 1991)

**Table 1** Comparison of material flows and stocks for selected activities for prehistoric and modern Man[a]. T/c.y stands for tonnes per capita per year

| | Material turnover t/c.y | | Material stock t/c | | Annual change in material stock t/c.y | |
|---|---|---|---|---|---|---|
| Activity | Prehistoric | Modern | Prehistoric | Modern | Prehistoric | Modern |
| To clean | <0.1 | 60 | 0 | 0.1 | 0 | <0.1 |
| To communicate | 0 | 10 | 0 | 160 | 0 | 3 |
| To reside | <0.1 | 10 | <0.1 | 100 | 0 | 3 |
| To breathe | 4 | 4 | 0 | 0 | 0 | 0 |
| To nourish | 1.6 | 1.7 | 0 | <0.1 | 0 | <0.1 |
| Total | 6 | 86 | <0.1 | 260 | ~0 | +6 |

[a] The most outstanding and unprecedented features of today's economies are the very large stock of materials that have accumulated in the anthroposphere. "To clean" comprises water, chemicals and equipment needed for laundry, dishwashing, personal hygiene, toilet etc.; "to communicate" takes account of the transport of persons, goods, energy and information due to the needs of private households (including materials for road construction); "to reside" consists of the buildings, furniture, appliances etc., needed for living; "to nourish" includes all flows of goods associated with the consumption of food within private households, e.g., food, water for cooking, etc.

high purchasing power, he/she is able to pull vigorously at the end of the material chain, buying products larger quantities of consumer goods and energy (Schmidt-Bleek *et al.*, 1996). The terms rucksack and gray characterize the invisible energy, materials and wastes associated with the production of a good during primary production and manufacturing of the constituents and the product itself.

The lifestyle of modern urban Man demands a large amount of materials and energy to sustain his/her metabolism. The reasons are manifold. Economic conditions in the affluent part of the world allow large consumption flows. Resources such as energy and minerals are still abundant and cheap. The early warnings about the limits to growth due to diminishing resources (Meadows *et al.*, 1972) proved to be (numerically, but not in principle!) wrong. Advanced technology enables the development of new products in shorter cycles, making many appliances obsolete before the actual end of their life. Consumption seems to be a value *per se*; many modern consumer products transfer social prestige from the product to the owner. Although there may be small signs of consumer fatigue or even opposition here and there, in general there is no realistic alternative to this growth in material consumption in sight. It remains to be shown that the decoupling of economic progress with the growth of material consumption is economically feasible. It is obvious that developing countries, which still consume at a much lower rate, wish to reach the same material turnover rates as in the most affluent societies.

Compared to the flows of goods, the increase in the flows of many substances, such as lead, is much more dramatic. It has been estimated (Settle and Patterson, 1980) that the mining of lead rose during the last 7000 years from about 1 ton year$^{-1}$ to more than 3 million tons in 1990 (Figure 2). The situation is similar for other metals, and for natural and synthetic organic substances. Due to technological and economic development, there are constant shifts in the use of materials. This is illustrated by the changes in the amounts of materials used for construction in the US (Figure 3). Wood is no longer the key construction material, concrete dominates, and plastic materials are becoming increasingly more important. Metals and organic additives are also growing in importance. In waste management, materials that were used for construction 25–100 years ago, have to be treated now (recycled and disposed of). The nature of these materials will change rapidly in coming decades. There will be more mixtures of more materials reaching waste management sites. The fraction of hazardous waste materials in urban wastes will increase because of the growing consumption of chemicals in the 1970s and 1980s used to stabilize components of manufactured goods. Even if these substances are not used anymore, there exist large reservoirs of banned substances such as chlorofluorocarbons (CFCs) and cadmium (Cd) in the urban stock. As a consequence, waste management must also be capable of handling materials that have not been in use for decades. Prevention is a strategy that has only a slow effect when applied to materials incorporated in the urban stocks with long residence times.

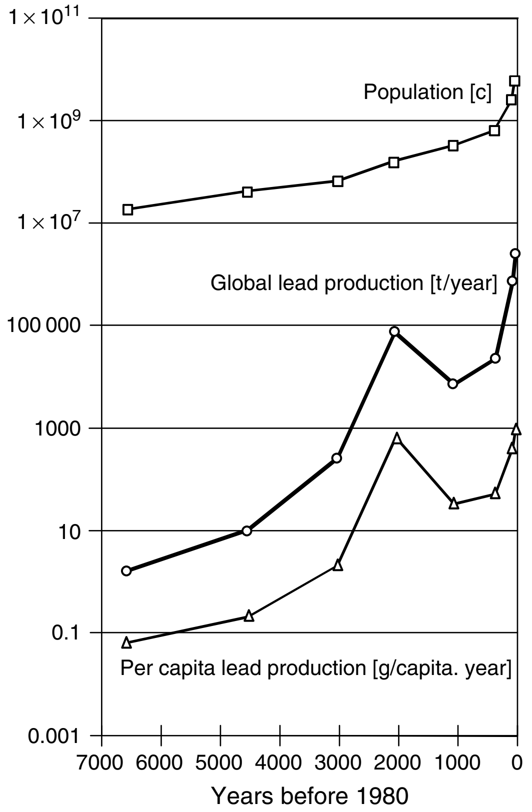

**Figure 2** Global production of lead: due to unprecedented progress in mining technology and economic development, the per capita mining of lead increased from 0.1 g capita$^{-1}$ year$^{-1}$ to 1000 g capita$^{-1}$ year$^{-1}$. In combination with the growth of the global population (which increased at a smaller rate than the per capita production), the total amount of lead produced from mining increased from 1 ton year$^{-1}$ to more than 3 million tons year$^{-1}$ (lead data from Settle and Patterson, 1980)

Goods with long residence times are typically incorporated into the infrastructure, such as housing, industry and manufacturing, traffic and communication systems, and so on. A large, and at present mostly unknown mass of substances is stored in this stock. Figure 2 serves as an example. There is little information about today's location of approximately 100 million tons of lead exploited over the last 7000 years. Part of the lead stock is still used as water piping or insulation for telecommunication cables. Another fraction has been dispersed via exhaust gases from cars fueled by leaded gasoline; it remains in the soil and in sediments, and a small fraction has shown up in the Greenland ice caps and other remote areas. Lead has also been land filled with industrial wastes and with municipal solid wastes (MSWs). For the city of Vienna, it has been roughly

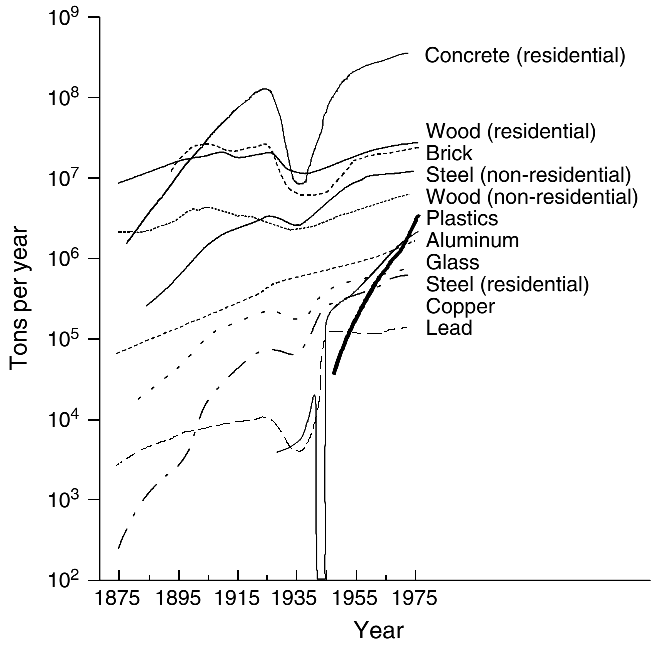

**Figure 3** Construction materials used in the US from 1875 to 1975 (adapted from Wilson, 1975). Around 1900, wood was surpassed by concrete as the main construction material. Plastics and aluminum were among the fastest growing construction materials in the 1970s. Change in the consumption of construction materials also alters the construction stock. Future waste management will have to deal with large amounts of plastics and metals such as aluminum and copper

estimated that about 90% of the lead stock is still within the city, either in use or hibernating, and that only 10% is stored in waste landfills (Hendriks *et al.*, 2000). From this point of view, the hazardous substances stored in the so-called hazardous landfills are less than the amounts still within the city anthropospheres. With a few exceptions, the long-term fate and environmental significance of the urban stock of metals and organic materials is unknown (Bergbäck *et al.*, 1998).

