# Use of material flow analysis for assessing solid waste management in Germany regarding sustainable solutions

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## Abstract

Production and consumption activities lead to the depletion of limited resources and to the pressure on environmental sinks. Despite their adverse effects on the environment heavy metals like cadmium are still used in industry and consumer products. As a consequence a special treatment of the resulting wastes is necessary in many cases. Material flow analysis was used to assess waste management practices in Germany regarding sustainability with a focus on ecological aspects. As an example cadmium was traced from its production, through its various applications to the recycling and disposal of the used products. Balances were performed for the years 1995 until 2000. Cadmium is generated as a by-product of zinc production. In the observed timeframe zinc production in Germany did not change significantly leading to constant cadmium amounts. However, due to recent regulations and voluntary agreements of the industry cadmium containing products like pigments and stabilisers have been banned increasingly from the German market. The consumption of Ni/Cd cells has stayed constant. To reduce the environmental releases of cadmium different measures have been taken: Maximising zinc recycling and cutting back on the use of primary zinc; Substitution of cadmium in products where it is possible e.g. in pigments and stabilisers and by replacing Ni/Cd cells by lithium- or NiMH-batteries; Collection and recycling of products in order to reduce the amount of cadmium in domestic wastes. Emissions of cadmium into air and water bodies are declining. However, concentrations in soils and sediments show no reduction. Input of cadmium in agricultural soils occurs mainly via two pathways: atmospheric deposition and application of mineral fertilizers. According to various sources in the literature, both input pathways lie in the same order of magnitude.
*Keywords: material flow analysis, cadmium, sustainable waste management.*

# 1 Background

Production and consumption activities for the supply of presently about 6 billion people lead to the consumption of limited resources, the generation of material flows and to the pressure on environmental sinks. According to the recent knowledge the presently performed way of keeping house and way of living is not sustainable regarding ecological carrying capacities or resources inventories.

Despite their adverse effects on the environment heavy metals like cadmium, mercury and lead are still used in industry and consumer products. As a consequence a special treatment of the resulting wastes is necessary in many cases. Up to now the knowledge about the material household and the material flows of mercury, lead and cadmium associated with waste management measures is neither sufficient to assess the waste industry with respect to sustainability nor to work out recommendations for a material flow oriented waste management.

Material flow analysis (MFA) is an instrument capable of contributing to a sustainable waste management by delivering the required information.

# 2 Aim of project and approach

The project aims to assess waste management practices regarding ecological criteria for a sustainable development in Germany. This was done by identifying the main applications and related material flows of one indicator-substance (cadmium) starting from extraction and production and culminating in waste recovery or disposal. Cadmium balances were performed for the years 1995 until 2000.

The focus was set on input-pathways of cadmium in the environment by various applications and their most important waste flows. Regarding sustainable development, limitations of sources and sinks and their sustainable use are important indicators.

For compiling data, apart from an internet search, numerous technical journals and statistics were evaluated. In addition, data was collected by questionnaires sent to representatives from the industry and personal contacts to the industry.

# 3 Results

A summary of the results regarding cadmium balances for consumption, import and export in the years 1995 until 2000 are given in tables 1, 2 and 3.

## 3.1 Extraction of cadmium

Before using cadmium in various products, it has to be extracted and produced. Primary cadmium is mainly generated as by-product of the primary zinc production. Zinc concentrates/ores are mainly imported and contain on the average 0.2 % cadmium. In each of the years from 1995 to 2000 zinc ores and concentrates containing about 1100 to 1300 t of cadmium were imported. In addition a small share of cadmium was brought in via secondary materials like EAF-dust of the steel industry.

Since cadmium is toxic, recent regulations in the EU aspire to reduce or restrict the cadmium input in many applications. Therefore, with the exception of Ni/Cd batteries as an application, cadmium containing products are banned more and more from the German market due to recent legal regulations and voluntary agreements of the involved industry. Still, more than 1000 t of cadmium were annually separated and transformed to cadmium metal and alloys. The produced cadmium metal and alloys were kept in stock, exported, or brought to the domestic market.

## 3.2 Main applications of cadmium

### 3.2.1 Ni/Cd batteries

On a quantitative basis the most important flow of cadmium results from the use of cadmium for Ni/Cd batteries (NiCads). NiCads can be roughly divided in two categories portable, sealed cells and open, vented cells for industrial use.

