Working Paper

Industrial Transformation and Development of Heavy Metal Emissions in Northrhine-Westfalia:

Decomposition and Material Flow Analysis

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WP-96-8
January 1996

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Preface

This paper presents a contribution to the Regional Material Balance Approaches to Long-Term Environmental Policy Planning project (IND project). The policy part of this project - the Ruhr/Katowice Policy Comparison - aims at a better understanding of policy options for cleaning up the Black Triangle. The comparison focusses on the Ruhr Area and the Katowice voivodship which were both identified as hot spots of heavy metal pollution. The Ruhr/Katowice Policy Comparison comprises a historical analysis of the Ruhr Area, which draws heavily on the evidence collected in IIASA´s previous Rhine Basin study and which investigates past policies to reduce heavy metal pollution in this area.

The investigation was performed by Sander de Bruyn and Simone Schucht during their participation in IIASA´s Young Scientists´ Summer Program. This paper describes, both quantitatively and qualitatively, the determinants of the reduction of atmospheric heavy metal emissions in Northrhine-Westfalia. It develops methods to describe quantitatively industrial transformation and applies these methods to the analysis of industrial change in Northrhine-Westfalia during the 1955 to 1988 period.

Table of contents:

List of figures and tables

(contains 21 figures and 12 tables)

Abbreviations

ARIMA	Autoregressive integrated moving average
Cd	Cadmium
CO	Carbon monoxide
CO_2	Carbon dioxide
ECE	Economic Commission for Europe
e.g.	for example
GVA	Gross Value Added
i.e.	that is
IHK	Industrie- und Handelskammer
IIASA	International Institute for Applied Systems Analysis
kWh	kilo Watt hours
Ld	Lead
LDS	Landesamt für Datenverarbeitung und Statistik Nordrhein-Westfalen
Mill.	Million
MWh	Mega Watt hours
NF-Metals	non-ferrous metals
NO_x	Nitrogen oxides
NRW	Northrhine-Westfalia
o.w.	of which
SO_2	sulphur dioxide
SPM	suspended particulate matter (dust)
s.t.	subject to
t	tonnes (metric)
UBA	Umweltbundesamt
VDI	Verband der Deutschen Industrie
Zn	Zinc

0. Abstract

As part of the Rhine/Black Triangle Policy Comparison Study at IIASA, this working paper describes, both quantitatively and qualitatively, the determinants of the reduction of atmospheric heavy metal emissions in a sub-region of the river Rhine basin: Northrhine-Westfalia. It develops methods to describe quantitatively industrial transformation and applies these methods in a historical analysis of industrial change in Northrhine-Westfalia (1955-1988).

We find that the emission levels in Northrhine-Westfalia have declined considerably over the last thirty years. These emission reductions can be analysed quantitatively by using decomposition methods. Decomposition methods assess the change in emission levels as a function of economic growth, intrasectoral changes (changes in the production methods) within sectors and intersectoral changes (changes in the structure of the economy). We find that decomposition methods have methodological problems with respect to the allocation of interaction effects and the sensitivity of the results for sectoral classification and suggests ways to improve the methods. Based on the aim to minimize the interaction effect, we develop a proportional decomposition method for our empirical analysis. Applying this decomposition method to the changes in heavy metal emissions in Northrhine-Westfalia, we find that intrasectoral changes are the main reasons for the decline in emission levels. This leads to the assumption that technological changes are generally more important for the reduction of atmospheric heavy metal emissions than changes in the structure of the economy. In the context of a material flow model, we analyse the different components of these technological changes. We find that substitution of material and energy inputs, application of end-of-pipe technology, increasing process efficiency and substitution of labour for materials are important determinants of technological changes. The application of decomposition methods, together with a qualitative description on the sectoral level, points to the importance of improved end-of-pipe technology and process technology in several sectors (e.g. non-ferrous metals, iron and steel, energy production, cement manufacturing). This is consisten with several amelioration and retrofitting programmes that were set up in Northrhine-Westfalia by the state government during the sixties. It seems that these programmes have been, to a certain extent, successful in supporting a modernization of industrial plants in an environmental respect and have therefore also contributed to the reduction of industrial heavy metal point source emissions.

In future work, the analysis applied here should be extended to include a closer analysis of the driving forces behind the observed developments in Northrhine-Westfalia. The methodology that has been developed here could also be integrated in scenario analyses for other regions, such as the Black Triangle.

1. Introduction

Industrial transformation is defined as a set of quantitative and qualitative changes in the performance and organisation of industries, and their environmental impacts over time. Industrial transformation includes different forms of changes (technological, spatial, structural and socio-economic), relevant for environmental pressure. Industrial transformation can play a prominent role in the reduction of atmospheric heavy metal emissions. Atmospheric heavy metal emissions deserve attention, because cadmium, lead and zinc belong to the most toxic metals [Olendrzynski, 1995]. Once emitted, heavy metal aerosols can travel long distances and deposit far from emission sources, for example on agricultural lands. Through the uptake by agricultural crops and leaching to groundwaters that serve as drinking water, heavy metals enter the human food chain with possible detrimental effects.

1.1. The Rhine/Black Triangle Policy Comparison Study

The sources of heavy metal emissions, their pathways through the environment and their impacts on agricultural soils are subject of investigation in the IIASA project Regional Material Balance Approaches to Long-Term Environmental Policy Planning. The region currently under study is the Upper Elbe/Oder Basin, also called the Black Triangle, covering parts of (former East-)Germany, Poland and the Czech Republic. This heavily industrialized area is in many respects the most polluted area in Europe. Forty years of communist regimes with their focus on heavy industry and a neglect of environmental problems have resulted in a severe environmental situation: heavily polluted soils and an industrial equipment inadequate to match the required environmental standards. Owing to these characteristics the Black Triangle Area issues a challenge for environmental policy orientated around industrial transformation; i.e. a transformation of the organisation, technologies, and structures of industrial production.

In order to evaluate the policy options for a mitigation of heavy metal pollution in the Black Triangle, a closer investigation of the historical process of industrial transformation in river basins in developed market economies is useful.

River basins incorporate specific characteristics with respect to (economic) infrastructure and pathways to transmit heavy metal pollution. An example of a river basin where ecological restructuring has taken place is the river Rhine basin, subject of IIASA's Rhine Study which investigated the development of heavy metal emissions to air and water in the Rhine Basin from 1955 to 1988 [Stigliani et al., 1993]. This study identified the Ruhr Area as the geographic locus of industrial pollution in the Rhine Basin and showed a substantial reduction of heavy metal emissions in this region over time [Stigliani/Anderberg, 1992]. An important element of this reduction may have been the economic restructuring of this area, the application of abatement technologies and a decline in the input of raw materials [Schucht, 1993].

Knowledge of the driving forces behind the industrial transformation in the Ruhr Area could serve as an important benchmark for formulating environmental policy options in the Black Triangle, of course subject to differences in the local conditions in both regions[1]. The Rhine/Black Triangle Policy Comparison Study, therefore, seeks to determine the social, political, and economic factors that led to the clean-up of the Ruhr Area, and whether lessons learned in that clean-up could be usefully applied to the clean-up of the Katowice voivodship. As the Katowice voivodship is characterized by much of the same heavy industry that dominated in the Ruhr Area and as it is therefore exposed to high heavy metal emissions, the Rhine/Black Triangle Policy Comparison Study will partly be conducted on a case-study comparison between the Ruhr Region as a sub-region of the Rhine Basin and Katowice voivodship as a sub-region of the Black Triangle [Blazejczak, 1995].

This paper gives a first impulse to identify these driving forces by developing a methodology that can be used for the study of industrial transformation and by applying this methodology to Northrhine-Westfalia, a federal state of Germany of which the Ruhr Area is a part[2]. In future work more attention will be paid to explanations behind the here observed developments in relation to legal/administrative changes and technology and structure enhancing policy.

1.2. Research aims

This paper specifically addresses economic origins of reductions in heavy metal emissions by investigating changes in economic activities that are influential on emission levels. The goal of this paper is twofold: on the one hand the development of a methodology that can determine factors that are influential on changes in emission levels, and on the other hand the application of this methodology in order to analyse the changes and causes of changes in atmospheric heavy metal emissions of lead, zinc and cadmium in Northrhine-Westfalia.

Emission reductions can be thought of as being influenced by different determinants of industrial transformation. We employ here the following classification scheme [Schucht, 1993; De Bruyn et al., 1996 (*forthcoming*)]:

1. intersectoral change (changes in shares of specific economic sectors);
2. Intrasectoral change (changes within specific sectors);
    2.1. intrasectoral structural shifts (increase or decline of shares of specific productions within an economic sector);
    2.2. application of different technologies (including process and product related technological shifts and the application of end-of-pipe technology);
    2.3.substitution of inputs;
3. economic growth.

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[1] Simply copying experiences from the Ruhr Area to the Black Triangle may be inappropriate [Blazejczak, 1995].

[2] It would be desirable to investigate the industrial change that took place in the Ruhr Area only instead of in the whole of Northrhine-Westfalia. Owing to the situation of statistical data it is only possible to investigate industrial change for the whole of Northrhine-Westfalia.

In order to identify the determinants of industrial change that have contributed to the clean-up in the Ruhr Area the following research aims have been defined:

- a description of patterns of atmospheric heavy metal emissions on the total industrial and sectoral level;
- the development of a quantitative methodology that can specify and analyse the factors that are influential on the changes in emission levels (decomposition method);
- an application of this methodology in order to quantitatively estimate the importance of the contribution of the various factors to the total reductions in emission levels in Northrhine-Westfalia to the extent where the respective data are available;
- a theoretical analysis of substitution options and technological changes that can reduce emissions and a qualitatively descriptive analysis of changes that could not be covered by quantitative analysis because of lacking data, and
- a preliminary investigation of driving forces behind the observed industrial transformations.

1.3. Outline of the Paper

In *Chapter 2* we first give an overview of the development of atmospheric cadmium, lead and zinc emissions in Northrhine-Westfalia between 1955 and 1988, as well as a description of the industrial activities most important for the atmospheric emission of these heavy metals.

In *Chapter 3* we present a decomposition methodology that can be used for quantitative analysis of industrial transformation. We decompose here the emission/output ratio[3] of Northrhine-Westfalia into intrasectoral and intersectoral effects. We also discuss problems previously overlooked when applying these methods and give some suggestions for improvements.

In *Chapter 4* the decomposition methodology developed in Chapter 3 is applied in order to analyse changes within the economic system that led to the decline in the level of heavy metal emissions in Northrhine-Westfalia. To be investigated are the contributions of inter- and intrasectoral effects to changes in the emission/output ratio. In order to depict more carefully the developments of intrasectoral change, we develop in *Chapter 5* a simple material flow analysis embodied in economic production theory. We show that the intrasectoral changes are in fact due to various different developments regarding technological changes, the structure of production and several substitution processes of inputs. An extended version of the decomposition method described in Chapter 3 can be a used as a tool to analyse these determinants of intrasectoral change, depending on the availability of appropriate data.

In *Chapter 6* the determinants of intrasectoral change are investigated on the level of individual sectors and productions. In a first step we look at the percentage changes over time in emissions, emission intensities and production shares of the individual sectors. In a second step we investigate the development of heavy metal emissions in relation to individual productions highly important for these emissions. In a third step some aspects

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[3] Or emission intensities, i.e. the division of emissions over monetary output (Gross Value Added), see chapter 3.

of intrasectoral change, that have led to the reduction of heavy metal emissions in Northrhine-Westfalia, are described. Especially this last step has to be considered as being preliminary[4].

Conclusions and suggestions for further research will be outlined in *Chapter 7*. Emphasis will be put on the need to more closely investigate the driving forces behind the here observed developments in terms of legal/administrative changes and technology and structure enhancing conditions in Northrhine-Westfalia.

In annex A we derive the decomposition method that has been used in this paper mathematically in combination with two other methods. A detailed description of the data is given in annex B.

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[4] Especially technological changes that took place after 1972 have to be further analyzed. This question will be further investigated in ongoing research [Schucht, 1995 forthcoming].