When all stocks associated with the material chain are included, a first assessment reveals the following: waste deposits from primary production (mining wastes such as tailings) comprise about 10% of the total stock; in use and in hibernating materials within the anthroposphere – about 80%; and land filled waste products about 10%. Hence, from a mass point of view, the most important future material reservoir is the urban stock, and not landfills and tailings. For an economic evaluation of this stock, the concentrations and speciations of the materials in these stocks may be even more important than the total amounts. The same is true for an environmental assessment. Up to now, the emission rates, chemical species, pathways, and final sinks of substances incorporated in urban stocks have not been investigated in a systematic and comprehensive way. Thus, aside from some specific case studies, it is not yet possible to discuss future effects on the environment, which may occur due to the dissipative material flows from urban stocks.

### *Anthropogenic Flows Exceed Natural Flows*

Due to the large growth rate of the exploitation of essential minerals, man-made flows are approaching and even surpassing the natural flows of many substances. As a consequence, the flows, stocks and concentrations of certain substances such as heavy metals and nutrients are rising, causing the biosphere to change more rapidly and

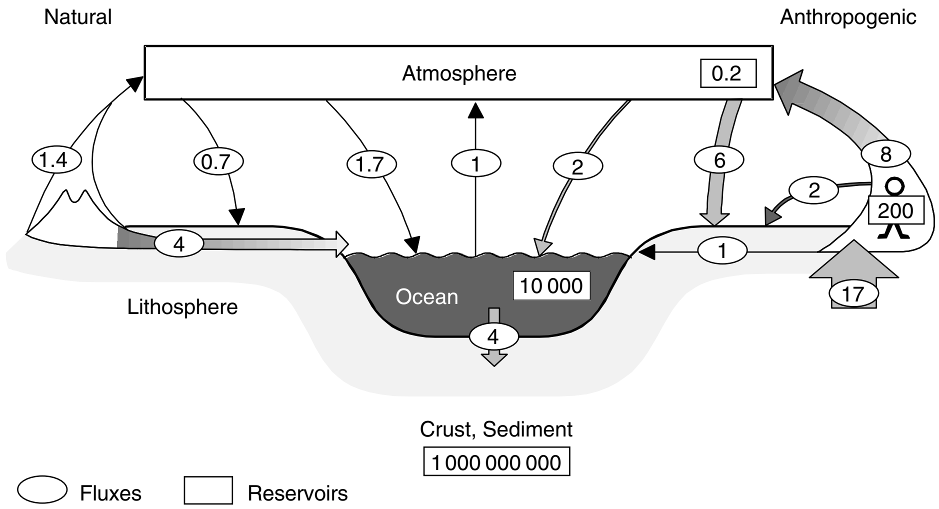

**Figure 4** Global anthropogenic and natural Cd flows and stocks in the 1980s, in Kilotons per year (flows), and Kilotons (stocks). The man-made flows surpass the natural flows. Comparatively high atmospheric emissions lead to a significant accumulation of anthropogenic Cd in the soil. The stock of anthropogenic Cd grows by 3% per year. It needs to be managed carefully in the future if long-term environmental impacts are to be avoided (Baccini and Brunner, 1991)

in different directions than without anthropogenic material flows. Cd is used herein as a case study to exemplify the importance of today's man-made flows. In this case there is an abundance of data available. In general, the gap between actual and toxic concentrations in soils is smaller for Cd than for other metals.

In Figure 4, the global natural and anthropogenic flows of Cd during the 1980s are summarized. The total man-made flows of about 17 Kt $year^{-1}$ are more than twice the size of the natural flows of about 6–7 Kt $year^{-1}$ due to erosion, volcanic eruptions, and sea spray. Also, the input into the anthroposphere (17 Kt $year^{-1}$) is larger than the sum of all outputs (11 Kt $year^{-1}$) of the anthroposphere. Thus, about 6 Kt $year^{-1}$, or 30% of the Cd annually mined from the Earth's crust, is accumulated in long-lived goods. The Cd stock in the anthroposphere grows with a rather short doubling time of 30 to 40 years. In the 1980s, the most important pathway for Cd from the anthroposphere to the environment was the atmosphere. This is due to (1) the physical–chemical properties of Cd, which has a comparatively high vapor pressure as an element and for most of its compounds; and (2) the lack of appropriate flue gas cleaning technology two decades ago. The man-induced global flows of Cd into the atmosphere were an order of magnitude larger than the natural flows. Today, the emissions into the atmosphere are lower, due to advanced flue gas cleaning technology in metallurgical and waste treatment processes.

The anthropogenic Cd flow by surface waters to the oceans is still smaller than the transport of weathered Cd by the large river systems. The main sink for Cd was and still is the soil, followed by ocean sediments. Regional Cd balances reveal that in densely populated areas, the atmospheric deposition of Cd onto the soil is greater than the output from the soil by leachate, erosion or plant uptake. This situation is indicated in Figure 4 as well. The global input into the soil by atmospheric deposition (6 Kt $year^{-1}$) and land filling (2 Kt $year^{-1}$) is much larger than the output by erosion and river systems (1 Kt $year^{-1}$). Comparing the natural side (ratio of deposition to leaching of 17 : 1) with the anthropogenic side (ratio of deposition to leaching of 8 : 1) in Figure 4, the large accumulation of anthropogenic Cd in the soil becomes evident.

For Cd and other metals, humans are already more important than nature as material transformers. This is true not only at the global level, but also, and more often, at the regional level. Investigations from Sweden (Figure 5) (Bergbäck, 1992; Azar *et al.*, 1996) show that the weathering rates of several heavy metals are surpassed by the weathering (or emission) rates due to anthropogenic activities.

The consequences for both regional and global levels are the same: the reservoirs in soils, the anthroposphere, and landfills are growing. For some materials, the industrial contribution has already caused the prehistoric concentrations in the reservoir to double, while for others, this will happen in the future, if material management does not change fundamentally. The long residence times of materials in the anthroposphere and, especially in the soil, will result in a long lasting challenge for future generations. Our successors will be given a large source of secondary raw materials, but at the same time they will have to make sure that the emissions from this source are small and under control.

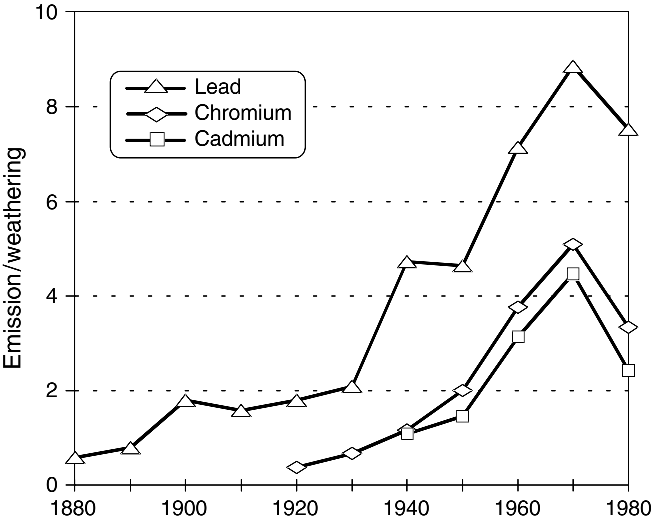

**Figure 5** Anthropogenic emission rates of lead, chromium, and cadmium are larger than natural weathering rates (Bergbäck, 1992). Although these examples come from Sweden, similar results have been observed in other countries with advanced economies

### *Consumption Emissions Surpass Production Emissions*

A third phenomenon of the metabolism of advanced societies is that production emissions are decreasing, while certain consumer emissions are increasing. The data (Bergbäck, 1992) indicate that for heavy metals in Sweden, the change in dominance of industrial sources towards non point sources occurred in the 1970s (Figure 6). This is due to, on the one hand, advanced technology and legislation in the field of industrial environmental protection. On the other hand, the high and still growing rate of consumption has led to large stocks of materials that have to be maintained and that discharge material that is hardly noticed, but in total is significant to water, air, and soil. Hot spots of such non-point sources are cities. Examples of consumer related emission sources are the weathering of surfaces of buildings (zinc, copper, iron, etc.), the emission of carbon dioxide and other greenhouse gases due to space heating and transportation, the corrosion and erosion (chassis, tires, brakes) of vehicles and infrastructure for traffic, and the growing problem of nitrogen overload.