More than 90 % of portable cells come on the market incorporated in electrical or electronic equipment (EEEq). The main applications by battery weight are cordless power tools and emergency lighting, but also cordless phones, remote control toys, and household appliances as dustbusters, shavers or tooth brushes. While there seems to be no real alternative for the use of Ni/Cd battery systems in power tools today, the share of NiCads used in other applications is ceasing. But even though the share of battery systems as NiMH and lithium is growing fast, the number of Ni/Cd cells sold in Germany remained approximately constant over the last 10 years because of the rapidly growing market of battery powered appliances.

Table 1: Cadmium consumption in Germany between 1995 and 2000. Range of share of cadmium in various applications and cadmium deposit in the total consumption of cadmium.

| | **Range in %** |
|---|---|
| Ni/Cd batteries | **60-80** |
| Pigments | **4-15** |
| Stabilisers in PVC window profiles | **1-5** |
| Mineral fertilizers | **2-4** |
| Cadmium deposit | **15-20** |

NiCads have the highest share in cadmium consumption (table 1), and regarding import and export (table 2 and 3). Since the production of portable Ni/Cd cells in Germany has stopped in 1999, increasing amounts have to be imported.

The European Union is discussing regulations, which will permit the use of cadmium in batteries in special applications only. However, even if batteries containing cadmium are no longer produced, the occurrence of cadmium in domestic wastes will continue for a long time due to the large stock of batteries which is still increasing.

Table 2: Cadmium import into Germany between 1995 and 2000. Range of share of cadmium extraction/production and cadmium in various applications in the total import of cadmium.

| | **Range in %** |
|---|---|
| Cadmium contained in zinc ore and concentrates | **45-55** |
| Cadmium metal, raw cadmium and powder | **<1-10** |
| Cadmium oxide | **2-6** |
| Ni/Cd batteries | **32-42** |
| Pigments | **<1-2** |
| Stabilisers | **4-6** |
| PVC window profiles | **<1-2** |
| Mineral fertilizers | **<1-2** |

### 3.2.2 Pigments, stabilisers and PVC window profiles

Until the year 2001, PVC stabiliser systems containing cadmium were used for the fabrication of window profiles. In 1980, the amount used for the production of these stabilisers was about 500 t, in 1995 less than 50 t and in 2000 less than 20 t. Import and export of stabilisers declined as well, having a small share concerning the total import and export (table 2 and 3). Meanwhile, due to voluntary agreements of the involved industry, stabilisers containing cadmium are no longer used in the European Union. However, the recycling of old windows leads to PVC-pellets, which still contain cadmium. These pellets have to be used for the production of new window profiles. The windows, which are not recycled, are exported, used as old windows in different application fields, disposed of or incinerated.

At the same time the production and consumption of pigments containing cadmium, their import and export has declined as well. Until 1980 the pigment production was one of the main applications fields for cadmium. While 1985 about 280 t of cadmium were used for pigment production, this value declined to 100 t in 1994 and further to 50 t in 2001.

### 3.2.3 Mineral fertilizers used in agriculture

Cadmium flows by mineral fertilizers regarding production, consumption, import and export have stayed constant from 1995 until 2000. The share of mineral fertilizers in cadmium import and export is negligible; nevertheless the share of fertilizer in cadmium consumption amounts to 2-4 % and exceeds the share of stabilisers in PVC window profiles (table 1, 2 and 3). This is due to the fact that the use of stabilisers has been cut down, while mineral fertilizer application needed to be retained constant.

Table 3: Cadmium export out of Germany between 1995 and 2000. Range of share of cadmium extraction/production and cadmium in various applications in the total export of cadmium.

| | **Range in %** |
|---|---|
| Cadmium contained in zinc ore and concentrates | **5-15** |
| Cadmium metal, raw cadmium and powder | **25-50** |
| Ni/Cd batteries | **30-45** |
| Ni/Cd battery waste | **5-15** |
| Pigments | **<1-5** |
| Stabilisers | **2-8** |
| PVC window profiles | **<1-2** |
| Mineral fertilizers | **<1** |

# 4 Discussion

## 4.1 Cadmium: steps on its way from the cradle to the grave

Cadmium can reach the environment through various phases of production, processing, usage and disposal processes. Possible sources for an environmental input are:

### 4.1.1 Production of zinc

The production of zinc is connected with emissions into air and water. A decrease of zinc consumption cannot be anticipated. In order to lower the cadmium emissions connected with zinc production, it should be aimed to maximize the share of secondary zinc related to the total production. However, according to information of the "WV-Metalle" [1] already today about 80 – 90 % of the zinc products are recycled at their end of life in Germany. Cadmium is a by-product resulting from the zinc production from ore. Since the demand for cadmium decreased clearly towards the end of the investigated period, a part of the cadmium has to be deposited. While from 1995 to 2000 about 15-20 % of the cadmium amount consumed in Germany was deposed (table 1), in the year 2001 this amount increased to about 50 %.