2. Industrial Activities and Heavy Metal Emissions in Northrhine-Westfalia

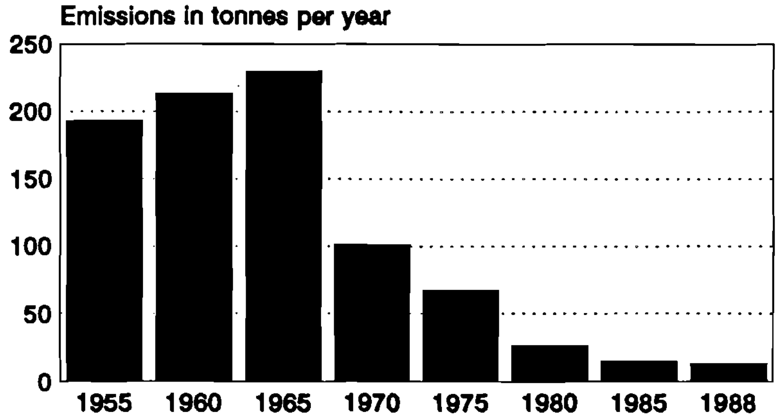
This study deals with atmospheric heavy metal emissions of cadmium, lead and zinc. In order to answer the questions that were put forward in Chapter 1., we look only at emissions[5] from industrial point sources since these are of the highest importance in heavily industrialized regions, and emission reductions have been most impressive for this kind of emissions in Northrhine-Westfalia. It is expected that also in the Katowice area major reductions of industrial emissions can be achieved.

In this chapter we will first give a rough overview of the development of atmospheric emissions of cadmium, lead and zinc caused by industrial point sources in Northrhine-Westfalia between 1955 and 1988[6]. In a second step the industrial activities most important for the atmospheric emission of heavy metals will be described.

2.1. Development of Atmospheric Heavy Metal Emissions in Northrhine-Westfalia

Atmospheric *cadmium emissions* of industrial point sources in Northrhine-Westfalia declined from a maximum of 230t per year in 1965 to 13t per year in 1988 (see Figure 2.1.). The highest reductions were achieved within the 1965 to 1980 period, when cadmium emissions dropped by 203t.

Figure 2.1. Atmospheric Cadmium Emissions - Northrhine-Westfalia



Sources: IIASA, own calculations

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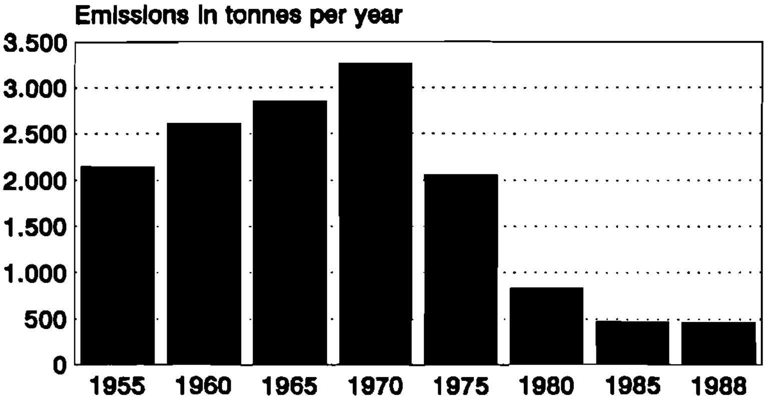
[5] If we subsequently use the term atmospheric emissions, only those stemming from industrial point sources are referred to.

[6] The emission data are average values for 5-year periods. For the sake of simplicity we denote time periods by their mid-value, e.g. 1955 denotes the period from 1953 to 1957.

Atmospheric *lead emissions* reached their peak level of approximately 3270t per year in 1970 (see Figure 2.2.). In the following years they declined by about 2430t to 840t in 1980 and stabilized by about 460t in the late eighties.

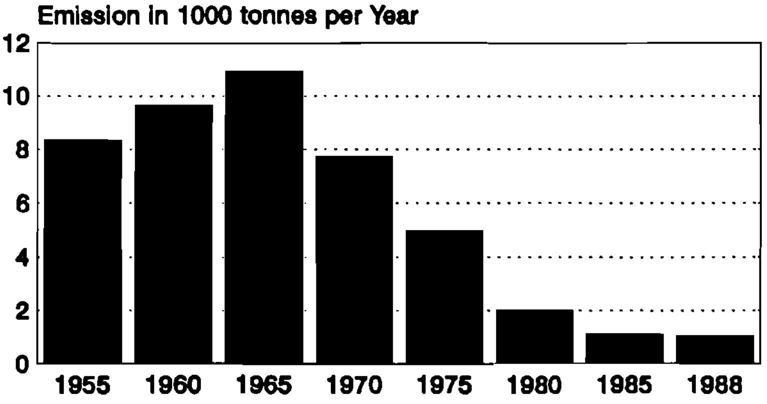
Figure 2.2. Atmospheric Lead Emissions - Northrhine-Westfalia



Source: IIASA, own calculations

Atmospheric *zinc emissions* - as well as the cadmium emissions - increased until the mid sixties, reaching a level of 10920t in 1965 (see Figure 2.3.). Until 1980 zinc emissions dropped very quickly by somewhat around 8910t to 2010t and reached a level of about 1060t in 1988.

Figure 2.3. Atmospheric Zinc Emissions - Northrhine-Westfalia



Sources: IIASA, own calculations

Concluding, we find that the major decreases in heavy metal emissions occurred during a relatively short period of time, from 1965 to 1980. These findings raise the question which industrial changes led to the distinct decline in the emission of cadmium, lead and zinc since the mid sixties. In this study we try to determine quantitatively as well as qualitatively the components of industrial change influencing the described developments of atmospheric heavy metal emissions.

2.2. Industrial Activities Causing Atmospheric Heavy Metal Emissions

Heavy metals are natural components of the earth's crust and enter the industrial economy e.g. in iron and non-ferrous ores, coal and oil [Stigliani and Anderberg, 1992; ECE, 1994]. The heavy metals particles are emitted by high temperature processes, such as fuel combustion for power and heat generation, in foundries and refineries. Waste incineration, as well as the use of certain metals to produce industrial goods are further significant sources of heavy metal emissions [ECE, 1994].

With respect to cadmium and zinc emissions the *non-ferrous metal refining* of copper, zinc and lead is of highest importance. As cadmium is a natural trace component of zinc ores, zinc refineries have been a major source of zinc, as well as of cadmium emissions, which are released to the exhaust air during the process of refining [Stigliani et al., 1993; Klepper et al., 1995].
Emissions of all three heavy metals considered in this study are strongly linked to the development of *iron and steel production*, as heavy metals occur as natural impurities in coke as well as in iron ores. An important source for zinc and cadmium emissions is also the use of scrap galvanized steel (zinc- and cadmium-coated) in the production of secondary steel [Stigliani et al., 1993; UBA, 1982].
As mentioned before combustion of coal and oil are important sources of atmospheric cadmium pollution. Therefore, *electricity production* leads to significant cadmium and zinc emissions [ECE, 1994]. Although the metal content in both coal and oil is rather low[7], emissions from these sources are significant because of the high volumes of coal and oil consumed.
In the *cement manufacturing* a major source of cadmium and zinc emissions was the use of discarded automobile tires serving as a source of fuel [Stigliani et al., 1993], as zinc is an additive in the rubber manufacture used in tires, and cadmium is a trace impurity of zinc.

2.3. Determinants of Change

The major reductions of heavy metal emissions did not have an impact on the economic activity in Northrhine-Westfalia. Figure 2.4. shows the development of the emission of the three heavy metals compared to the development of Gross Value Added of Northrhine-Westfalia. This figure shows that despite the increase in economic activity, the emissions of heavy metals have declined over the last thirty years. This de-linking of economic growth from emission levels for certain pollutants is a well-known fact in empirical economic literature[8].

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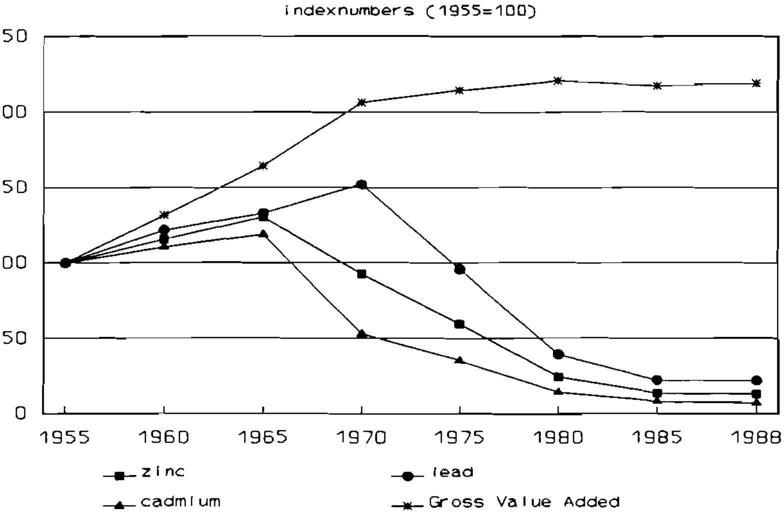
[7] The content of these metals in coal is higher than in oil.

[8] See Selden and Song [1994] and Shafik and Bandyopadhyay [1992] for empirical evidence on de-linking for SO_2, NO_x, CO and SPM emissions. For a critical review see De Bruyn et al. [1995].

Figure 2.4. Development of Heavy Metal Emissions in Relation to Economic Growth



Sources: IIASA, LDS, own calculations

The reasons for this development are in general poorly understood. Selden and Song [1994, p147] state that "positive income elasticities for environmental quality" account for this development. This explanation, however, does not provide us with information in what way the emission levels have declined: as the result of the application of end-of-pipe technology (enforced by environmental policy), as the result of endogenous changes in the structure of final demand or as the result of the application of new product design and process technologies that led to a saving in materials and energy consumed. A description of the actual causes of the decline in emission levels in Northrhine-Westfalia may point at possible strategies to be followed for industrial transformation in the Black Triangle Area. In order to assess these causes we will use decomposition analysis, that can be used to decompose the change in emission levels into several effects. In the following chapter we describe the technique of decomposition analysis when applied to main effects only: the effects we describe there are intersectoral (changes in the structure of production) and intrasectoral (changes in the technology of production). This does not imply that decomposition analysis is restricted to these effects: as will be seen in Chapter 5, the number of effects can be extended considerably if data are available.

3. Decomposition Analysis

Decomposition analysis can be defined as a method to distinguish changes within an economic system by means of investigating in a comparative static way the set of variables that describe the economic system. By rewriting these variables into complex identities, the contribution of the separate change in each variable to the total change in the economic system is made visible. The change in the economic system is decomposed into the change of the components of that system.

Decomposition analysis is often concerned with the effect of changes in the *structure* of the economy for example on employment, energy demand or emission levels, and can hence be denoted as structural change analysis, or structural decomposition analysis [Skolka, 1989]. While employment, energy demand or emission levels can be directly measured by statistical offices, the influence of structural changes on each of them is not directly measurable and has to be approximated. Changes in output occur in a wide range of economic sectors and the question is how to add these changes up in order to determine their influence on employment, energy demand or emissions. This has a connection to the well-known economic problem of how to measure the rate of inflation which relates decomposition analysis to the statistical-economic theory of index numbers [Allen, 1975; Liu et al., 1992].

3.1. The Problem of Decomposition in Relation to Heavy Metal Emissions

Decomposition analysis can be used as a quantitative tool to assess industrial transformation. First, we have to define the economic system. For this study the economic system is the industry in Northrhine-Westfalia that consists of $j = \{1..n\}$ sectors, where each sector produces one output, value added ($Y_{j,t}$), using one input, atmospheric emissions of heavy metals ($E_{j,t}$). E can be cadmium, lead or zinc and t is a time subscript. Define then the variables without subscript j as the sum over all the j sectors:

$$X_t = \sum_j X_{j,t} \qquad \{X_t, X_{j,t}\} = \{E_t, E_{j,t}\}, \{Y_j, Y_{j,t}\}, \textit{ etc.} \tag{3.1}$$

so that E_t becomes the total emissions and Y_t becomes GNP of Northrhine-Westfalia if all the sectors in an economy are taken into account. Define then the following variables:
$U_{j,t}$ = emission intensity of pollutant h in sector j = $(E_{j,t}/Y_{j,t})$
$S_{j,t}$ = value added share of sector j = $(Y_{j,t}/Y_t)$

Decomposition analysis starts by specifying an identity where the total emissions are a function of the emission intensities, the value added shares and the level of GDP:

$$E_t = \sum_j U_{j,t} S_{j,t} Y_t \tag{3.2}$$

The first variable on the right hand side of (3.2) gives the emission intensities of sector j ($U_{j,t}$) which specify the amount of emissions that are "needed" to create one unit of value added for sector j. In economic theory, this is determined by the production function, a topic that will be elaborated in Chapter 5. For now it is enough to acknowledge that the amount of emissions per unit of value added is dependent on *technological factors* such as process-technology, end-of-pipe technology, product design etc.