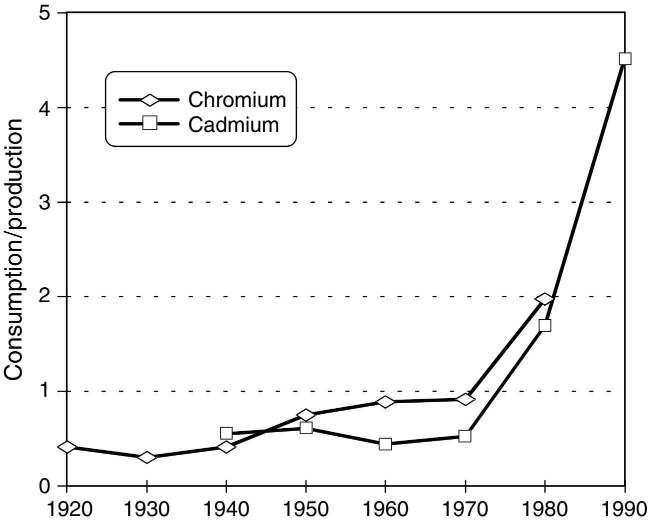

**Figure 6** Rates of consumption emissions versus production emissions (Bergbäck, 1992): for modern economies with a high environmental standard, consumption is relatively more important than production. This requires a shift in pollution abatement: future environmental management must concentrate more on non-point sources and on the design of environmentally acceptable products, and has to include consumer behavior and lifestyles

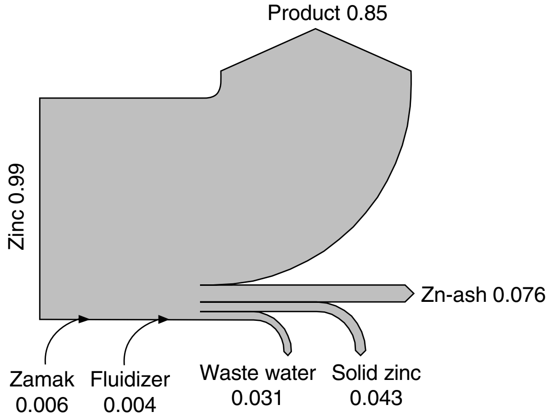

**Figure 7** Zinc flow through an advanced electroplating plant: 85% of the zinc used is sold with the product; it protects the product surface against corrosion. Nearly all of the 15% zinc not sold is recycled. Emissions to the environment during production are very small. During use of the zinc-coated product, the major part of the zinc is dispersed in the environment due to corrosion. Hence, despite the effort to protect the environment by pollution prevention measures in the factory, most zinc ends up in the environment

In Figure 7 (Brunner *et al.*, 1996), an example is given to illustrate the significance of consumer emissions versus production emissions. Modern electroplating plants produce only small residues; most of the metals used to protect surfaces leave the factory incorporated in the product. In general, the solid and liquid metal residues are recycled to a large extent, resulting in low losses of metals to the environment. Thus, from a company point of view, the goal of pollution prevention has been achieved, and most of the zinc or chromium leaves the factory as coatings on products. Nevertheless, during the lifetime of the product, processes such as corrosion and weathering damage the surface coating, resulting in losses of heavy metals to the environment. Hence, despite pollution prevention measures during the electroplating process, as much as 85% of the zinc may end up in the environment (Figure 7). Since the corrosion process is slow and the residence time of metals on surfaces can be rather long, the flows of metals to the environment last for years to decades. The legacies of today's protected surfaces are tomorrow's environmental loadings. At present, the significance of such emissions has not been assessed and evaluated. There are no methods available yet to measure and appraise these sources of pollutants to the environment.

To prevent consumer-related emissions is more difficult than to stop industrial pollution: (1) it is a much more demanding challenge for a company to change or discontinue a product than to add an air pollution device to its production facility; (2) the number of (consumer) sources is many orders of magnitude larger than of production facilities; (3) the individual emission may be very small, and only the multiplication by the large number of sources may cause a hazard for the environment. Thus, consumer awareness for the overall relevance of his/her small contribution must be created first, in order to be able to tackle the problem. (4) In general, emissions of industrial sources can be reduced with a much higher efficiency than small-scale household emissions. An example is waste combustion: due to sophisticated air pollution control systems, the specific emissions per tons of waste incinerated has decreased in the last 50 years by several orders of magnitude (reduction of e.g., dust $>10^5$; lead $>10^5$; dioxin $>10^3$). Attempts to decrease emissions by changing consumer behavior (collection of potentially hazardous materials such as lead or chlorinated materials) are not as effective. They reduce the flows by a maximum of one order of magnitude only. So far, the general public does not notice the large cumulative power of consumer emissions. It has not been anticipated yet that the poor practice of burning waste materials in a few home heating systems and wood stoves leads to higher overall loads of dioxins than nationwide state-of-the-art waste incinerators.

### *The Linear Metabolism of Cities and Their Hinterlands*

Today's cities are mainly linear throughput reactors. The material inputs into cities are slightly larger than the outputs, resulting in a growing stock of materials. In Figure 8, the anthropogenic metabolism of Vienna is presented as a

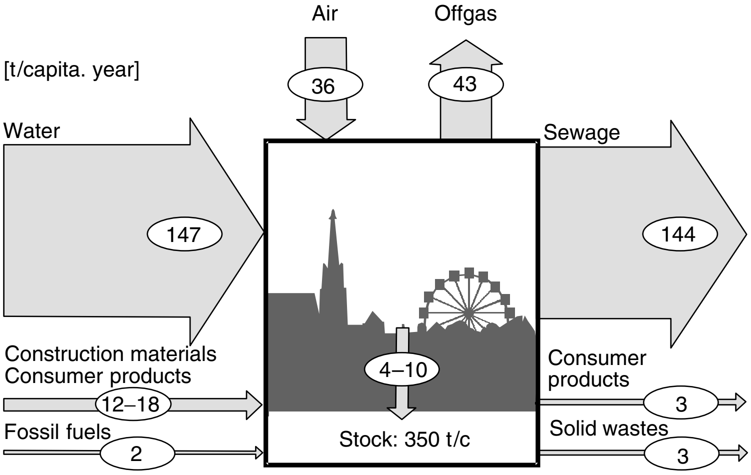

**Figure 8** The flows and stocks of materials in the city of Vienna. Inputs (200 t $c^{-1}$ $year^{-1}$) of materials into the city are larger than outputs, resulting in continuous growth of the already large stock, which doubles in 50 to 100 years. Basically, the modern anthropogenic metabolism can be characterized as a linear throughput reactor, with less than 1% of materials being involved in regional cycles

typical example (Obernosterer *et al.*, 1998). The material stocks in private households, the public and private sectors, and the infrastructure double in about 50 to 100 years. This stock is made up from materials exploited from a local, regional and global hinterland. The hinterland of a city is not a specific geographical area, but it comprises many scales, depending on the materials discussed. In the case of Vienna, the flow of water, which comprises the largest single flow of a material for all current cities, comes from regional mountain springs, while most construction materials are drawn from local resources. For many metals and nutrients, Vienna depends on a global hinterland. Even if some of the essential materials could still be found locally, it is often more economical to bring in these materials from a globalized world market. Rees calls the impact a city has on the hinterland the *ecological footprint* (Rees, 2001). This footprint comprises materials included in the production of goods, such as water needed to grow food produced in the hinterland but consumed within the city (*see* **Ecological Footprint**, Volume 3).

The large and growing stock of materials in cities represents a resource for the future, if certain conditions are met: the materials must be incorporated into the structure of a city in a way which allows one to find, collect and separate valuable substances again. The concentrations of the substances must be high enough for economic recovery, or low enough for environmentally safe disposal. At present, this is not the case for most materials. Exceptions are extremely valuable substances such as gold, or highly toxic materials such as plutonium, both of which are managed very carefully. The elevated concentrations of these materials in their final sinks (soils and sediments) show how difficult it is to control the flows of materials.

The linear flow through cities means that the hinterland has to cope with the leftovers of urban activities. Hence, the hinterland serves as a supply system for the city on the one hand, but is also a disposal system on the other hand. Actually, the second function is becoming increasingly important. The growth in material flows implies more wastes as well. Due to the build-up of long-term stocks, there is a time lag between material input and output. Future amounts of waste materials will be much larger than nowadays, even if consumption were to remain at present rates. Hence, the city's metabolism and corresponding stock determines tomorrow's emissions and state of the environment in the hinterland!

The importance of the hinterland depends on the waste management system of a city, and the substances involved. For nutrients such as nitrogen, the receiving waters of the hinterland are crucial. While many anthropogenic nitrogen emissions such as $NO_x$ from automobiles or industrial sources can be reduced, the direct nitrogen flows from humans cannot be changed significantly; they can only be decreased by expensive wastewater management and treatment methods. Thus, the fast growth of large urban populations can have a severe impact on the receiving water system. In addition, the lifestyle of the urban population is important: if the nitrogen is consumed as animal protein, the hinterland emissions for the production of this protein are very high. If the dietary nitrogen stems from plant sources, the hinterland emissions will be 50% smaller. Thus, in order to protect surface waters as well as adjacent groundwaters, and the estuaries where the rivers join the sea, nutrient management programs on a large scale are necessary, integrating agriculture as the primary source with food industry emissions, traffic emissions and other urban nutrient flows.

While nutrient flows are of concern on a watershed (regional to continental) level, greenhouse gas emissions are of global significance. For every city, the most important hinterland, from a disposal point of view, is the global atmosphere. Without this large conveyor belt and intermediate sink for carbon dioxide, the energy metabolism of cities could not survive a single day! It is the stock of materials in the infrastructure of a city that determines the emissions of greenhouse gases. If this stock includes advanced insulation of residential and commercial buildings, city-wide central heating systems, efficient public transportation, appropriate structures to shorten transportation distances for commuting, shopping and leisure etc., the emissions could be much less than in present cities. Since the residence time of the city stock is long (decades to centuries), a rapid change of materials and structure of the stock is not feasible. Thus, the present stock of materials will determine future emissions of greenhouse gases for quite some while.