### 4.1.2 Production of products containing cadmium

With the use of cadmium for the fabrication of certain products cadmium emissions are connected, however, they are small compared to those of other cadmium emitters. Thus, within the European Union the emissions connected with the production of cadmium-containing products contribute with scarcely 4 % to the total cadmium emissions. Therefore, further restrictions of the production of cadmium-containing products will lead only to a small reduction of the emissions into the air. On the other hand a larger amount of cadmium would have to be deposited because of its reduced demand.

 
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### 4.1.3 Recycling and disposal of products

In order to reduce the amount of NiCads found in domestic wastes an obligation to take back, recycle or properly dispose these batteries after use was set into force. Almost 90 % of the industrial Ni/Cd batteries put in circulation are collected, the cadmium is recovered domestically and used again for the production of new industrial batteries. Portable Ni/Cd cells which are seized over collecting systems like the German "GRS Batterien" are also recycled, however abroad. The export of NiCad waste to France for recycling lies steady within a range of 5-15 % of the total cadmium exported (table 3). Of this cadmium the largest share is recovered. This reduces the quantity of primary cadmium needed for production.

Nevertheless, despite considerable logistic efforts it is impossible to prevent the occurrence of NiCads in domestic wastes. According to a rough estimation the publicly collected household wastes and household type industrial wastes in Germany contain 100-150 t cadmium in the year 2001. For additionally resulting quantities of waste types similar to domestic wastes, which are not publicly collected for disposal, no representative analyses concerning their cadmium content are available. On the assumption that the cadmium concentration in this fraction corresponds to that of the household waste or the household type industrial waste, the total amount of cadmium within the waste to be disposed of can be estimated with 150-230 t. After a rough estimation of Recharge [2] approx. 80 t of cadmium within this waste are due to not properly disposed NiCads. Of the 150-230 t cadmium a share of approx. 46 % reaches the municipal solid waste incinerators (MSWI), the other approx. 54 % are deposed directly. Of the fractions treated within the MSWI, approximately 25 % of cadmium is contained in slags, the other 75 % can be found in the ashes, which are deposed and/or stored for further use in salt deposits.

Depending on their quality, slags from MSWI are used for road construction or for base sealings of landfill sites. It has to be mentioned that this type of use is potentially associated with a wide distribution of heavy metals. Thus, due to the leaching of heavy metals an environmental hazard can not be excluded on a long-term time scale.

## 4.2 Cadmium input into the environment

In order to reduce cadmium emissions and therewith the cadmium input into the environment, various measures have been taken since the Council resolution in 1988 [3]. To which extent the cadmium exposition of humans has been reduced hereby is unclear.

Due to measures taken, emissions of cadmium into air and water bodies are declining and as a result reduced cadmium concentrations in air and precipitation arise. However, cadmium is a stable environmental contaminant; it tends to accumulate in the biosphere, being preferentially stored in soils and sediments [4]. It has to be assumed that due to atmospheric deposition and the use of fertilizers a constant increase of heavy metal concentrations in soils is occurring to a small extent [5]. Therefore, although emissions are declining, recent measurements of soils, river- and ocean-sediments show problematic cadmium levels.

The main uptake of cadmium by humans occurs by food. The provisional tolerable weekly intake (PTWI) of cadmium was set at 7 $\mu g\ kg^{-1}$ of body weight [6]. Due to results of the Belgian study CADMIBEL [7] it is recently discussed that this value is too high and it is recommended to reduce the value by half, therefore to a value of 3.5 $\mu g\ kg^{-1}$ body weight (PWTI). According to the Enquete-Kommission [8] the weekly cadmium intake of an average adult ranges between 1 and 4 $\mu g\ kg^{-1}$ body weight already.

In order to prevent any further increase of cadmium in agricultural soils which are likely to increase the dietary intake of future generations, the WHO recommended that airborne levels of cadmium should be as low as possible and not exceed 5 $ng\ m^{-3}$ in rural areas and 10 $ng\ m^{-3}$ in urban or industrial areas [9]. Air measurements in Germany in the years 1995 until 2000 show a reduction from 1.7 to 0.9 $ng\ m^{-3}$ in industrial locations and from 1.1 to 0.7 $ng\ m^{-3}$ in urban and rural regions [10]. The values are well below the proposed limits.