The second variable gives the share of value added of sector j in the total GDP. This describes emissions as determined by the *structure* of the economy.

The third variable gives the level of GDP; the emissions thus are also dependent on the magnitude of monetary output, or income.

Equation (3.2) gives the relationship between emissions as a function of the level of GDP, sectoral composition and technology for one moment in time. But the question we address is basically a dynamic one: what factors were influential for the patterns of emissions of heavy metals in Northrhine-Westfalia from 1955-1988? From equation (3.2) we have three such factors (changes in technology, in the structure of the economy and in levels of income) and the question is how much each has contributed to the total change in emission levels over this period.

Here we encounter a major problem, since the change in emissions is not simply the sum of changes in each of the variables on the right hand side of (3.2)[9]. The problem therefore consists of *adding up* the change of emission intensities, value added shares and production growth of several sectors so that it matches the growth of the total emissions. Decomposition analysis is concerned with solving this *addition problem*: splitting the change in emission levels into the different factors that influence the levels of emissions.

3.1.2. Reduction of the Problem

Although decomposition with three variables has been performed frequently [Ang and Lee, 1994; Binder, 1993; Park, 1992; Boyd et al., 1988], it has been shown that the addition problem can be rewritten as a two variable case [Howarth et al., 1991]. Notice that we can rewrite (3.2) as a system of two equations (which are also identities):

$$E_t = V_t Y_t \qquad (3.3)$$

and

$$V_t = \sum_j U_{j,t} S_{j,t} \qquad (3.4)$$

where V_t equals the emission intensity of the total economy ($= E_t/Y_t$). In order to avoid confusion with the sectoral emission intensities we will call V_t the emission/output ratio. Since the first equation does not contain any summation signs, decomposition analysis is

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[9] If the summation sign was absent in (3.2), it would be possible to express the growth in emissions as a function of the growth of each ratio by transforming (3.2) into natural logarithms and take the first differences. Owing to the summation sign this is not possible (since for example ln5 is not the sum of ln3 and ln2).

only needed for the second equation: to decompose the change in the emission/output ratio[10]. Another reason for focusing on equation (3.4) instead of (3.2) deals with the objective of this study. Since our main focus is to identify factors that influence emission levels that can be controlled by the policy makers, the influence of economic growth on emission levels is not of much importance. Reducing economic growth is in general not considered as a realistic option in environmental policy. As a final reason, we would mention that industrial transformation does not take place by reducing GDP but consists of changes of technology and changes in the structure of the economy: both are captured in (3.4).

Excluding economic growth, our decomposition problem reduces to equation (3.4), and to decompose the change in the emission/output ratio into changes in value added shares and sectoral emission intensities.

3.2. Decomposition Methods: The Problem of Weighting Changes

Decomposition analysis has been performed in a wide range of economic subjects: employment [Skolka, 1989]; energy demand [Ang and Lee, 1994] or CO_2 emissions [Torvanger, 1991]. In general many authors have used different decomposition methods that differ in the way change is being measured and the way these changes are being weighted[11]. As being described in Annex A, change in emissions (and any other variable) can be described in:
(i) absolute terms (E_T-E_0);
(ii) percentage changes (E_T-E_0)/E_0;
(iii) exponential growth rates (ln{(E_T/E_0}).

This will yield three different decomposition methods, which are described in Annex A. The decomposition method exemplified here is based on absolute change[12].

3.2.1. Decomposition Analysis Based on Absolute Changes

The continuous change in the emission/output ratio between two years, 0 and T, can be calculated by differentiating expression (3.4) towards time which results in:[13]

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[10] We do not necessarily need decomposition analysis in the first identity. The (exponential) growth in emissions can be calculated as the sum of the growth in each of these two components.

[11] This classification is ours: others [Liu et al., 1992; Ang & Lee, 1994; Ang, 1994] have pointed out that decomposition methods are in fact discrete approximations of two continuous Divisia line integrals. This connection with Divisia indices [Allen, 1975] is however complicated and nowhere derived formally.

[12] This equals the PDM2 decomposition method in additive terms as being given in Ang [1994].

[13] Variables with a dot indicate derivatives towards time.

$$\dot{V}_t = \sum_j \{\dot{U}_{j,t} S_{j,t} + \dot{S}_{j,t} U_{j,t}\} \tag{3.5}$$

This continuous expression gives on the left hand side the change in the emission/output ratio which is equivalent to the sum of the two terms on the right hand side. The first term on the right hand side of (3.5) defines the *intrasectoral change* as the summed change in each sector's emission intensity holding the value added share constant. The intrasectoral change is then defined as the summed changes in emission intensities that take place *within* sectors that can be an indicator for technological changes.

The second term on the right hand side defines the *intersectoral change* as the summed change in each sector's value added share holding the emission intensity constant. These summed changes are defined as intersectoral since they consist of the shifts of value added shares *between* sectors.

Since decomposition analysis is discrete time analysis, we need to find some discrete equivalents of (3.5). Over a time interval $<0,T>$ we can find this discrete equivalent by integrating (3.5) over this time interval, which results in:[14]

$$\int_0^T \dot{V}_t \, dt = \int_0^T \sum_j \dot{U}_{j,t} S_{j,t} dt + \int_0^T \sum_j \dot{S}_{j,t} U_{j,t} dt \tag{3.6}$$

The discrete equivalents of the integrated derivatives in (3.6) are fully defined as the absolute change in the variable (see also Annex A). So the expression on the left hand side becomes: $V_T - V_0$. Similarly, the discrete equivalents of the integrated derivatives on the right hand side are fully defined as $U_{j,T} - U_{j,0}$ and $S_{j,T} - S_{j,0}$ respectively. It is with the constants on the right hand side of (3.6) that we encounter a problem: we do not know the time path of these variables over the time interval $<0,T>$. So for example in the first integral on the right hand side, the constant $S_{j,t}$ is not likely to remain constant itself between year 0 and T. Over the time interval considered, $S_{j,t}$ takes the values between $S_{j,0}$ and $S_{j,T}$. So we could use either $S_{j,0}$ (base year) or $S_{j,T}$ (current year) or some combination of both in order to weight the absolute change in emission intensities. Following Liu et al. [1992] we transform the time paths of the constants $S_{j,t}$ and $U_{j,t}$ into the following *parametric weighting functions* (see also Annex A):

$$w_{s_j} = S_{j,0} + \alpha_j (S_{j,T} - S_{j,0}) \qquad ,0 \leq \alpha_j \leq 1 \tag{3.7}$$

$$w_{u_j} = U_{j,0} + \beta_j (U_{j,T} - U_{j,0}) \qquad ,0 \leq \beta_j \leq 1 \tag{3.8}$$

where the parameters α_j and β_j can be chosen in order to determine the time path of the constants. Using these in (3.6) will give the following decomposition method:

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[14] Conditions under which a solution to this integral path exists are described in Ang [1994] and Liu et al. [1992].

$$V_T-V_0 = \sum_j w_{s_j}(U_{j,T}-U_{j,0}) + \sum_j w_{u_j}(S_{j,T}-S_{j,0}) + \sum_j R_j \tag{3.9}$$

The first term on the right hand side of (3.8) defines the *intrasectoral* effect as thc weighted change in each sector's emission intensities. The second term defines the *intersectoral* effect as the weighted change in each sector's value added share. Choosing values for α_j and $ß_j$ in the weighting functions then defines the time path of $S_{j,t}$ and $U_{j,t}$ respectively. Choosing $\alpha_j = 0$ for every j means that the value added share in the base year 0 is used as a weighting factor. Choosing $\alpha_j = 1$ means that the value added share in the end year T is used as a weighting factor. A general assumption of integration is that the values of the variables do not exceed the values they take in the observed years 0 and T. This implies that we cannot choose values for α_j or $ß_j$ that are lower than zero or greater than unity, so that the values of S_j and U_j are bounded by the base and end years.

A residual term R_j is added in (3.8) since the two effects normally do not add up together because of joint-effects. This residual can become quite substantial if the time interval $<0,T>$ is lengthy and both the values for α_j and $ß_j$ are either 0 or 1 [Ang and Lee, 1994]. A large residual would eventually defeat the purpose of decomposition since it does not provide us with an explanation on which effect was dominant.

Ang [1994] and De Bruyn and Van den Bergh [1995] have proposed to choose values for α_j and $ß_j$ that minimize the residual term R_j.

Solving the residual term from (3.8) using (3.6) and (3.7) results in the following expression:

$$\sum_j R_j = \sum_j (1-\alpha_j-\beta_j)(U_{j,T}-U_{j,0})(S_{j,T}-S_{j,0}) \tag{3.10}$$

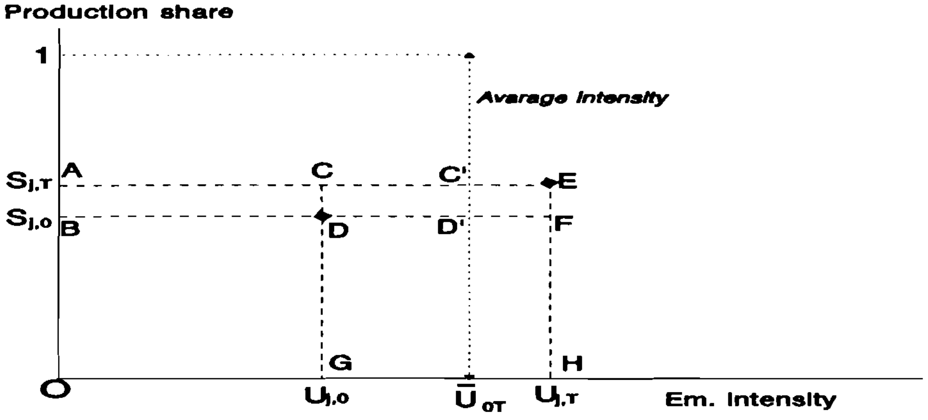
From this expression follows immediately that any combination that fulfils $\alpha_j + ß_j = 1$ for all j will give a decomposition result without a residual.

3.2.2. The Problem of Choosing Values for α_j and $ß_j$

Most authors implicitly choose values for α_j and $ß_j$ of 0 or 1 a priori. These two values are however extremes and influence the results critically, as we will show with the following graphical exposition.

In Figure 3.1 the hypothetical developments of the emission intensity and value added share of a copper producing sector is depicted with emissions of cadmium between year 0 and T. Assume that due to a shift from secondary to primary copper refinery the emission intensities drastically increase from $U_{j,0}$ to $U_{j,T}$. Over the same period, the copper producers were able to raise their value added share from $S_{j,0}$ to $S_{j,T}$. Notice that $1-S_{j,0}$ gives the value added share of the other sectors in year 0 and $1-S_{j,T}$ in year T. Let us furthermore assume that the total emission/output ratio did not change during these years and remained constant at U_{OT}[15].

Figure 3.1. Developments of Value Added Share and Emission Intensity of Sector j



As defined in equation (3.4), the *contribution* of this sector to the emission/output ratio is given by the multiplication of the emission intensities and the value added shares. This contribution changed over the period considered. This change can be depicted by substraction of the rectangle OBDG from OAEH which results in the sum of three positive rectangles: BACD, DCEF and GDFH.

The choice of values for α_j and ß_j in the weighting function can now be shown to be critical to the division between intersectoral, intrasectoral and residual terms of the change in the contribution to the emission/output ratio. Table 3.1. gives the outcome of decomposition using different values for α_j and ß_j.

Table 3.1. Contribution of Sector j to the Decomposition Results

Values	Intra	Inter	Residual
$\alpha_j = \text{ß}_j = 0$	GDFH	BACD	DCEF
$\alpha_j = \text{ß}_j = 1$	GDFH + DCEF	BACD + DCEF	-(DCEF)
$\alpha_j = 0,\ \text{ß}_j = 1$	GDFH	BACD + DCEF	0
$\alpha_j = 1,\ \text{ß}_j = 0$	GDFH + DCEF	BACD	0
$\alpha_j = \text{ß}_j = 0.5$	GDFH + 0.5(DCEF)	BACD + 0.5(DCEF)	0

The reason for these different outcomes, is that the changes in emission intensity and value added share are weighted differently, depending on the choice for the parameters. So it appears that the choice for the parameters is a critical element in decomposition analysis. This has an implication for interpretations too. Let us consider the following

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[15] This implies that the total of other sectors declined their emission intensities over the time period considered.

question: did the increase in production of the copper sector result in structural improvements of the emission/output ratio or in a structural deterioration[16]?