Besides the large global and regional emission pathways, there are local sinks for urban wastes, such as landfills. Today, most of the minerals imported into cities are disposed of in sanitary landfills. Although these anthropogenic sediments currently contain not more than about 10% of the stock of metals within a city, they will grow and may become an important source of resources in the future. In particular, if specific wastes are concentrated and accumulated for future reuse and are not diluted with other wastes or additives such as cement, future amounts may become large enough to make re-use economically feasible.

## Analysis: How to Assess Material Flows and Stocks?

First attempts to determine the metabolism of urban regions date back to the 1970s. Duvigneaud and Denayeyer-De Smet compared the city of Brussels with a natural ecosystem, and concluded that the knowledge about the material and energy turnover of cities was still very small (Duvigneaud and Denayeyer-De Smet, 1975). They suggested redesigning the city metabolism in a way that allows more recycling, less pollution and better use of resources. Newcombe *et al.*, describe the metabolism of Hong Kong in a similar way. They, too, ask for a better understanding of the key metabolic processes in order to improve future urban design (Newcombe *et al.*, 1978). A comprehensive method to describe the metabolism of anthropogenic systems was developed in the 1980s, and is described by Baccini and Brunner: *material flow analysis* (MFA) is based on the following definitions (Baccini and Brunner, 1991; Brunner *et al.*, 1994): the term *material* stands for both substances and goods. A *substance* consists of uniform units (atoms or molecules) and is a chemical element (e.g., lead, carbon) or a chemical compound (lead chloride, carbon dioxide). Substance flows are measured in mass per time units, substance fluxes in mass per time, and cross section. The cross section can be an entire region, a household, or a person; hence the flux unit might be kg *per capita* and year. The selection of substances for an MFA is a demanding task. In general, for several reasons (data availability, limited resources) the number of investigated substances is small. Therefore, it is necessary to select certain so-called indicator substances. These are elements or compounds that show a behavior typical for a group of substances. For instance, the partitioning of Cd in a combustion process can be regarded as exemplary for volatile elements such as zinc, antimony, and tin. Iron serves as an indicator for non-volatile metals such as cobalt, chromium, manganese, and nickel. The selection of appropriate indicator elements also depends on the goods and products investigated. Regarding the combustion of coal, for example, arsenic and selenium are appropriate indicators because coal is a major source for these elements (Greenberg *et al.*, 1978). One way to determine indicator elements is to establish the ratio of elemental concentrations in the product to the average in the earth's crust. Elements with high ratios are candidates for the MFA (cf. Table 2). Another criterion for the selection of substances can be emission limits as defined by environmental legislation.

As stated above, a *good* consists of one or many substances, such as a pipe made of lead, or gasoline containing benzene. A good has a negative (e.g., waste) or positive (e.g., car, drinking water) economic value. In the economic sense, goods can also be energy, information, or services. In classic MFA, which is the subject of this article, the term is applied to material goods only.

A *process* is defined as a transport, transformation, or storage (stock) of goods, materials, energy, and information.

**Table 2** Ratio of elemental concentrations of oil, coal and MSW (Municipal Solid Wastes) to the average on the earth's crust as a means of selecting indicator elements for an MFA[a]

| | Cl | As | Cd | Co | Cr | Cu | Hg | Ni | Pb | Se | V | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Oil/ØEC | *0.7* | *0.4* | 0.05 | 0.04 | 0.01 | 0.06 | *0.3* | *0.7* | 0.02 | **10** | **1.5** | 0.05 |
| Coal/ØEC | *7.7* | **13** | 2.5 | 0.4 | 0.2 | 0.6 | *5* | 0.4 | 1.5 | **38** | 0.3 | 0.7 |
| MSW/ØEC | **77** | 2 | **50** | 0.2 | 2 | *11* | **100** | 1 | **62** | 6.3 | 0.03 | *17* |

[a] Bold figures indicate high relevance, italic figures medium. (Fiedler and Rösler, 1993; Merian, 1984; Tauber, 1988; Zimmermann *et al.*, 1996; Frischknecht *et al.*, 1995).

A transformation often involves a change in the value of a good. There are processes possible on all levels: a car engine may be looked at as a process in the same way as the human body, a private household, a waste incinerator, a branch of a regional economy, or an entire region.

Finally the investigated system comprises the processes that are linked via flows of materials and goods. The system boundary is defined in space and in time. Depending on the objective of the MFA and the availability of data, the boundary in time can be hours, days, or a year.

An *activity* is defined as a set of processes and fluxes of goods, materials, energy, and information serving an essential basic human purpose, such as to nourish, to clean, to reside, or to communicate. Hence, the concept of activities allows one to evaluate the design and management of entire material flow and stock systems with the objective of meeting certain goals such as sustainability. For example, the activity to nourish, comprising the production, upgrading, storage, distribution, preparation, and consumption of food, involves large fluxes of energy, nitrogen and phosphorus, which have an impact on water, air, and soil. An MFA of the entire activity to nourish, including agricultural production, industrial processing, distribution of food, and preparation and consumption of meals reveals those processes and flows of goods which are most important from the point of view of resource conservation and environmental loadings. Thus, MFA is an essential tool for the analysis and design of sustainable systems.

Each flow or flux has a process of origin and a process of destination, and thus is precisely defined. Equally, each process is linked with other processes by means of fluxes or flows. A good, which flows from Process A to Process B (Good 3) is called an output good for Process A and an input good for Process B. Import (Good 1) and export (Good 2) goods are defined as goods which cross the systems boundary. The same terminology applies to the flux of substances. In Figure 9, a process is graphically presented by a square, a good by an oval, and fluxes of goods or materials by arrows. Although these definitions seem tedious, they become important as soon as one attempts to link various data about the flux of materials of individual processes. Often the measurement of the output good X does not yield the same result as the measurement of X as an input good into the next process. For example, the figure for consumption of drinking water varies by 20–30% depending on whether it is measured at the water supply (output good) or the consumer (input good). Daxbeck & Brunner (1993) subdivide an MFA into the following nine steps.

1. Outline of the objectives of the MFA.
2. Definition of the system, including the selection of system boundaries (space and time), processes, goods and substances. First rough assessment of balances of goods and substances, using easily available data in order to identify the relevant goods and processes.

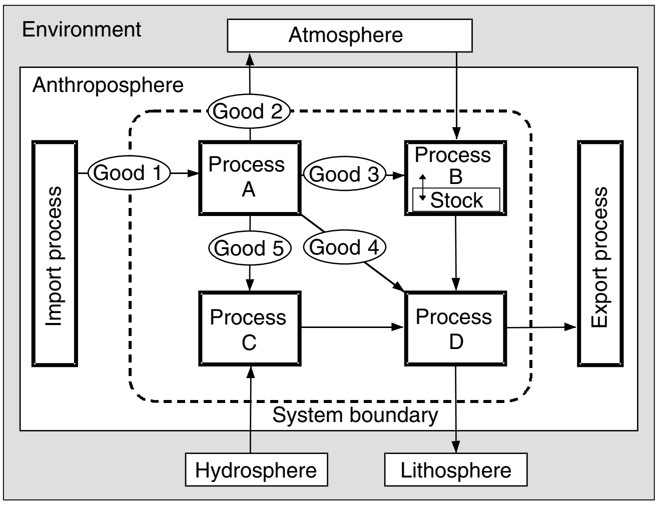

**Figure 9** Example of definitions and symbols for system boundaries, processes, and flows of goods as used in MFA methodology

3. Establishing a program for the investigation and measurement of flows of goods and substances, taking into account the necessary accuracy of the final results.
4. Determination of the mass-flows of the goods ($m$). Mass balance for goods for process A in Figure 9:

$$\sum_{i=1}^{1} m_i = \sum_{i=2}^{5} m_i$$

5. Determination of concentrations ($c_j$) of the selected substances ($j$) in the goods.
6. Calculation of the substance flows ($m \times c_j$) including an estimation of the uncertainty of the results. Substance balance for process A in Figure 9:

$$\sum_{i=1}^{1} c_{i,j} \times m_i = \sum_{i=2}^{5} c_{i,j} \times m_i = X_{A,j}$$

7. calculation and optimization of the transfer coefficients ($k_j$): transfer coefficient of substance $j$ for good 3 of process A in Figure 9:

$$k_{A,3,j} = \frac{c_{3,j} \times m_3}{X_{A,j}}$$

8. popular presentation of the results and interpretations including a detailed report to ensure transparency and reproducibility.