However, although emissions and cadmium concentrations in air and precipitation are declining, cadmium concentrations in foodstuff still sometimes exceed guideline levels [11]. On the other hand, cadmium levels in molluscs fall well below guideline levels, but show no clear reduction from 1996 to 2001 [12]. However, consumers of oil seeds, kidneys, molluscs and chocolate are warned to achieve high cadmium intakes [11].

Table 4: Cadmium flows into agricultural soils by the two input pathways atmospheric deposition and mineral fertilizer application according to data cited in literature. Values given in $g\ ha^{-1}\ a^{-1}$.

| **Atmospheric deposition** | | **Mineral fertilizer** | |
|---|---|---|---|
| 1.5 | [13] | 1.2 | [18] |
| 1.7 - 5 | [14] | 1.5 | [19] |
| 2.1 | [15] | 1.7 | [13] |
| 2.3 | [5] | 1.7 | [20] |
| 3.9 | [16] | 5.6 - 18.1 | [21] |
| 4 | [17] | | |

There is no doubt that the accumulation of heavy metals in soils is caused by anthropogenic inputs [5]. Input of cadmium in agricultural soils occurs mainly by two pathways: atmospheric deposition and application of mineral fertilizers. According to various sources in the literature, both input pathways lie in the same order of magnitude (table 4) although airborne levels of cadmium have already been declining.

However, from a food chain perspective, perhaps most important inputs of cadmium in soil are those that occur as a result of fertilization with fertilizers, which contain cadmium as an impurity [22]. Under these circumstances the cadmium is located in the immediate rooting zone and is also incorporated with plant nutrients, which stimulate proliferation of plant roots, thus enhancing crop access to the cadmium input.

The mass balance of cadmium in many fertilized agricultural soils is positive i.e. more cadmium is added in fertilizer and other sources than leaves the soil in food products, percolating waters or as soil particles through erosion [22]. If we wish to achieve a zero net cadmium addition to soils, it is debatable whether leaching or plant uptake is an environmentally acceptable way to minimise soil cadmium accumulation. The long-term goal needs to be minimisation of cadmium inputs to soil.

For reducing the environmental releases of cadmium various strategies are being suggested [3, 23], some of them already being implemented:

- Cut back on producing and consuming zinc
- Limitation of the uses of cadmium in cases where suitable alternatives do not exist
- Collection and recycling of products containing cadmium
- Prevent the flow of cadmium in the environment by using cadmium in a safe way.

Regarding regulations concerning the industrial use of cadmium leading to emissions from point sources, many measures have been already taken as has been mentioned in section 4.1. However, the diffuse distribution of cadmium and emissions of cadmium as a minor constituent is gaining of importance. For fertilizer application the next step is made: a proposal on an EU wide regulation on cadmium in fertilizers, reducing maximum cadmium concentrations in mineral fertilizers in three stages.

Table 5: Fields of human activity, some typical wastes and important waste flows related to cadmium. Selected activity fields taken from [24].

| Activity field | | Typical wastes | Wastes related to cadmium |
|---|---|---|---|
| **AF1:** | **Mobility and transportation** | Scrapped cars, wastes from transportation techniques | Ni/Cd batteries |
| **AF2:** | **Housing and construction** | Construction waste | PVC (windows), stabilisers, pigments |
| **AF3:** | **Nutrition and agriculture** | Organic wastes from households and agriculture, fertilizer | Mineral and organic fertilizers |
| **AF4:** | **Information and communication** | Electronic scrap, batteries | Ni/Cd batteries, solar cells |

## 5 Outlook

In the preceding sections it is pointed out which cadmium flows arise in Germany with a special focus on cadmium containing products. For sustainability reasons it is inevitable to reduce the use of cadmium or other heavy metals such as lead or mercury to a minimum. These heavy metals can appear as by-products with the production of goods or they can be added intentionally as components of certain goods (e.g. cadmium in NiCads). In either case they emerge to the waste stream after the use of these products.

In order to assign such risky material flows to certain human activities (consumption patterns) and to derive measures to reduce or avoid them, waste flows are to be allocated to different activity fields according to the integrative sustainability concept of the HGF (Hermann von Helmholtz Association of National Research Centers) [24]. These activity fields are e.g. mobility /transportation, housing/construction, nutrition/agriculture. Waste management itself is no activity field on its own, but can be classified as a cross-section activity. A first attempt to assign waste flows to activity fields is shown in table 5.

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