In order to answer that question, notice first that the emission intensity of the copper sector is *below* the emission/output ratio in year 0 and *above* in year T. Decomposition with $\alpha_j = \beta_j = 0$ weights the change in value added share with the emission intensity in year 0. The increase in the value added share of the copper sector has then resulted in structural improvements, since the relatively cleaner copper sector has expanded its production relatively to the more polluting sectors. Things are reversed when taking $\alpha_j = \beta_j = 1$ (end year weighting). The increase in the value added share of the copper sector has then resulted in structural deteriorations since the relatively more polluting copper sector has expanded the production at the expense of the relatively cleaner sectors.

So it is the case that the choice for the parameter values are quite critical to the results and interpretation of decomposition analysis. Base year decomposition has been performed by Howarth et al. [1991] and Park [1992]. End year decomposition has been performed by Binder [1993]. Basically there are no guidelines which parameter values should be chosen [Vogt, 1979]. Park defends base year weighting because the economic concept of change corresponds more closely to the change of a variable compared to the base period rather than to the end period. Indeed, the percentage change of a variable X_t is normally interpreted as $(X_T-X_0)/X_0$ rather than $(X_T-X_0)/X_T$; i.e. the change in X will normally be weighted by the base year. Binder [1993] argues that base year decomposition does not use information on the current state of affairs. Since the technology (as a proxy for emission intensities) changed during the period considered, Binder is interested in viewing the influence of intersectoral change according to newest technology. It should be added however that end year weighting does not use information on the old technology: none of these parameter values describe actually the *path* along which technology develops over the time period considered.

In the light of these considerations, Ang [1994] emphasized decomposition with $\alpha_j = \beta_j = 0.5$, which gives the *arithmetic mean* between the base year and the end year. Decomposition with these parameters has the nice feature of a zero residual.

It can be shown that choosing other values than 0 or 1 for the parameters has the effect of adding an α_j share of the residual term to the intrasectoral effect and a β_j share to the intersectoral effect. Hence with $\alpha_j = \beta_j = 0.5$, the residual is completely and equally allocated to both effects (see also Table 3.1.). But if we look at Figure 3.1, we can see that this way of allocating the residual would result in a relatively larger increase in the intersectoral effect than in the intrasectoral effect. That is, compared to base year decomposition, the intersectoral effect has relatively risen more than the intrasectoral effect. Because both effects differ in magnitude, the equal distribution of the residual term may bias the distribution between both effects in favour of the smaller effect. Therefore De Bruyn and Van den Bergh [1995] proposed to allocate the residual in such a way that the share of the added residual is proportional to the size of the original effects.

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[16] Structural improvements give a negative figure for intersectoral change, structural deterioration gives a positive figure for intersectoral change.

This would result in the following parameter values for α_j and β_j (see Annex A.2.):

$$\alpha_j = \frac{|\tilde{U}_j|}{|\tilde{S}_j| + |\tilde{U}_j|} \qquad (3.11)$$

$$\beta_j = \frac{|\tilde{S}_j|}{|\tilde{S}_j| + |\tilde{U}_j|} \qquad (3.12)$$

where

$$\tilde{X} = \frac{X_T - X_0}{X_0}, \qquad X = U, S \qquad (3.13)$$

The values of α_j and β_j are based on the percentage changes of the variables U_j and S_j. The interpretation is quite straightforward: if the relative change in the emission intensities is larger than the relative change in the value added shares, α_j will be larger than β_j and a greater part of the residual will be added to the intensity effect. The values for α_j and β_j lie by definition between the boundaries of 0 and 1 and therefore are consistent with the restrictions put on the values of the parameters. Moreover, this "proportional" decomposition method has the advantage over arbitrarily choosing values for α_j and β_j as the data determine their values. The values will differ between the sectors so that the total outcome will be more sensitive to sectoral differences in changes in intensities and value added shares. Finally, using these values for α_j and β_j in equation (3.6) results in a residual term that by definition is equal to zero so that the sum of intrasectoral and intersectoral changes always matches the total change in the emission/output ratio.

The values for α_j and β_j can be substituted in the weighting functions and used for decomposition of absolute changes, as defined in equation (3.8). With this *proportional decomposition method* we use both the information of the base year and the end year in a sophisticated manner: it provides us with an estimation of the time paths of the variables over the time period considered.

3.2.3. Percentage Change Decomposition

Change can be measured in three ways: in absolute change, in percentage change and in growth rates. Absolute changes of variables without reference to base years do not contain much information. The knowledge that the emissions of cadmium declined with 20 tonnes between 1980 and 1985 may be informative but without knowing the initial values we cannot assess the relative importance of the achieved reduction. Therefore, percentage changes provide more information. Percentage change decomposition can be obtained by dividing every term of equation (3.8) by V_0. Using equations (3.6), (3.7) and (3.9) and rearranging terms we get the following decomposition method (see also Annex A.2.3.):

$$\tilde{V} = \sum_j \frac{E_{j,0}}{E_0}(1+\alpha_j\tilde{S}_j)\tilde{U}_j + \sum_j \frac{E_{j,0}}{E_0}(1+\beta_j\tilde{U}_j)\tilde{S}_j + \sum_j \frac{E_{j,0}}{E_0}(1-\alpha_j-\beta_j)\tilde{U}_j\tilde{S}_j \qquad (3.14)$$

This decomposition method decomposes the percentage change in the emission/output ratio into intrasectoral percentage change and intersectoral percentage change plus a residual term. Since this decomposition method is derived from the absolute change decomposition method, the values for α_j and β_j in the proportional decomposition method remain unaltered. In Chapter 4 we will use this proportional decomposition method based on percentage changes.

3.3. Further Topics in Decomposition Analysis

Decomposition analysis is a descriptive tool in analysing changes within economic systems. In order to make fully understood the technique it is necessary to point at some particular characteristics and assumptions.

3.3.1. The Level of Sector Disaggregation

The decomposition method described in Section 3.2 results in decomposing the changes in the emission/output ratio into intrasectoral and intersectoral effects. Intrasectoral effects are the summed weighted changes in emission intensities of all the sectors taken into consideration. Intersectoral effects are the summed weighted changes in value added shares of all the sectors considered. It should be obvious that the results depend on the level of sector disaggregation that is chosen (the number of sectors). When the economy is disaggregated into only few sectors, many intrasectoral effects will be in fact due to shifts in productions that take place within a sector. Take for example the non-ferrous metals industry. This sector consists of a number of production processes, such as copper, zinc, lead, nickel, aluminum etc. If the cadmium emission intensity of this sector declines it could be the result of the application of (c)leaner technology in this sector, but it could also be related to the shift from copper, zinc and lead production towards aluminum production. It is clear that the first development is a change in technology but that the second development is a change in the composition of output, which we would like to identify as intersectoral change. If data were available on the level of individual products we could treat the intrasectoral changes as true shifts in technology applied and the intersectoral changes would be true shifts in the composition of output [Jenne and Catell, 1983]. Normally this is not the case. Value added statistics and emission statistics choose a level of sector disaggregation that distinguishes the most important sectors according to both statistics. The important sectors, however, need not necessarily be the same for both statistical records. Since we have to match the emissions and value added data on the sectoral level, we often end up with a higher level of aggregation than presented in both statistical records. This means that we add up the data of one statistical record in order to match the lowest level of disaggregation possible of the other statistical record.

The effect of a higher level of sector disaggregation on the division between intrasectoral and intersectoral effects is uncertain. Contrary to what is often thought, enlarging the number of sectors does not necessarily contribute to an increase in the importance of intersectoral change (and vice versa) [Ang, 1993]. Notice that the intersectoral changes are defined as the changes in the value added shares weighted by the emission intensities. Whereas the change in value added share of a sector j can be defined as the sum of changes in each subsector, the emission intensity of sector j cannot be seen as the sum of emission intensities in the subsectors[17]. Hence, if we split one sector into several subsectors, the weightings that are used are not comparable. This would make the outcome on the distribution between intersectoral and intrasectoral effects uncertain if we enlarged the number of sectors.

Take the following example with hypothetical data (arbitrary units) on two industries, as presented in Table 3.2.

Table 3.2. Sector Disaggregation and Decomposition Outcomes

	Data		Calculus		Intersectoral Effects	
Industry	$E_{i,0}$	$Y_{i,0}$	$U_{i,0}$	ΔS_i	n=2	n=4
Non-ferrous metals	80	40	2	-0.3	-0.6	
o.w. copper	60	20	3	-0.1		-0.3
o.w. other	20	20	1	-0.2		-0.2
Stones and clay	15	60	0.25	0.3	-0.075	
o.w. cement	10	10	1	0.2		0.2
o.w. other	5	50	0.1	0.1		0.01
Total	95	100	0.95	0	-0.675	-0.301

Remarks: Absolute change decomposition with $\alpha_j = \beta_j = 0$, n = number of sectors.

This table gives two sectors: non-ferrous metals and stones and clays, which are both divided into two subsectors. So we could decompose with the two main sectors (n=2) or with all the four subsectors (n=4). The last two columns of this table give the outcome for decomposition for these two sector classifications. As can be seen from Table 3.1., enlargement of the sectors leads to a reduction of the intersectoral effect. The reason is that although the change in the value added shares is equal in both decompositions, the weights (the emission intensities) have been changed. Since the emission intensities of the subsectors do not add up to the sectoral emission intensities, there is in general not much to say about the development of the intersectoral effect if we enlarge the number of sectors: the results of decomposition are only valid for the level of sectoral disaggregation that is chosen [Ang 1993]. It should therefore be emphasized that we cannot conclude that the intersectoral changes are underestimated because the decomposition is conducted with a low level of sectoral disaggregation.

A possible way out to handle this problem is to analyse the shifts within sectors as *intrasectoral structural changes*. This would mean that we always conduct decomposition on a fairly aggregated level, but accompany this with a second step of decomposition in which we look more closely at the causes of change within the sectors. The intrasectoral changes are then decomposed into a number of technological changes

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[17] Emission intensities are defined as the ratio E_j/Y_j. If both emissions and value added in sector j are composed of the sum of emissions and value added in sector 1 and 2, the emission intensity of sector j is not composed of the sum of emission intensities in sector 1 and 2 (compare for example 4/8 does not equal 2/5 + 2/3).

(application of end-of-pipe technology, process improvements etc.) and a shift of the internal structure of the sector. This brings us into the topic of nested decomposition analysis, a topic that will be discussed in Chapter 5.

3.3.2. Decomposition of Time-Series

If data were available over a time period <0,1,2,..T> we could conduct decomposition analysis in two ways: we could decompose the total cumulative change between year 0 and T, or we could decompose the change between all the intermediate periods. Whereas the *total cumulative decomposition* provides us with one decomposition result of the developments between the base year and the end year, the *period-wise decomposition* provides us with numerous decomposition outcomes for all the intermediate years[18]. These time-series give us the developments of intersectoral and intrasectoral change over the time period considered.

Whether cumulative or period-wise decomposition should be applied depends on the questions that one wants to answer. It should be noted however that data collection for cumulative decomposition is much less cumbersome than for period-wise decomposition. The outcome of cumulative decomposition should however not be mistaken. Ang and Lee [1994] present data for Singapore where the intersectoral effect in cumulative decomposition between 1975 and 1990 is zero. However, when analysing period-wise decomposition (1975-1976, 1976-1977 etc.), there was proven to be a lot of structural shifts over the period considered.

In general, period-wise decomposition provides us with much more information than cumulative decomposition. One would like the sum of period-wise decomposition to add up to the outcomes of cumulative decomposition. Unfortunately, this is not the case. The intersectoral effects of cumulative decomposition do not equal the sum of intersectoral effects of period-wise decomposition. The same applies to intrasectoral effects. The reasons are similar to the ones discussed in the context of sector disaggregation: the weights do not remain constant over the time period. Take for example the intersectoral effects of a sector j between a time interval <0,1,2>. Using for simplicity absolute change decomposition with $\alpha_j = \beta_j = 0$, it is completely clear that:

$$U_{j,0}(S_{j,1}-S_{j,0})+U_{j,1}(S_{j,2}-S_{j,1}) \neq U_{j,0}(S_{j,2}-S_{j,0}) \qquad (3.15)$$

assuming that the emission intensity between year 0 and 1 has been changed for this sector. Since the weights are then not equal, the results from period-wise decomposition do not add up to the results of cumulative decomposition. So the sum of results from period-wise decomposition changes the division between intrasectoral and intersectoral effects compared to the results of cumulative decomposition (it biases the division).