### Evaluation: How to Determine the Environmental Significance of the Flows and Stocks?

The results of an MFA are mass balances for goods and several substances. Obviously they can be interpreted separately, as they indicate the most important processes and goods from which appropriate strategies for an optimized materials management can be derived. In this section, some additional, more or less established, methods for evaluation are briefly described. Initially, these methods were not developed for the urban metabolism, and with the exception of the second approach they have not been applied to the metabolism of cities either. This might be partly due to the lack of data availability, and the practicability and complexity of the methods.

### Evaluation by Emission Limits

A first way to evaluate a material-balance of a system is to compare substance concentrations in various mass-flows with emission standards of related legislation. Usually such limits are laid down for gaseous and aqueous emissions in the various national environmental protection directives. For instance, emissions of factories, power plants, waste treatment facilities and so on, are controlled this way by local authorities. However, non-point (dissipative) emissions and emissions via products and goods can hardly be evaluated by this approach. Therefore, estimates of emissions exclusively by concentrations are not yet sufficient; the total loads discharged into the environment have to be considered as well. The advantage of a complete balance is that the flows of a substance via residues and products that are not regulated by legislation are also evaluated. Nowadays, this aspect is becoming more and more important. For example, as most of today's applied waste treatment technologies obey stringent emission limits, their emissions are negligible and no longer important for decision-making. Nonetheless, due to different process technology, they produce completely different amounts and qualities of residues. A comparison based exclusively on emissions would yield no difference between such technologies, and is therefore not sufficient and is not goal-oriented.

### Evaluation by Relating Anthropogenic to Natural Flows and Stocks

This approach investigates the changes of natural flows and stocks through anthropogenic activities (flows and stocks, induced by society). Accordingly, this approach considers the following two important requirements for sustainability (Enquete-Kommission, 1994; SUSTAIN, 1994). First, substance flows from the anthroposphere to the environment should neither exceed local and global assimilation capacity nor surpass the range of natural substance flows. Second, substance flows should be managed in a way to prevent the depletion of useful (resources) substances and the accumulation of harmful substances in the environment. These goals reflect the *precautionary principle* as laid down in modern environmental legislation (*see* **Precautionary Principle**, Volume 4). The principle is derived from the realization that controlling the urban metabolism exclusively via threshold values is not yet possible. First, these values continuously change as a result of enhanced knowledge, and second, they are mostly a result of damage to human health and the environment that has already happened.

The following example demonstrates how the method can be applied. The change in soil by the emission of Cd from a MSW incinerator (anthropogenic-induced material flow) is investigated. The plant processes 200 000 tons of MSW year$^{-1}$. It is equipped with an advanced flue gas treatment system, which results in an extremely low transfer coefficient of Cd into the off-gas: $k = 0.001$ ($\approx 0.002\,\mathrm{mg\,Cd\,Nm^{-3}}$). The mean concentration of Cd in MSW is about $10\,\mathrm{mg\,kg^{-1}}$. This yields an annual emission of 2 kg Cd to the atmosphere. The plant is situated in an urban area with a population density of 4000 inhabitants km$^{-2}$. Waste generation rate amounts to about 150 kg per person and year. Thus, the incinerator has a catchment area of roughly 300 km$^2$. Assuming that the 2 kg of Cd are evenly distributed over this area, a deposition rate of about $7\,\mu\mathrm{g\,m^{-2}\,year^{-1}}$ can be calculated. (Actually, due to the aerosol character of the Cd emission, the burdened area would be much larger, and the real deposition essentially lower.) The content of Cd in natural soil is about $70\,\mathrm{mg\,m^{-2}}$. Therefore, the incinerator would cause a doubling of the Cd content within 10 000 years. Even considering the above simplifications, such an emission can be judged as environmentally compatible with this approach.

Contrary to the evaluation via emission limits, this approach considers the load of an emission or product. It has been successfully applied to the metabolism of a city by Paumann *et al.* (1997).

### Entropy-based Evaluation (MASTER)

MASTER (Method for the Analysis of the Substance concentrations of Treatment End-products and Recycling goods) was initially developed as an evaluation tool for waste management.

The MASTER approach quantifies the power of a system, be it an engine, a factory, or a city, to dilute or concentrate substances with a single measure (Rechberger, 1999). This method can be directly applied to the results of any MFA. While the basis of an MFA is the principle of the conservation of mass (a special case of the First Law of Thermodynamics), MASTER is based on the Second Law (known also as the Entropy Law): the approach utilizes Statistical Entropy to evaluate substance partitioning of a system. It can be expected that entropy is one of several appropriate measures to judge urban metabolism, as it quantifies the dissipation caused by point and non-point emissions as well as of stocks. The advantage of linking MFA and MASTER is that one single measure in the range between [0, 1] per substance and system is derived. Therefore, this coupling is well suited to establish time series for urban material balances.

### *Life Cycle Assessment (LCA) and Swiss Eco-Points (SEP)*

LCA (SETAC, 1996) and SEP (BUWAL, 1998) are methods for evaluating the emissions caused by a product, a process or a system. An LCA consists of the following steps: classification, characterization, and evaluation. First, emissions are identified, inventoried and assigned to predefined stressor categories such as greenhouse effect, ozone depletion, human toxicity, etc., (classification). Second, the contributions of the different emissions are assessed, calibrated and aggregated into relatively homogenous categories (characterization). In the evaluation step, which is optional and not entirely based on scientific principles, but on socio-political (subjective) values, the impacts are weighted and aggregated to one final single index. The SEP method is a one-step process based on the concept of limited environmental absorption capacity for pollutants. Therefore, it uses a weighting system to aggregate substance flows (eco-points) by considering critical loads and actual total loads of selected substances mostly at the national level.

### *Material Input per Service Unit (MIPS)*

MIPS (Schmidt-Bleek, 1994; Schmidt-Bleek *et al.*, 1998) is a measure for the aggregated mass flow due to the consumption of a defined service (e.g., the total material and energy used to transport a good from A to B). In the MIPS concept, all materials including ores, mining wastes, auxiliary goods, water, air, off-gas, etc., which are required to render a certain service, are taken into account for the entire lifetime of the goods associated with the service. The MIPS method defines the procedures to set system boundaries, to generate data and determine how to handle the issue of lack of data. The method is limited to the level of goods and does not allow one to evaluate the substance flows needed for services. It serves well as a method for a first assessment of different options. However, without considering individual substances, the MIPS concept can result in misleading conclusions.

### *Sustainable Process Index (SPI)*

The SPI (Krotscheck, 1995) is based on the assumption that for sustainability, solar *exergy* (available solar energy) is the limiting factor. The utilization and conversion of solar energy into usable exergy by photovoltaic cells, biomass or other means requires a land area. Hence, in an SPI-evaluation, all material and energy flows of the investigated product (or process or system) are transformed by a defined procedure into land area equivalents. The SPI equals the total area calculated for the product, divided by the specific area available for an average person living in the investigated region. Sustainability is achieved if the SPI is $<1$. The SPI is a so-called holistic approach as it considers not only traditional resources (materials, energy, area) but also attempts to include social aspects such as employment, residential area of employees, etc.

The methods summarized above do not yet allow one to comprehensively evaluate the environmental relevance of the anthropogenic metabolisms. So far, no method exists to appraise the diffusive emissions resulting from the weathering of surfaces in a city, surfaces exposed to the atmosphere (roofs, cars), or buried in the ground (pipes, cables). Also, the long-term fate of materials hibernating in cities has not yet been investigated. Thus, new methods have to be developed in order to supplement existing evaluation methodologies.

## Case Studies

The following two case studies illustrate how material flow and stock analysis can be used to assess, evaluate and control the anthropogenic metabolism. Both examples have been developed and used to support decisions in the field of environmental and waste management. They are presented here to point out the qualitative and quantitative importance of material stocks. Efficient decisions regarding environmental protection and resource conservation can be taken only if all flows and stocks of a material and their contributions to the total metabolism are known.

### *Plastic Materials*

The flows and stocks of plastic materials in Austria have been investigated by an MFA (Fehringer and Brunner, 1997). This assessment is summarized in Figure 10. The total per capita consumption of plastics amounts to about 140 kg (8.1 million inhabitants); 50 kg are incorporated into the stock, and 90 kg are collected and treated by waste management systems; 84% of the plastic wastes are land filled, 10% are incinerated, and 6% are recycled. There are two important plastic stocks: the accumulation in the consumption process (buildings, transportation and communication systems, households, industry and trade, etc.), and the waste plastic deposits in landfills. Landfills contain more plastic and grow faster than any other stock.

In addition to polymers such as polyethylene or polyvinylchloride, plastic goods contain additives such as softeners, stabilizers, biocides and fire retardants (Table 3). These additives are much less abundant in packaging materials. The stock of some of the potentially hazardous additives in use and hibernating in Austria amounts to several 10 000 tons. The mass of additives in landfills is even larger. Information on the chemical composition of the plastic flows and stocks is scarce and hard to collect. Hence, an important base for environmental and resource management is lacking at present.

An evaluation of the plastic flows and stocks in view of the goals of the Austrian Waste Management Act (protection of mankind and the environment, conservation of resources materials, energy and space) reveals

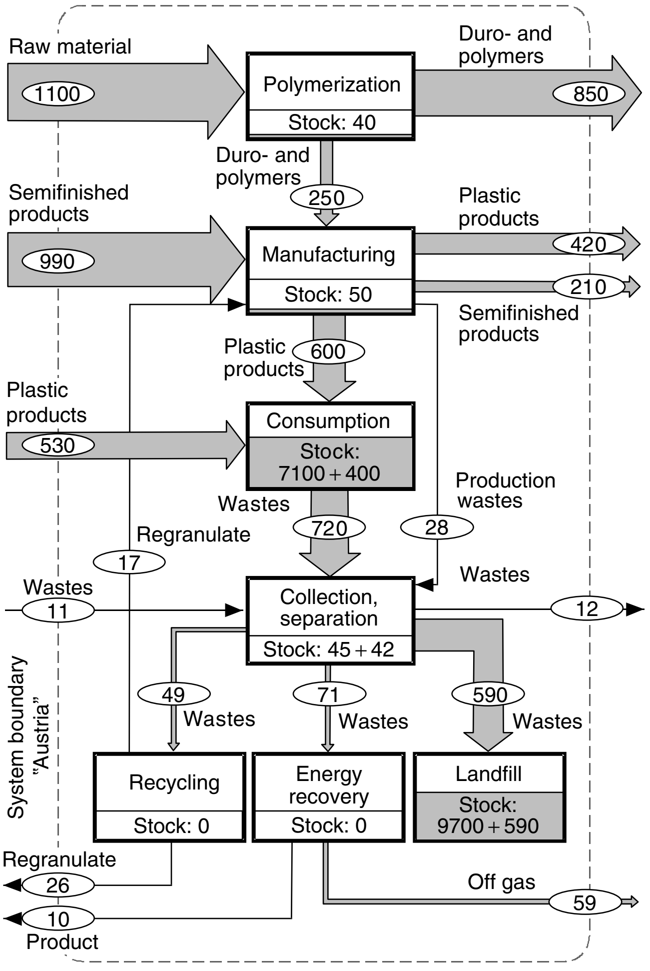

**Figure 10** Flows and stocks of plastic materials in Austria in 1994 in kt/year: 40% of the annual consumption of plastic materials is accumulated in the stock. Most of the residual 60% is disposed of in landfills, which are already the largest and fastest growing stocks of plastics in Austria. The federal packaging ordinance, which requires separate collection and recovery of plastic packaging materials, has little effect (<10%) on the overall plastic flows and stocks (Fehringer and Brunner, 1996)

the following. There are hardly any immediate and direct environmental hazards resulting from present plastic waste management. Nevertheless, since the fate of in excess of 10 000 tons of heavy metals and organic substances contained in land filled waste plastic is not known, a long-term risk may exist. This risk needs to be addressed, taking into account slow biogeochemical reactions of polymers and additives, as well as immobilization and mobilization reactions in landfill environments. It must be pointed out that most of today's landfill research is directed towards comparatively fast reactions, which take place within months to years, rarely decades. In the case of polymers, investigations are needed concerning slow reactions, which take place over decades to centuries. First assessments of the behavior of landfill liners indicate that plastic materials are not as stable in landfill environments as anticipated.

Land filling plastic wastes means burying valuable fuel. In Austria, about 500 000 tons of fuel oil equivalents are disposed of in landfills every year. This clearly contradicts the goal of conservation of resources of the Waste Management Act. On the other hand, about 50 000 tons of packaging plastics are recycled at extremely high cost. Recycling of stabilized plastic wastes means keeping the hazardous constituents within the anthroposphere. This cycle either needs to end in an advanced waste treatment plant, where the hazardous materials are extracted, concentrated and immobilized, or the cycle must be improved by new, sophisticated technologies not available yet. In order to integrate products made from plastic wastes, such as artificial wood fences, roof tiles or concrete artifacts in an environmentally sound waste management strategy, concepts for the safe final disposal of these products must be developed as well. Otherwise, the hazardous constituents are dispersed in the environment by burning the artificial wood in household furnaces, etc. The general public cannot be blamed for such practices, since the origin and legacy of recycling products is neither known nor trackable.

**Table 3** Characterization of the plastic flows and stocks in Austria. Packaging polymers contain few additives. In contrast, plastic materials with long residence times, e.g., for construction purposes, have to be protected against degradation by light, temperature, mechanical, chemical and biochemical stress. Hence, they often contain large amounts of heavy metals and organic stabilizers. These constituents may jeopardize future recycling. If not properly managed, they will also pollute the environment (data from Fehringer and Brunner, 1996)

| Material | Consumption kt 1994 | Packaging material kt 1994 | Stock kt 1994 |
|---|---|---|---|
| Polymers | 1100 | 200 | 7100 |
| Softeners | 14 | 0.2 | 140 |
| Ba/Cd-stablizers | 0.27 | 0.0002 | 2.6 |
| Pb-stablizers | 1.8 | 0.002 | 18 |
| Fire retardants | 2.3 | 0 | 22 |

In the future, decisions regarding the management of plastic materials and wastes should be based on appropriate, comprehensive information, including figures about individual polymers, additives, stabilizers and so on. In order to control the risks and exploit the resource potential arising from large stocks and flows of plastic materials, the management of plastic goods needs to be redesigned. Most polymers are produced from fossil fuels. The largest part of fossil fuels is used for traffic systems, heating, power generation and industrial purposes; plastic manufacturing is of minor importance. The incineration of waste plastics can reduce the overall consumption of fossil fuels and of greenhouse gas emissions. Incineration is especially important for polluted plastic materials, containing hazardous constituents. It is essential that appropriate final sinks be found for these constituents, such as an efficient thermal process for organic substances, or a secure landfill for immobilized heavy metals in incineration residues. Recycling cannot solve these problems, unless new technologies are developed to extract the hazardous components from waste plastic mixes. Packaging ordinances cover only a small part of the total flows and stocks of plastics, are inefficient and do not tackle the problem of the hazardous constituents (cf. Table 3). In general, the total pathway and stocks of plastic materials should be taken into account when new plastic goods and management schemes are developed. It may be advantageous to start a new plastic era, where additives are omitted for environmental and recycling benefits, and where clever chemists find new polymers with better functions with less heavy metals and hazardous organic compounds.

### *CFCs*

CFCs are a group of highly volatile compounds that contribute to the degradation of the stratospheric ozone layer. They have been widely used in aerosol sprays, in fire extinguishing systems, as foaming agents in insulation materials for construction and refrigeration, as cooling agents, and as solvents and cleaning chemicals. In 1987, most CFCs were banned by the Montreal Protocol, due to their stratospheric ozone depletion properties. This treaty had an immediate effect on the consumption of CFCs, and on the emissions of short-term applications such as aerosol sprays. However, the influence on the stocks of existing CFCs in use and hibernating is long-term. Waste management will have to deal with large amounts of CFCs during the coming decades, and recovery of the ozone layer will be a slow process.

In order to evaluate environmental and waste management strategies in the field of CFCs, the flows and stocks of these chemicals were comprehensively investigated in a case study for Austria (Obernosterer, 1994). In Figure 11, the results of an MFA are summarized in ozone depletion units (ODP); these units are applied to account for the different effects of individual CFCs on the stratospheric ozone layer. The largest stock consists of insulation materials in construction. Other foams, coolants and fire extinguishing agents account for about half of the CFC stock, household refrigerators for less than 3%. The OPD units in the present stock account for about one-third of all CFCs ever used in Austria. Thus, if not properly disposed of, the degradation of the ozone layer by CFCs will continue.

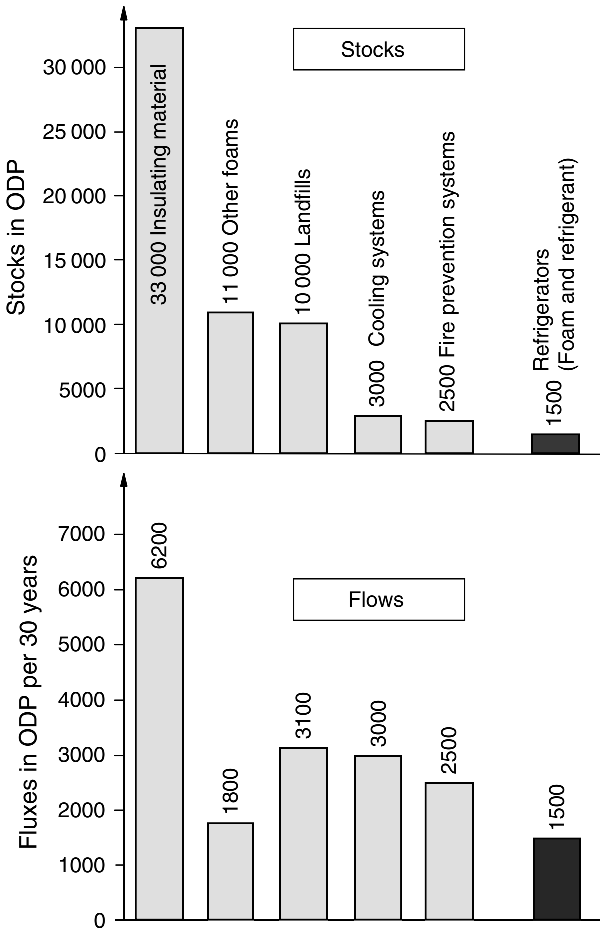

**Figure 11** CFC stocks and emissions in Austria over the next 30 years, expressed as ODP. The largest stock and emission is due to insulation materials for construction. At present, waste management regulation focuses mainly on refrigerators, but this comprises less than 10% of the entire CFC stock and emissions in Austria (Obernosterer and Brunner, 1997)

The largest flow (emission) over the next 30 years will come from the stock of insulation materials in buildings. MFA reveals that top priority should be given to the efficient collection and disposal of construction wastes. At present, legislation in the field of waste management focuses mainly on refrigerators, which account for less than 10% of the emissions.