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[18] We apply here a different terminology than employed in Ang & Lee [1994].

3.3.3. A Short Overview of Other Related Topics

Description Versus Explanation

Unlike regression analysis, decomposition provides only a *description* of changes in the economic system. It provides no *explanation* why for instance the intersectoral effects were much more pronounced than the intrasectoral effects. The influence of prices of copper on the emission/output ratio can hence not be determined by decomposition analysis. It has been suggested [De Bruyn and Van den Bergh, 1995] that if enough data were available over a long period of time, the results of decomposition analysis could be used in time-series analysis, such as ARIMA processes or co-integration [Enders, 1995]. We could then test whether price changes result in changes in the structure of the economy or in changes in the technology that is applied. This may provide us with an explanation on the observed components of the change in the emission/output ratio. Moreover, the application of time-series on the results of decomposition analysis may lead to more reliable estimates than the application of time-series on the emission/output ratio alone. As has pointed out by many authors [Auty, 1985; Mannaerts, 1993; De Bruyn et al., 1995, 1996 (*forthcoming*)] prices provide normally weak explanatory power in regression analysis on materials, energy and emissions. This may be improved if prices are regressed on the outcomes of decomposition analysis. The promising integration of decomposition with time-series analysis remains to be open for future research.

Constant Returns to Scale

As was pointed out by Wyckoff [1992], decomposition assumes that each industry's production process adheres to linear, or fixed, economies of scale. If a sector doubles its output but uses the same technology, this should have an effect only on the intersectoral effect. However, with increasing or decreasing returns to scale, part of the increase in production will be reflected in the intrasectoral effect.

Linked Effects and Input-Output Decomposition

Although decomposition based on sectoral data as described in this chapter is quite useful in order to address questions of structural change, some authors [Wyckoff, 1992; Skolka, 1989] advocated the use of input-output tables (see for a mathematical treatment Rose and Chen [1991]).

The main advantage of the use of input-output tables is that the indirect (linkage) effects on changes within one sector can be analysed. For example, a decline in the automobile industry will result in reduced demand for steel, aluminum and plastics. Hence the value added shares of these industries may decline. Decomposition with input-output tables correctly distinguishes between direct or linked effects and can also include import and export in the figures. This makes it possible to base decomposition on the structure of final demand, instead of on the structure of production as has been done in this paper. In environmental-economics literature, there is an emphasis to conduct studies based on consumption patterns instead of on production patterns [Opschoor and Reijnders, 1991; Pearce, 1993], since the consumption reflects the true "ecological footprint" or "ecological backpack" of a region or country.

Despite the clear advantages of using input-output tables in decomposition analysis, it is also clear that the data requirements are more restrictive. For these reasons, we do not conduct this kind of decomposition. Moreover, the problem of the allocation of the joint-effects in input-output decomposition is not yet solved.

3.4. Conclusions

Decomposition can be used as a quantitative tool to analyse in a comparative static way industrial transformation. It should be emphasized that the technique is only descriptive and that the here presented analysis lacks input-output structure which makes it difficult to trace back causes of change with respect to changing import/export conditions and structure of intermediate deliveries. These limitations are mainly due to the statistical data available for this study. With yearly data, the results of decomposition could be used in time-series regression analysis, while with the availability of input-output tables, causes of change could be traced back.

The main methodological problems with decomposition analysis are the a-priori choices that influence the division between intrasectoral and intersectoral effects. The researcher who wants to employ decomposition methods has to make the following choices:
(i) the choice for parameter values in the weighting functions;
(ii) the choice for the level of sector disaggregation;
(iii) the choice for cumulative decomposition results or the sum of period-wise decomposition results.

In this chapter we have summarized the various treatments for the choice of the parameter values in the weighting function. Based on the aim to minimize the residual term, we have described that a proportional allocation of the residual may offer a decomposition method where the data determine the choice for the parameter values. We will employ this proportional decomposition method in the next chapter in order to decompose the change in the emission/output ratio in Northrhine-Westfalia from 1955 to 1988.

4. Decomposition of Heavy Metals Emission Intensities in Northrhine-Westfalia (1955-1988)

In this chapter we apply the proportional decomposition method based on percentage changes (see Chapter 3.) in order to analyse intersectoral and intrasectoral changes within the economic system that led to the decline in atmospheric cadmium, lead and zinc emissions in Northrhine-Westfalia. While in this chapter mainly the level of total economy of Northrhine-Westfalia is looked at, changes within the individual sectors are discussed in Chapter 6. Possible explanations on the here observed developments will also be given in Chapter 6.

4.1. Description of the Methodology Employed

Decomposition methods based on percentage changes quantify the contribution of inter- and intrasectoral effects to changes in the emission/output ratio. To allocate the residual, which occurs as the inter- and intrasectoral effects normally do not add up to the total effects (see Chapter 3.1.1.), we follow the suggestion of De Bruyn and Van den Bergh [1995] to set the parameters of the weighting function α_j and β_j in such a way that the share of the residual added to each of the components is proportional to the size of the original inter- and intrasectoral effects (see Chapter 3.2.2.). That is, the values for α_j and β_j are based on the relative changes of the variables U_j and S_j. This results in the proportional decomposition method as described in Chapter 3.

4.1.1. Data and Sectoral Decomposition

IIASA's Rhine Basin Project determined inter alia the atmospheric heavy metal emissions caused by a variety of productions, namely of copper, zinc and lead, of coke, cement, iron and steel and electricity for the time period of 1955 to 1988 (see Annex B.1. for data description). The major part of atmospheric cadmium, lead and zinc emissions is covered by these productions.

In order to employ the decomposition method we decided to match the emission data with the economic data of value added. We chose value added instead of e.g. gross production data as it excludes the costs of intermediate inputs and thus does not result in double counting when adding up figures for various sectors.

Gross Value Added (GVA) data however are available only on sectoral level, but not on the level of individual products. Therefore, the emission data of the various non-ferrous metals have to be added up to the non-ferrous metals sector in order to match it with the sectoral level of GVA data. Thus, we employ the decomposition analysis to seven sectors: electricity production, coal-mining, chemical industry[19], stones and clays, iron

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[19] Regarding the chemical industry only the emissions caused by the production of electricity within this sector are taken into account (see Annex B.1.2.).

and steel, non-ferrous metals production and other industry[20]. Concerning the aggregate sector "other industry" we assume that its emissions are zero.

As has been shown in Chapter 3.3.1., the results of the decomposition method depend on the level of sector disaggregation, that is on the number of productions/sectors investigated. As a disadvantage of the chosen level of sector classification the main effects occur in only one sector, the non-ferrous metals sector, so that the total outcome is heavily influenced by the development of this sector. This shows the disadvantage of one big sector in the sector disaggregation. Unfortunately the economic data necessary for a more disaggregated investigation are not available.

4.1.2. Presentation of the Results

Decomposition results can be presented in a cumulative or period-wise manner (see 3.3.2.). From the data, we have observations for 8 periods in time: 1955, 1960, 1965, 1970, 1975, 1980, 1985 and 1988. Investigating the contribution of intersectoral and intrasectoral effects to changes in the emission/output ratio we look first at total effects - i.e. the summed effects for all sectors over this time-period. The graphs in this chapter contain two time-series: (i) cumulative decomposition as the results of decomposition between a fixed base year (1955) and subsequent end-years, and (ii) period wise decomposition that describes the changes that took place within each 5-year period investigated (1955-1960, 1960-1965, ..., 1985-1988).

Additionally, we discuss the contribution of each sector to the cumulative total result over the time period 1955-1988. It is clear that sectors with high emission intensities or high value added shares will have a greater contribution to the total results than sectors with low emission intensities or low value added shares. So the sectoral *contributions* to the total emission/output ratio should not be confused with relative reductions achieved within sectors (as explained in Figure 3.1.). The relative reductions achieved within sectors are topic of Chapter 6.

4.2. Cadmium Emissions

Cumulative Total Effects

The emission/output ratio (of the total industry) declined by about 97% between 1955 and 1988 (see Figure 4.1.). This was the result of a high decrease (-110%) of emission intensities due to intrasectoral change, which overcompensated increases due to intersectoral change (+15%).

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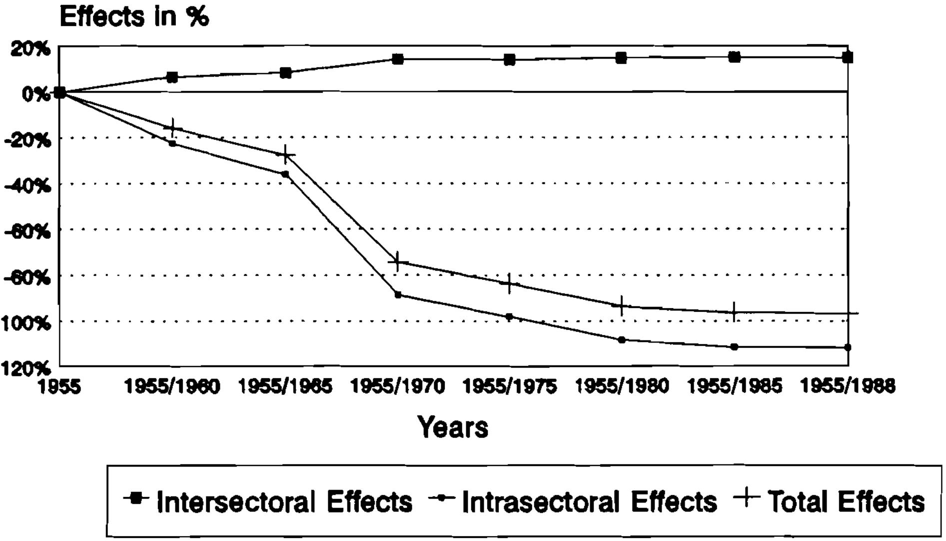
[20] It should be noted that this sectoral classification is broader than the production classification, i.e. within the sectors many productions are included that do not cause heavy metal emissions. Matching emission data of a lower classification with value added data of a higher classification may lead to errors in the results as the development of GVA of one production may diverge from the development of GVA of the total sector in which the respective production is located.

Figure 4.1. Decomposition Results: Cadmium, Cumulative Effects



Sectoral Effects

As can be seen from Table 4.1., this increase in emissions due to *intersectoral change* was mainly determined by the rising value added share of the non-ferrous metals industry. A decrease in the value added share in 1988 compared to 1955 occurred in the industries of coal mining, stones and clays and iron and steel.

All sectors contributed to the decline in emission intensities (*intrasectoral change*). However, the main reductions were achieved by changes within the non-ferrous metals industry and to a lesser extent within the electricity production and the iron and steel sector. All sectors contributed to the decline in the emission/output ratio, as can be seen from the sum of intersectoral and intrasectoral effects. Most important however was the development of the non-ferrous metals industry and - to a considerably less extent - of the iron and steel industry and electricity production.

Table 4.1. Sectoral Decomposition Results: Cadmium

	Intersectoral 1955/88	Intrasectoral 1955/88	Sum Effects 1955/88
Non-Ferrous Metals	15.6%	-101.8%	-86.2%
Iron/Steel	-0.9%	-3.7%	-4.5%
Electricity Production	2.1%	-4.8%	-2.8%
Coal-Mining	-1.7%	-0.4%	-2.1%
Stones/Clays	-0.2%	-0.8%	-1.0%
Chemical Industry	0.2%	-0.5%	-0.3%
Total Industry	15.1%	-112.0%	-96.9%

Period Wise Total Effects

Figure 4.2. indicates that the main reductions of emission intensities due to intrasectoral changes took place in the periods of 1965 to 1970 and 1975 to 1985.