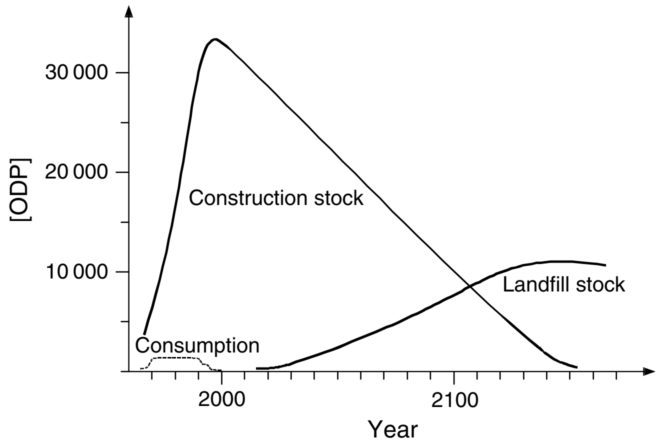

**Figure 12** Consumption, buildup and shift of stocks of construction-related CFCs. During a relatively short consumption period of 25 years, a large stock of CFCs in insulation materials has accumulated, which will have to be managed carefully for the next 100 years. According to present waste management practice, this stock will be shifted gradually to landfills. If no counter measures are taken, CFCs will be lost to the stratosphere from both stocks – construction and landfills

The case studies of plastics and CFCs represent typical examples of many modern chemicals (Figure 12). During a relatively short period (approximately two decades), a large amount of a specific material is consumed and accumulated in the anthropogenic stock. If, due to changes in technology or new information about environmental risks, the production of the chemical ceases, there is already a legacy of a large stock of the chemical to be managed in the future. For safe and efficient material management, it is important to assess the significance of a material before large amounts are accumulated in the anthroposphere. In any case, technology needs to be developed to treat and dispose of the large accumulation of stock of materials. For CFCs and plastics in construction materials, this could be energy recovery with state-of-the-art flue gas cleaning, producing mainly carbon dioxide, water, chlorides, fluorides, and concentrated metals, when properly incinerated in a modern municipal waste incinerator (Vehlow *et al.*, 1992, 1994; Rittmeyer *et al.*, 1993, 1994).

## LEGACIES DERIVED FROM THE ANTHROPOGENIC METABOLISM

Modern economies depend on a high material turnover. The stocks they build up and maintain amount to several hundred tons of materials *per capita*. This is not only an economic fact, but also a cultural reality. Material growth is incorporated into Western culture; it defines progress like no other single criteria. Future generations will have to deal with this stock; they can use, renew, recycle or dispose of it. The materials contained in the stock can serve as future resources. They also imply future problems in so far as they contain hazardous substances. During and after the use of the stock, substances will be lost, and they will pollute the environment. The maintenance and disposal of the stock will bring about considerable costs for future generations. Will future generations value this stock as a precious asset or as a technology/economy brake?

It is undisputable that if the present metabolic rate is maintained, there will ultimately be constraints for development. These may occur as resource scarcities at the supply side, or as environmental degradation at the disposal side of the anthroposphere. Will these constraints become effective in decades, centuries or millennia? Probably the most important legacy from today's anthropogenic metabolism is the addiction to it. The high growth rates and large stocks became so attractive and convenient to consumers and producers that alternative economic and cultural models do not seem to be noteworthy, and other metabolic options are neither studied nor implemented to a significant degree. The metabolism of an affluent society seems to confirm the Latin saying *plenus venter non studet libenter* (a full stomach does not like to study)!

### Cities as Hot Spots

The largest anthropogenic material stocks have been built up in cities. Soon, more than half of the world's population will be living there, thus the urban stock will continue to grow. From a materials management point of view, this is an advantage. Human needs can be fulfilled more efficiently and with less supply of materials and energy in a densely populated area. From an environmental point of view, the same applies. Environmental protection measures are more efficient if many people are connected to a compact urban system than if the same number of persons are joined through a wide and sparse rural system. On the other hand, the material flow density in cities, expressed, for example, in mass per time and area, or in mass per deposition rate, is orders of magnitudes higher than in most rural areas. Modern cities are material hot spots containing more hazardous materials than most hazardous landfills. The case studies of plastics and CFCs exemplify the large stocks of anthropogenic materials. This stock is not managed nor has it been noticed yet. It is built into the urban infrastructure in a way that does not allow one to economically recover the materials without losses. On the contrary, many materials are used so that re-use becomes impossible, leaving a large mass of hibernating materials in cities. In particular, underground networks for the transportation of water, sewage, energy (gas, electricity) and information are not yet recoverable when their lifetime is over. Other examples are materials used to prevent corrosion and weathering (e.g., surface coatings, pigments), such as zinc and copper. The emissions from these sources surpass the flows from point sources such as production facilities.

Cities are also hot spots for flow-through materials. In particular, nitrogen is of long-term concern, since this is an essential element for human nutrition. Wastewater treatment technology will have to be improved, and costs will rise, if large river systems and estuaries are to be protected from nitrogen overload. Alternative wastewater management concepts may become competitive, if urbanization continues to increase the nitrogen flows to surface waters.

While the dietary nitrogen emissions cannot be tackled by a prevention strategy, carbon dioxide flows, which are mainly produced for transportation and room heating, can. From a technical point of view, these emissions can be avoided by switching from fossil to solar energy sources. Thus, to tackle the hot spot city, a multi-facet strategy is needed, including prevention, new technologies and state-of-the-art waste management.

## Limits at the Back End and Not at the Front Side

For most of human history, the anthropogenic metabolism was limited at the supply side. The foremost challenge of prehistoric mankind was to find enough food and shelter to meet essential needs. The development of civilization was accompanied by increasing requirements for supplies beyond basic physiological needs. Since the beginning of history, the search for energy and raw materials has led to many innovations, conquests, and wars. Today, the need for resources is greater than ever, the rate of consumption is large and growing, and a fair distribution of goods seems a much bigger challenge than exploitation of resources. At the beginning of the third millennium, the supply problem has been solved by modern technology, and severe resource limits at the front end are not in sight in the next few decades.

Today, the new question arises at the output side of the metabolism: how can we safely dispose of the very large amounts of waste materials? The need for resources is paralleled by the need for final sinks for these resources. This challenge is new. Never before has mankind had to care about the dissipation of anthropogenic materials on a global level, such as carbon dioxide or CFCs, although industrial activities always relied on the dissipation of residues in air and water. In the 20th century, the anthropogenic energy metabolism depended on the seemingly unlimited possibility of dispersing $CO_2$, the main product of energy conversion, in the atmosphere. However, $CO_2$ dispersal is no longer acceptable because of the concern about global climate change. This will require fundamental changes in the future anthropogenic metabolism, since, for example, a solar energy supply will result in significantly different material needs than a fossil fuel supply.

The search for appropriate final sinks is not only important for linear flow-through materials such as carbon and nitrogen compounds. Ultimately, materials in the stock and materials recycled need to be disposed of in final sinks as well. Up to a certain level, materials can be diluted in the environment without negative effects. On a global level, the limits for dissipation are not yet known. The controversy about carbon dioxide emissions causing greenhouse effects and leading to climate change shows how difficult it is to define these limits. Considering the large exploitation of metals displayed in Figure 2, two questions arise: where are these minerals now (in use, hibernation, in landfills, or dissipated in water, air and soil?), and where should they finally be? Neither question has been adequately addressed so far. There are no global inventories of the most important resources yet. While information about mining and primary production is abundant, data about product use and consumption are much more limited. Besides a few exotic examples such as gold and plutonium, there is very little information about the stocks, and there is virtually no systematic information about the fractions of materials already dispersed in soils, sediments, water, air, or landfills.

## The Soil as a Long-Term Sink and Source

Sinks for anthropogenic materials either transform organic substances into mineralized natural materials (e.g., organic compounds are transformed to carbon dioxide and water) or store immobile inorganic materials safely for long time periods. They include:

- the atmosphere, where organic emissions may be transformed by reactions such as photolysis;
- the soil, where materials are deposited by atmospheric deposition, by agricultural and industrial practice, and by waste management;
- the sediments, which trap the pollutants imported into lakes and oceans by rivers and atmosphere.

If a sink for metals and inorganic matter is defined as a sphere on the globe where materials have residence times longer than several centuries, the soil may be called the most important sink, either for dispersed materials, or for wastes in landfills.

Material balances such as the cadmium example in Figure 4 reveal for all scales (local, regional, global), that, in general, the anthropogenic input of metals into regions is larger than the output (the sole exceptions are mining areas). The difference between the input and the output is in part built into the anthropospheric stock, in part accumulated in the soil because of atmospheric deposition, direct agricultural input or land filling with wastes. Soil monitoring programs confirm the results of material balances. They show increasing concentrations of heavy metals, organic chemicals, and phosphorous in soils, with doubling rates for concentrations from decades to centuries. These accumulations have long-term consequences. On the one hand, there is now a phosphorous reservoir in many agricultural soils, which can supply valuable phosphorous. On the other hand, in mountainous areas, this stock is subject to erosion and is gradually transported to surface waters, causing eutrophic lakes for long periods, even if the agricultural application of phosphorous is stopped. The soil is only an intermediate sink for phosphorous, and it is a long-term source as well.

The same legacy corresponds to several metals in soils. According to the soil properties and the metal inputs, cadmium, lead, zinc and other heavy metals accumulate in soils, and may pose a future threat to food production and quality. This is a long-term process. Soil conditions, which are determined by the underlying rock formations, the rate of soil creation, inputs from the atmosphere and farming, and agricultural practice, are in a state of constant change. It is not possible to predict atmospheric deposition, soil use, and agricultural practice for long periods such as centuries. Therefore, since chemical speciation, and thus the availability of metals, depends upon the changing soil characteristics, a truly long-term forecast of the availability of heavy metals is difficult if not impossible. Stigliani talks about chemical time bombs (Stigliani, 1991) (*see* **Contaminated Lands and Sediments: Chemical Time Bombs?**, Volume 3). This is the reason why some nations have chosen to apply the precautionary principle, and to limit total concentrations of heavy metals in soils. The question remains what should be done once these maximum values are reached, which in densely populated, affluent areas is likely to occur within the next few centuries. A safe strategy for long time periods would be to adjust all inputs into the soil to the outputs, trying to balance soil concentrations continuously. This would require a large effort in air pollution control, cautionary and balanced agricultural practice, and considerable improvements in waste management concepts and practice. Such a challenging strategy does not appear feasible at this time.

### Waste Management as a Future Key Process

The goals of waste management are to protect humans and the environment, to conserve resources such as energy, materials and land, and to reduce long-term risks from the disposal of wastes to an acceptable level. Hence, waste management is the paramount means to control the flows from the anthroposphere to the environment in a systematic and efficient way. In particular, land filling has a very important function. It must ensure that the large quantities of materials obtained from the ground find a long-term safe final storage place. A final storage landfill is defined as a (mainly inorganic) landfill with low emissions that do not alter the material flows in the surrounding environment (ground and surface waters, atmosphere) for long time periods ($>1000$ years). For most wastes, this can be achieved only if the wastes are mineralized and then immobilized.

The amounts of materials under waste management will increase because of rising consumption, and the huge amounts of materials in the stock that has to be renewed. Waste management inherits most of the materials in the stock. The composition of the long-living stock is more hazardous than the short-lived consumer products, which are recycled today, such as packaging materials. Even if recycling is extended, there will be large and rising amounts of metals and organic substances to be treated and disposed of safely. Waste management systematically closes the anthropospheric cycles of materials, giving them back to the Earth's crust in a controlled and environmentally sound manner.

Recycling is only an intermediate and not a final solution for materials management. It does prolong the residence time in the anthroposphere, but for thermodynamic reasons, recycling cannot prevent the need for an ultimate sink. Recycling can be an excellent means to reduce the overall environmental impact of those materials requiring much energy and producing vast amounts of wastes and emissions during primary production. It also reduces the need for final storage landfill space by decreasing the amount of primary material needed. However, recycling will not decrease the materials already used, and thus cannot change the future need for the disposal of materials already in the anthroposphere. At present, recycling is looked at primarily from a process technology point of view. In future, recycling has to be integrated into the design of new systems, processes and goods. The stock of a modern urban system can be efficiently extracted only if there is information available about the density and location of individual materials. As for geological exploration of natural resources, specific tools are needed to identify and locate the future urban ores.

## FUTURE STRATEGIES

The present metabolism of the anthroposphere is not sustainable for long periods of times. Emissions at the back end, the lack of appropriate sinks, as well as the scarcity of resources at the supply side, set limitations. The majority of the global population does not enjoy an affluent metabolism yet, but it has the same objective, i.e., to reach a similar material turnover as that of wealthier parts of the world. There are no signs yet indicating that in the future the developed world will break its growth path and slow down material consumption. Therefore, it is highly probable that global material flows and stocks will considerably increase in years to come. The first warning signs are there already, such as the steady growth of the ozone hole, increasing greenhouse gas concentrations, nutrient overloadings in surface and groundwaters and others indicating that it is time now to take action to redesign the present anthropogenic metabolism.

Today's situation may be compared to other ruptures in the development of society and technology, such as the introduction of industrial fertilizer or the change from biomass to fossil fuels for energy. Both of these changes allowed mankind to overcome severe constraints in the advancement of civilization. In the coming decades, equivalent changes in technology, economy and culture may occur. The anthropogenic metabolism must be redesigned to satisfy the needs for a global population based mainly on renewable resources without impairing the environment.

As a consequence, a new material management strategy is needed. Environmental considerations must become an essential part of material science. Decisions about material alternatives can be taken only if the fate of a material from source to final sink is known. Analysis and modeling of total material flows and stocks over long periods are needed. The availability of a final sink for all materials used is an important design consideration. If no appropriate final sink can be assigned to a material, it should be phased out and replaced. The possibilities and limitations of waste management to recycle and dispose of materials safely should be considered at the design stage. The new goals are that only three kinds of residues should result from the use of goods:

- residues and emissions that can be either completely mineralized or that can be safely dispersed in appropriate final sinks;
- clean residues suitable for multiple recycling;
- residues with final storage quality for which an appropriate final sink is available.

For modern economies with advanced environmental standards, emissions during consumption are relatively more important than emissions during production. This requires a shift of priorities in environmental management. Future measures must concentrate more on non-point sources, on consumer-related sources, and on the design of environmentally acceptable products; they must take into account consumer behavior and lifestyle. Also, a new awareness for materials must be created. At present, questions like Where is the final sink for this material? or How can this complex mixture be dismantled? are rarely asked by consumers and often not answered by designers.

In order to make better use of the stock, MFA must be supplemented by material accounting, i.e., the continuous monitoring of flows and stocks at a few key points of the anthropogenic metabolism. This allows for early identification of the accumulation and depletion of valuable resources, and for assessment of the future burden on the environment. In a competitive material economy, material accounting can result in a comparative advantage, as was the case when financial accounting was introduced.

City mining may eventually replace traditional mining of ores. Since the urban stock of materials grows constantly, cities become attractive concentrations of many minerals. If properly designed and maintained, it will be more economical to exploit the anthropogenic material stock than natural resources. Future urban areas may redevelop into partially industrial cities, taking advantage of their own stocks and taking a large part of their supply from their own domestic sources. Material extraction and transformation results in considerable amounts of waste energy, which in contrast to remote mining areas can be used in cities for heating and industrial purposes. The residues, which have to be land filled are much smaller for urban mining than for traditional mining.

It is not known how much time is left to counteract the negative effects of today's anthropogenic metabolism. In any case, the longer it takes until measures are introduced for better management of material flows and stocks, the larger the metabolic crisis will be. It is time now to take a close look at the way we manage materials, to start crucial research and careful experiments, and to make a next quantum leap towards a new anthropogenic metabolism which fulfils the needs of both mankind and the environment in the third millennium.

In a companion article in this volume (*see* **Contaminated Lands and Sediments: Chemical Time Bombs?**, Volume 3), William Stigliani draws attention to the impacts that climate change (and other types of global change) might have on the mobilization, and sometimes the immobilization, of anthropogenically produced substances in the environment. Sometimes the changes will take place long after the material had stopped entering the biosphere, and seemed to be safely buried in the sediments of a harbor, or locked up in the urban fabric. This behavior presents a major challenge to simulation modelers to model the long-term behavior of urban metabolism.

*See also*: **Contaminated Lands and Sediments: Chemical Time Bombs?**, Volume 3; **Industrial and Anthroposystem Metabolism**, Volume 3.

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