Figure 4.2. Decomposition Results: Cadmium, Period Wise

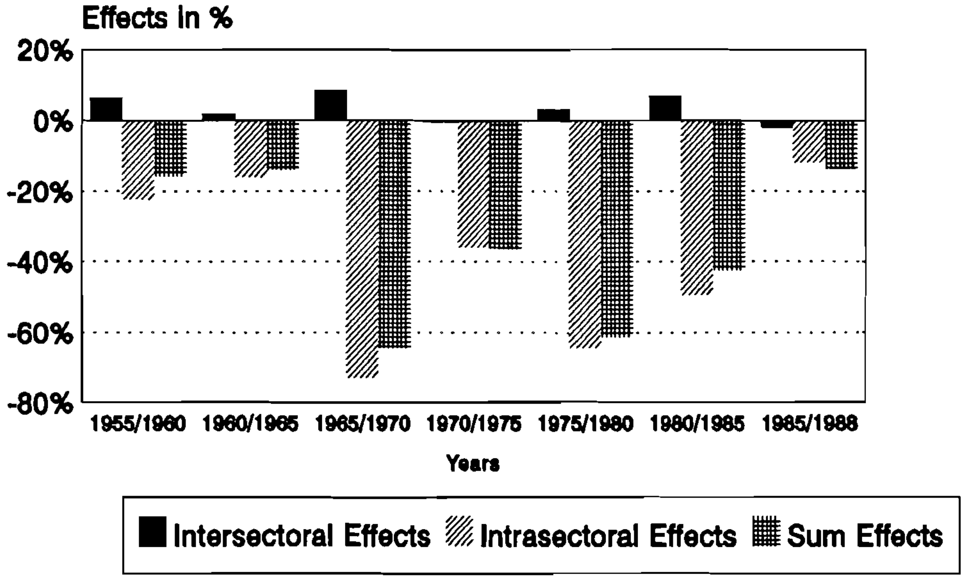


Figure 4.2. also shows that the influence of intersectoral change on emission intensities was positive for all periods except for the years 1970 to 1975 and 1985 to 1988. It is interesting that in these years with intersectoral decreases, the intrasectoral decreases were rather modest.

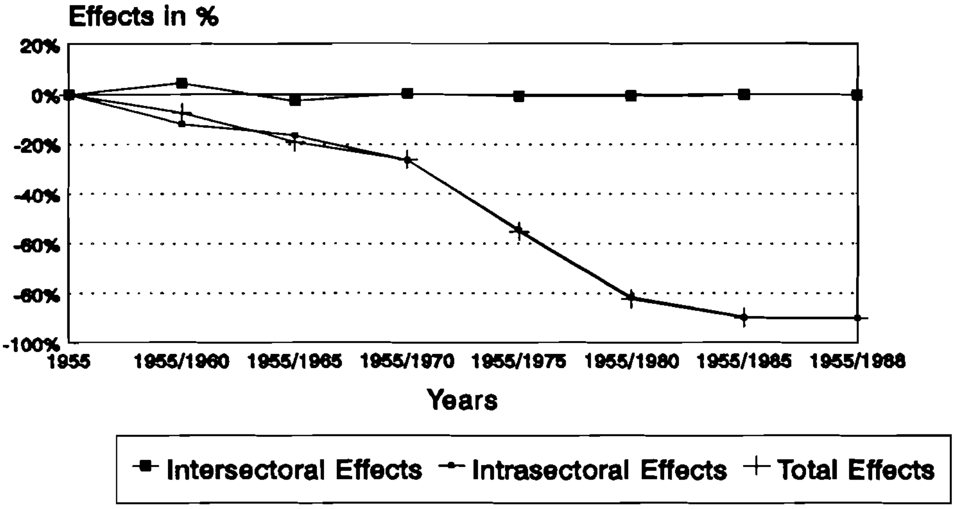
This regularity, which was also found in decomposition of energy intensities in the Dutch economy [De Bruyn and Van den Bergh, 1995] deserves closer attention in further research. One possible explanation may be that dirty industries in decline lack financial capabilities to invest in clean technologies and that hence the pace of intrasectoral changes is slowed down.

4.3. Lead Emissions

Cumulative Total Effects

The emission/output ratio for lead declined between 1955 and 1988 by 90% (see Figure 4.3.). Changes in emission intensities due to intersectoral change reached values only slightly below zero and thus were hardly of any importance. Accordingly, the decline in the emission/output ratio was almost totally explained by intrasectoral change.

Figure 4.3. Decomposition Results: Lead, Cumulative Effects



Sectoral Effects

There has been an increase in the effects of *intersectoral change* due to the growing share of the non-ferrous metals production in total value added which has been overcompensated however by declines in sectoral shares of the industries of iron and steel, stones and clays and coal mining (see Table 4.2.).

Table 4.2 Sectoral Decomposition Results: Lead

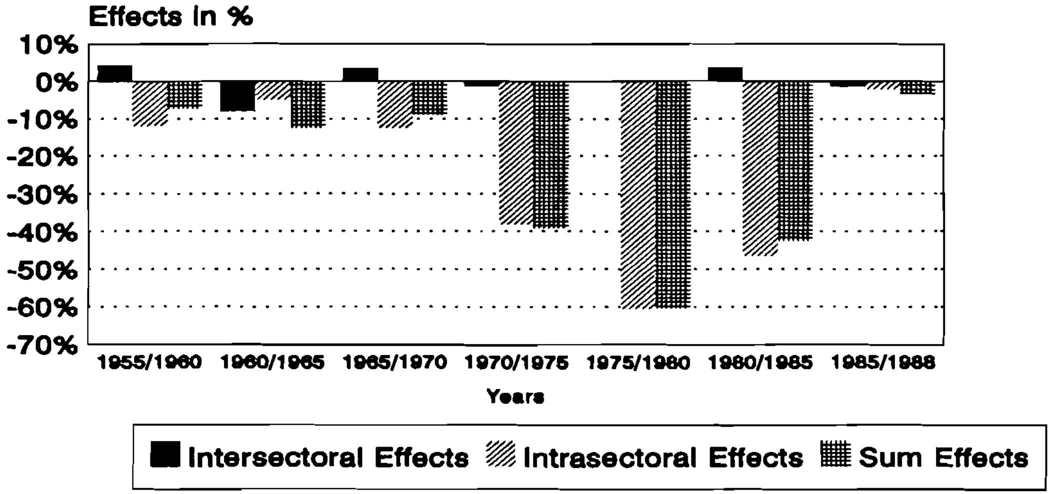
	Intersectoral 1955/88	Intrasectoral 1955/88	Sum Effects 1955/88
Non-Ferrous Metals	7.2%	-43.0%	-35.9%
Iron/Steel	-7.7%	-38.7%	-46.4%
Electricity Production	2.1%	-5.5%	-3.4%
Coal-Mining	-1.7%	-0.4%	-2.1%
Stones/Clays	-0.4%	-1.8%	-2.2%
Chemical Industry	0.3%	-0.6%	-0.3%
Total Industry	-0.2%	-90.0%	-90.2%

Again all sectors contributed to the declines in emission intensities due to *intrasectoral change*. Most important were changes within the non-ferrous metals industry and the iron and steel industry. Also the *sum effects* were negative for all sectors. Of highest importance for the decline in the emission/output ratio was the iron and steel industry, but the non-ferrous metals industry also contributed strongly to this development.

Period Wise Total Effects

With regard to lead emissions the influence of intersectoral change on emission intensities has been negative for the periods of 1960 to 1965, 1970 to 1975 and 1985 to 1988 (see Figure 4.4.). The main reductions of emission intensities due to intrasectoral changes in order of magnitude took place in the periods of 1975 to 1980, 1980 to 1985 and 1970 to 1975.

Figure 4.4. Decomposition Results: Lead, Period Wise Effects

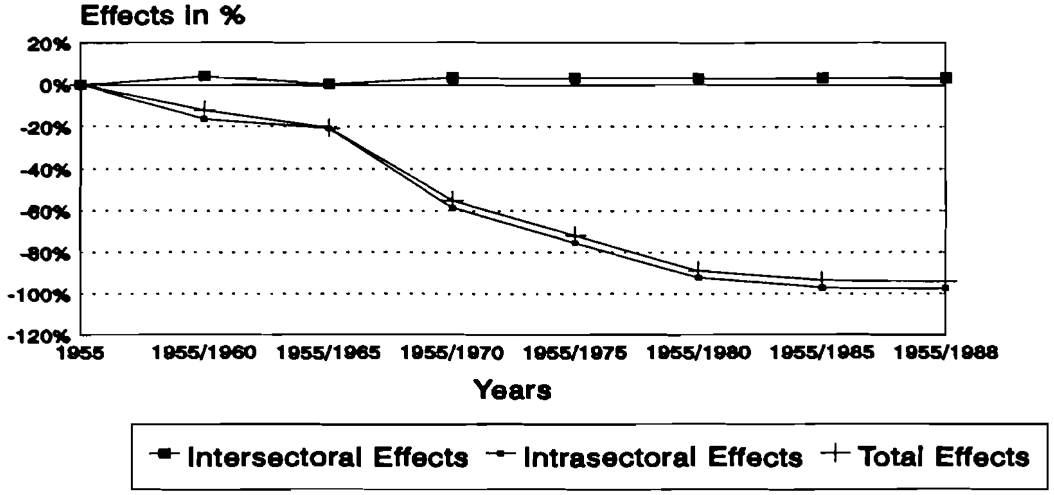


4.4. Zinc Emissions

Cumulative Total Effects

As in the case of lead emissions, the influence of intersectoral change on the development of the emission/output ratio between 1955 and 1988 was of little importance.

Figure 4.5. Decomposition Results: Zinc, Cumulative Effects



The emission intensities grew due to intersectoral change by somewhat about 3% only. There was a contribution of changes of emission intensities due to intrasectoral changes of around -98%, the sum effect (emission/output ratio) shows a decline of -94%.

Sectoral Effects

The positive *intersectoral effects* were again mainly influenced by an increase in the value added share of the non-ferrous metals sector which was only partly compensated by declines in the value added shares of the iron and steel, stones and clays and coal mining industries (see Table 4.3.).

Table 4.3 Sectoral Decomposition Results: Zinc

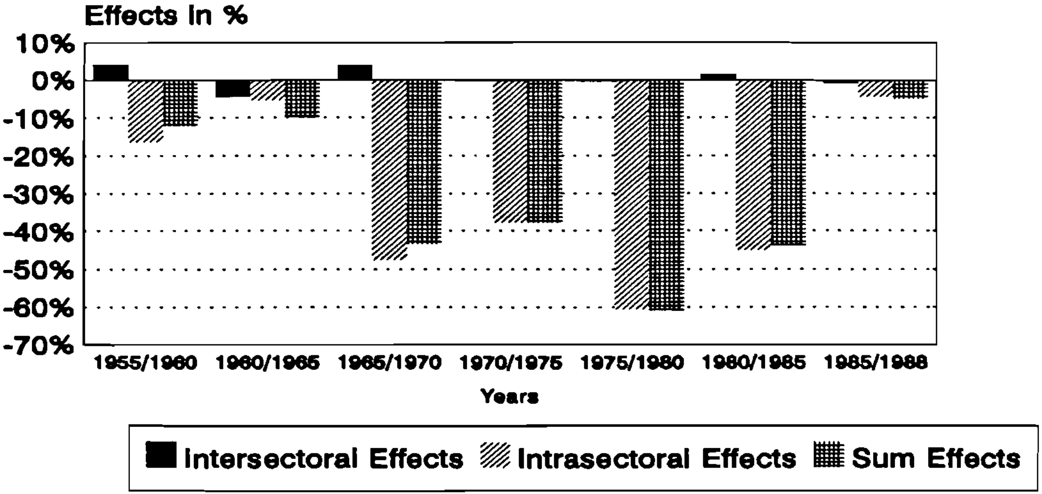
	Intersectoral 1955/88	Intrasectoral 1955/88	Sum Effects 1955/88
Non-Ferrous Metals	10.0%	-65.2%	-55.2%
Iron/Steel	-4.8%	-23.9%	-28.7%
Electricity Production	1.1%	-2.8%	-1.7%
Coal-Mining	-2.2%	-0.7%	-2.9%
Stones/Clays	-0.9%	-4.7%	-5.6%
Chemical Industry	0.1%	-0.3%	-0.2%
Total Industry	3.4%	-97.6%	-94.2%

Most important for the decrease in the emission intensity due to *intrasectoral change* were - apart again from the changes within the sector of non-ferrous metals - the iron and steel production and with considerably lower importance changes within the stones and clays sector and the electricity production. Again the decline in the emission/output ratio was mainly influenced by the development of the non-ferrous metals production and the iron and steel industry.

Period Wise Total Effects

Figure 4.6. shows that the most important intrasectoral changes occurred in the years 1965 to 1985, in particular in the period of 1975 to 1980. Intersectoral change contributed to the decline in the emission/output ratio in the periods of 1960 to 1965, 1970 to 1975, 1975 to 1980 and 1985 to 1988.

Figure 4.6. Decomposition Results: Zinc, Period Wise Effects



4.5. Conclusions

The application of the proportional decomposition method for an investigation of industrial transformation and the identified reductions in atmospheric heavy metal emissions in Northrhine-Westfalia between 1955 and 1988 showed that intrasectoral change dominated the development of emissions. Only in regard to lead emissions intersectoral change contributed slightly to the decline in the emission/output ratio. All sectors contributed to the decline of emissions due to intrasectoral effects. Most important were the industries of non-ferrous metals and iron and steel and - in regard to zinc emissions - also the stones and clays industry. Of lower importance but still significant were also changes within the electricity production. The intersectoral effects were dominated by the growth of the non-ferrous metals industry. Altogether the analysis shows that the development of the non-ferrous metals sector influenced the total effects to a great extent.

The analysis also showed that the main reductions in the emission/output ratio due to intrasectoral change were achieved in the period between 1965 and 1985 for atmospheric cadmium and zinc emissions, where the changes were most significant between 1965 and 1970 as well as 1975 and 1980. Concerning atmospheric lead emissions the main reductions were achieved in the periods between 1970 and 1985, where the highest reductions occurred between 1975 and 1980.

The results in this chapter show that there is no support for viewing structural change as an important determinant of the decline of the emission/output ratio, given our level of sector classification. The fact that all reductions were due to intrasectoral changes suggests that these were achieved by improvements of technology or by structural shifts in productions within sectors (intrasectoral structural shifts). In order to determine the different types of technological change and intrasectoral structural shifts, we will develop in Chapter 5. a framework that can be used in quantitative analysis.

5. Determinants of Change of Sectoral Emission Intensities: Material Flow Analyses

As we saw in the previous chapter, intrasectoral changes explained to a large extent the changes in the emission/output ratio. In this chapter, the determinants of these intrasectoral changes will be described.

Intrasectoral changes are the weighted changes in the sectoral emission intensities. The emission intensity of a sector j is simply the division of the emissions (E_j) over the value added (Y_j). Basically, these both variables have a loose connection to each other. Emissions are only through a couple of intermediate steps related to value added. In this chapter we analyse these intermediate steps with the aid of a simple material flow model. A detailed description of the material flows through the industrial economy shows the ways in which the inputs of materials and energy are transformed into emissions. If these material flow analyses are linked to economic variables, the emissions can be described as a function of the sectoral value added.

5.1. A Simple Model of Intrasectoral Change

In order to clarify the determinants of sectoral emission intensities, we can think of describing the sector j, as the sum of k=1..n productions. Each of these k productions produces one homogenous product, Q_k which is produced with the use of capital (K_k), labour (L_k) and physical inputs of i=1..m materials, energy and intermediate products, which we assume to aggregate to I_k. As an unwanted side-effect, emissions E_k occur which include emissions to air, water and the generation of process waste. We assume that we can count both Q_k as I_k in physical terms (i.e. in tonnes). Given the productions under investigation in this project (steel, energy, copper, zinc, lead, cement and coke), this is not an unlikely assumption.

The emissions are normally seen as some function of quantity and quality of the inputs of the production process [Jänicke et al., 1989], while the value added is related to the quantity and quality of the amount of products Q_k that is produced. So the relationship for the emission intensities of producing product k is set up by two different functions:

$$E_k = f(I_k) \quad \wedge \quad Y_k = g(Q_k) \tag{5.1}$$

In order to more precisely describe these functions and their interrelations we describe the production process by using a production function, as specified in economic theory. Unlike economic theory, however, we embody production firmly into a material balance approach.

5.1.1. Production Functions and Value Added

In economic theory, the relation between the products produced and the inputs is set by the production function. The production function of producing product k can be set up in many forms, but simply using the Cobb-Douglas form will yield at any point of time:

$$Q_k = A(K_k^{\gamma_1} L_k^{\gamma_2} I_k^{\gamma_3}) \qquad \text{with } \gamma_1, \gamma_2, \gamma_3 > 0 \;\wedge\; \gamma_1 + \gamma_2 + \gamma_3 = 1 \tag{5.2}$$

where the γ's represent the elasticity of output with respect to the specific inputs. The constant A can be seen as the efficiency factor and represents the state of the technology. Under conditions of perfect competition, there are no profits so that the total sales equal the prices paid to the factors of production:

$$p_k Q_k = wL_k + rK_k + cI_k \tag{5.3}$$

where p_k is the price of product k and w, r and c respectively are the wage level, rent and costs of inputs.

The *value added*, Y_k, is however made up by the sales minus the costs of inputs of materials, energy and intermediates:

$$Y_k = p_k Q_k - c_k I_k \tag{5.4}$$

From this it follows that value added is only influenced by the amount of labour and capital and their prices:

$$Y_k = wL_k + rK_k \tag{5.5}$$

This analysis shows that given a certain number of products Q_k, the value added can only increase by substitution of inputs of material, energy and intermediates for labour and capital. Changes in the ratio Q_k/Y_k then give an indicator of the amount of this substitution and we denote this ratio as the *physical intensity of production*. It gives an indication on how much of the physical products is needed to produce a given level of monetary output. In general, most products nowadays incorporate more knowledge and less material content than twenty years ago. For several products, the share of material costs in the total costs has become increasingly smaller [Auty, 1985]. This is even true for producers of raw materials, such as steel, since scientific research has resulted in high quality steels regarding strength and moulding [McSweeney and Hirosako, 1991]. So there is some partial evidence that γ_3 has decreased considerable over time, while A has increased considerably (see also [Dasgupta and Heal, 1979; Wadell and Labys, 1988]). On the other hand, Cleveland [1988] presents figures that suggest that γ_3 of energy inputs has increased significantly in the mining sector leading to substitution of labour for energy.

The efficiency factor A in equation (5.2) is normally believed to specify the rate of autonomous technological progress. However, the possibilities of technological progress are not equal for all the inputs in the production function. The transformation of inputs of material and energy into physical products Q_k is bounded by the natural laws (a transformation that is 100% efficient cannot be improved), whereas improvements in for example labour productivity are not so clearly limited. It is therefore very likely that technological progress also influences the elasticities of substitution over time towards more material savings [Dasgupta and Heal, 1979].

5.1.2. Materials and Energy Substitution

Besides substitution of labour and capital for materials and energy, substitution may also occur within the group of material and energy inputs. We can distinguish between three types of substitution: (i) substitution between materials inputs; (ii) substitution between energy carriers; (iii) substitution between energy and materials. The first type can occur for reasons of process-efficiency or product design, while the latter two types will be mainly induced by process considerations.

Reasons for substitution of materials and energy will normally be cost-induced. Each producer aims at the minimization of the costs of material and energy inputs, subject to the condition that output does not change:

$$\begin{aligned} &\textit{minimize} \quad cI_k = \sum_{i=1}^{m} c_i I_{i,k} \\ &s.t. \quad Q_k(K_k, L_k, I_k) = Q_{k,0} \end{aligned} \qquad (5.6)$$

Since material and energy costs are not incorporated in the value added, the physical intensity of production (the ratio Q_k/Y_k) is not affected by a substitution of materials as long as material substitution does not result in a change in γ_3 (the elasticity of output with respect to material/energy input) or in a change in A (the efficiency factor). The question whether materials substitution has contributed to a decline in the physical intensity of production needs more attention in future research.

5.1.3. The Efficiency Factor in a Mass Balance Context

The efficiency of transforming the $I_{i,k}$ material and energy inputs into products is determined by the efficiency of the processes that are applied in the production of Q_k. The total *input* of materials and energy i is not equal to the physical outputs Q_k as transformation losses occur during the production process. In the production function, these transformation losses are determined by the technological coefficient A. We want here to interpret this technological coefficient with respect to materials in a mass balance context so that the economic model presented above is consistent with conservation of mass[21].

In order to determine the efficiency of transformation, we have first to define the material composition of the final product Q_k. As noted above, we define Q_k in physical units, such as tonnes or MWh. Sometimes the product Q_k consists only of one material

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[21] A general criticism of economic models is that they lack a mass balance context and therefore may be in conflict with physical laws [Ayres & Kneese, 1969].

(for example cement, copper, zinc etc), but in many cases (such as steel or consumer products) Q_k consists of more materials. If we define the amount of material i embodied in product k as $Q_{i,k}$, we can define the total physical unit of Q_k as the sum of its components, i.e. the embodied materials:

$$Q_k = \sum_i Q_{i,k} \tag{5.7}$$

The efficiency of transforming the input of material i into products can then be given by the efficiency coefficient $a_{i,k}$:

$$Q_{i,k} = a_{i,k} I_{i,k} \qquad 0 \leq a_{i,k} \leq 1 \tag{5.8}$$

Because of the First Law of Thermodynamics (conservation of mass), $a_{i,k}$ cannot exceed unity. The efficiency of production can be seen as being a function of process technology as well as recycling techniques for the process wastes. The ratio Q_k/I_k gives the transformation efficiency.

The mass balance comes in when comparing the inputs with the materials embodied in the products:

$$I_{i,k} = Q_{i,k} + E_{i,k} \tag{5.9}$$

The differences between the inputs of material i and the amount of material i embodied in the product are the emissions due to the use of material i. Emissions are here interpreted in a broad sense and include emissions to air and water and the generation of solid waste during the production process. To distinguish the emissions to the several compartments we can add a subscript c with c = 1,2,3 for air, water and solid waste:

$$E_{i,k} = \sum_c E_{c,i,k} \tag{5.10}$$

The amount of emissions caused by a certain production depends in general on three factors: (i) the efficiency of the process technology; (ii) the application of end-of-pipe technologies for water and air emissions and of recycling techniques for process wastes, and (iii) the total quantity of inputs that enter the production process. If we choose $b_{c,i,k}$ as the parameter representing the state of the process and end-of-pipe technologies that is applied, we can describe the relationship between inputs and emissions as:

$$E_{c,i,k} = b_{c,i,k} I_{i,k} \qquad 0 \leq b_{c,i,k} \leq 1 \tag{5.11}$$

Another interpretation of the parameter $b_{c,i,k}$ is the *emission coefficient of the inputs of production*.

A different way to calculate emissions, is to use emission coefficients of the *output of production* (which has been used in this study, see Annex B). Dividing every element in the mass balance equation (5.9) by $Q_{i,k}$ and summing over all the i materials yields the following emission coefficients of the output of production:

$$\frac{E_{c,k}}{Q_k} = \sum_i \frac{E_{c,i,k}}{Q_{i,k}} = \sum_i \frac{I_{i,k}}{Q_{i,k}} - 1 \qquad (5.12)$$

It appears that the emission coefficients of production output are determined by the inverse of the transformation efficiency. The emission coefficients of the output of production themselves can be rewritten as a function of the emission coefficients of the output of production and the inverse of the transformation efficiency:

$$\frac{E_{c,k}}{Q_k} = \sum_i \frac{E_{c,i,k}}{I_{i,k}} \frac{I_{i,k}}{Q_{i,k}} = \sum_i a_{i,k}^{-1} b_{c,i,k} \qquad (5.13)$$

For air emissions, the emission coefficient of production thus changes as the result of (i) application of end-of-pipe technology; (ii) improvements in the process technology and (iii) improvements in the overall efficiency of the technology. Material substitution may also lead to a decrease in the emission coefficients of production if materials with high emission coefficients are being substituted by materials with low emission coefficients. For example, the substitution of coal for oil results in a decline in emissions if:

$$a_{c,oil,k} b_{oil,k}^{-1} < a_{c,coal,k} b_{coal,k}^{-1} \qquad (5.14)$$

Similar relations can be set up with respect to the substitution of material inputs by recycled inputs. There is some evidence that the increased use of recycled inputs has led to an increase in heavy metal emissions because of the higher degree of heavy metal impurities in recycled inputs (such as paint). In this model this shows if the emissions per unit of input for recycled materials are higher than for primary (virgin) materials (i.e. $b_{c,i,k}$ is higher for recycled materials).

We can incorporate the effects of material and energy substitution by using equations (5.12) and (5.13) and rewrite the emission coefficient of production in the following way:

$$\frac{E_{c,k}}{Q_k} = \sum_i \frac{E_{c,i,k}}{I_{i,k}} \frac{I_{i,k}}{Q_{i,k}} \frac{Q_{i,k}}{Q_k} \qquad (5.15)$$

where in dynamic analysis, the last term on the right hand side depicts the substitution of materials in the product k. In the case of substitution of energy carriers, we encounter a problem using equation (5.15) since energy used for fuel combustion is not embodied in the final product. Here we may set up a different equation for describing the emission coefficient:

$$\frac{E_{c,k}}{Q_k} = \sum_i \frac{E_{c,i,k}}{I_{i,k}} \frac{I_{i,k}}{I_k} \frac{I_k}{Q_k} \qquad (5.16)$$

The second term on the right hand side then determines the influence of fuel substitution on the emission coefficient of production, while the last term determines the energy-efficiency for producing a given amount of Q_k.

5.2. Nested Decomposition Analysis

While we could, by assigning cost-functions to technological improvements, use the above developed model for optimization, we are in this study mainly interested in descriptive analysis in order to assess the components of change in the sectoral emission intensities. In the model developed above, we described the relation between the emission intensities of producing *product* k as the function of two components, (i) the physical intensity and (ii) the emission coefficient of production. These two components influence changes in the emission intensity of product k, which can be labelled as intrasectoral technological changes[22]:

$$\frac{E_k}{Y_k} = \frac{E_k}{Q_k} \cdot \frac{Q_k}{Y_k} \tag{5.17}$$

In a *sector* j, however, many productions take place. The non-ferrous metals sector, for example, produces zinc, copper, aluminium, etc. A shift in value added shares of these productions has a consequence on the *sectoral* emission intensities, which have been identified as a major source of the change in the emission/output ratio in Northrhine-Westfalia (see Chapter 4). In order to distinguish intrasectoral structural shifts (shifts of value added shares of productions within a sector) from the above defined intrasectoral technological shifts, we can set up the following identity:

$$\frac{E_j}{Y_j} = \sum_k \frac{E_{j,k}}{Y_{j,k}} \frac{Y_{j,k}}{Y_j} \tag{5.18}$$

Changes in the second ratio on the right hand side of equation (5.18) then express intrasectoral structural shifts.

Combining (5.16), (5.17) and (5.18), we can describe the change in the sectoral emission intensities as the product of five ratios:

$$\frac{E_j}{Y_j} = \sum_i \sum_k \frac{E_{i,j,k}}{I_{i,j,k}} \frac{I_{i,j,k}}{I_{j,k}} \frac{I_{j,k}}{Q_{j,k}} \frac{Q_{j,k}}{Y_{j,k}} \frac{Y_{j,k}}{Y_j} \tag{5.19}$$

If all data for the variables described in equation (5.19) were available, we could use decomposition analysis in order to assess the change in each of these ratios. It is here that we encounter a new difficulty when applying decomposition analysis: the residual term tends to become quite substantial when decomposing more than two variables. The reason is that the number of interaction terms increases exponentially with the number of terms to be decomposed. While we have shown that decomposition with two variables, say $y = ab$, will yield one interaction term, Park [1992] has shown that decomposition with three variables ($y = abc$) already results in four interaction terms: one interaction term consisting of the change in every variable and three interaction terms consisting of the level of one variable and the change in the two others. Similarly, it can be shown that decomposition with 4 variables will result in 9 and decomposition with 5

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[22] Since we focus in this study only on air emissions we will in the following neglect the subscript c.

variables in 16 interaction terms. A large residual term would eventually defeat the purpose of decomposition, which aims to disentangle single effects and not a number of 16 joint-effects [Ang and Lee, 1994].

The methodology presented in Chapter 4 to proportionally allocate the interaction term to both effects is not applicable for more than two variables. It seems not possible to develop an algorithm that can decompose all these terms in a proportional manner.

A possible solution out of the problem how to allocate the interaction terms in the case of more than two variables, is to apply *nested* decomposition analysis with a proportional allocation of the residual. Nested decomposition analysis takes every time two ratios, applies the decomposition analysis, and then tries to explain the variation in one of the decomposed variables as the change in another two variables.

Decomposing (5.19) in a nested manner, we may first distinguish between intrasectoral structural shifts and intrasectoral technological shifts, as defined in (5.18). Using proportional decomposition methods, this would result in decomposing the sectoral emission intensities into (i) weighted changes in the structure of the sector (intrasectoral structural shifts) and (ii) weighted changes in the emission intensity of producing product k (intrasectoral technological shifts). Analogous to the analysis in Chapter 3, this would result in two weighting functions: w_{is} for describing the time path of the variable $Y_{j,k}/Y_j$ and w_{it} for describing the time path of the variable $E_{j,k}/Y_{j,k}$:

$$w_{it} = E_{j,k,0}/Y_{j,k,0}+\alpha_j(E_{j,k,T}/Y_{j,k,T}-E_{j,k,0}/Y_{j,k,0}) \qquad ,0 \leq \alpha_j \leq 1 \qquad (5.20)$$

$$w_{is} = Y_{j,k,0}/Y_{j,0}+\beta_j(Y_{j,k,T}/Y_{j,T}-Y_{j,k,0}/Y_{j,0}) \qquad ,0 \leq \beta_j \leq 1 \qquad (5.21)$$

where the parameters α_j and β_j can be analogous to equations (3.11) and (3.12) defined for a proportional allocation of the interaction term. The weightings can then be used in for example absolute change decomposition of the sectoral emission intensities:

$$\frac{E_{j,T}}{Y_{j,T}}-\frac{E_{j,0}}{Y_{j,0}} = \sum_k w_{it}(\frac{Y_{j,k,T}}{Y_{j,T}}-\frac{Y_{j,k,0}}{Y_{j,0}}) +\sum_k w_{is}(\frac{E_{j,k,T}}{Y_{j,k,T}}-\frac{E_{j,k,0}}{Y_{j,k,0}}) \qquad (5.22)$$

The first term on the right hand side of (5.22) describes the intrasectoral structural shifts, while the second term describes the intrasectoral technological shifts. In a next step these intrasectoral technological shifts could be decomposed into changes in emission coefficients and changes in physical intensity of production, as defined in (5.17). Similar to the analysis above, this would yield two weighting functions, w_{ec} and w_{pi}, where w_{ec} describes the path of the emission coefficients $(E_{j,k}/Q_{j,k})$ and w_{pi} describes the path of the physical intensity of production $(Q_{j,k}/Y_{j,k})$. This would then yield the following decomposition result for the emission intensity of product k:

$$\frac{E_{j,k,T}}{Y_{j,k,T}}-\frac{E_{j,k,0}}{Y_{j,k,0}} = w_{ec}(\frac{Q_{j,k,T}}{Y_{j,k,T}}-\frac{Q_{j,k,0}}{Y_{j,k,0}}) +w_{pi}(\frac{E_{j,k,T}}{Q_{j,k,T}}-\frac{E_{j,k,0}}{Q_{j,k,0}}) \qquad (5.23)$$

The first term on the right hand side of (5.23) then describes the changes in the physical intensity of production, while the second term gives the changes in the emission coefficients of production k.

Notice now that the left hand side of (5.23) exactly equals the last term on the right hand side of (5.22). So we could fill (5.23) in (5.22) in order to asses the influence of changes in the emission coefficients and physical intensity of *production* k on the emission intensities of *sector* j. Notice that we then get a double weighting for the change in the emission coefficients and changes in the physical intensity. So for example the change in the emission coefficients would then be weighted by $w_{ec}w_{is}$. This procedure may be called "nested decomposition analysis". According to similar procedures, the change in the emission coefficients could further be decomposed according to (5.16).

Applying the proportional decomposition method in a nested manner, equation (5.19) is fully decomposed into changes in each ratio and all interaction terms have vanished. It should be noted however, that the division of the effects is sensible to the hierarchy of nesting: i.e. the decision on which step of decomposition is to be taken first in the nested decomposition analysis influences the division of the components of change in the sectoral emission intensities. There seems no logical arguments in favour of one or another hierarchy. This unsatisfactory situation deserves closer attention in future research.

5.3. Conclusions

In this chapter we looked at the determinants of intrasectoral change. Emissions and value added proved to be linked to each other through a number of intermediate steps. We distinguished five sources of intrasectoral change, as set up by the identity (5.19). Changes in one ratio or a combination of ratios can describe adequately the sources of intrasectoral change that are found in the literature. We develop here the following classification scheme, that will be employed in the analysis of Chapter 6:

1. Changes in the application of end-of-pipe technology.

This can be measured by the weighted changes in the emission coefficients of the inputs $(E_{i,j,k}/I_{i,j,k})$.

2. Substitution of the inputs (material and energy substitution).

This can be measured by the weighted changes in the ratio $I_{i,j,k}/I_{j,k}$. If materials with a lower emission coefficient are substituted for materials with a higher emission coefficient, this will yield to a decrease in emissions (ceteris paribus).

3. Process related technological changes.

If the technological change leads to a reduction of the use of materials and energy, this will show up in a decrease in the ratio $I_{j,k}/Q_{j,k}$. If the process related technological changes have also consequences for emissions, this will result in changes in the ratio

$E_{j,k}/Q_{j,k}$. Process modifications and good housekeeping are in general mentioned to decrease process related emissions.

4. Product related technological and structural changes.

Product related technological changes may reduce the material content of the products: the physical intensity of production can decline by substituting labour and capital for materials and energy. This will result in a decrease of the ratio $Q_{j,k}/Y_{j,k}$ and is also called dematerialisation [Herman et al., 1989]. Product related structural changes consists of changes in the relative shares of productions within sectors and can be given by changes in the ratio $Y_{j,k}/Y_k$.

To the extent that data are available, we will analyse in the next chapter, quantitatively the consequences of each of these changes for the development of the sectoral emission intensities. For the many cases that no data are available, we will use more qualitatively descriptive analysis by investigating the literature on technological changes and federal programs.

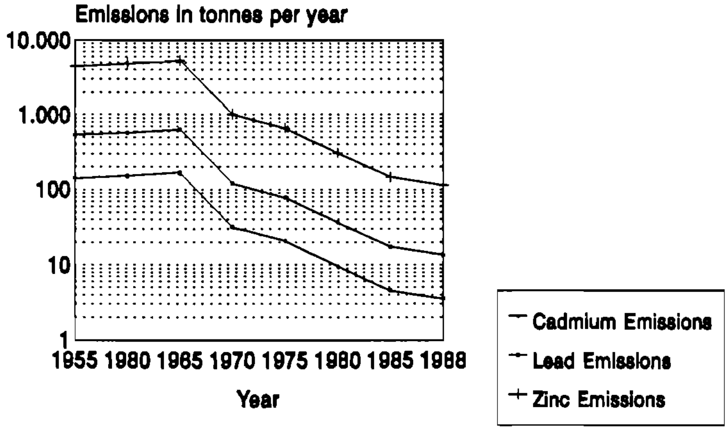
6. Sectoral Analysis

The decomposition analysis in Chapter 4 has shown, that intrasectoral change (measured as the weighted changes in sectoral emission intensities) was the major cause for emission reductions in Northrhine-Westfalia. In Chapter 5, we showed that changes in sectoral emission intensities may be due to different developments within sectors and productions. Hence, we need a sectoral approach in order to clarify the determinants of change behind the significant decline in the emission/output ratio in Northrhine-Westfalia. In this chapter we will empirically analyse in more detail the developments of the industrial sectors most relevant for atmospheric heavy metal emissions. We will employ three approaches of investigation for each individual sector.

In a first step we will look more closely at the percentage changes of emissions, emission intensities and value added shares of the individual *sectors* between 1955 and 1988. These outcomes diverge from the results of the decomposition analysis in Tables 4.1. to 4.3. where the changes in emission intensities and value added shares are weighted which is a central characteristic of decomposition analysis. In Chapter 4 we found that the contribution of the non-ferrous metals sector to the development of the emission/output ratio was very significant, while the contributions of the other sectors were relatively small. However, this does not mean that there were no distinct changes in the emissions over time within each of these industries. These changes are subject of this chapter.

In a second step we will investigate the development of heavy metal emissions in relation to individual *productions* highly important for the emission of heavy metals. In Chapter 4, as well as in the first step in this chapter, we matched the emission data with economic data of sectoral gross value added, as we assumed, that the emission data included the major part of heavy metal emissions caused by these sectors. However, the emissions are only caused in a small part of activities in those sectors. Therefore, as a further step we will now match the emission data with production data in physical units of the specific productions that caused these emissions.

Figure 6.1.Cadmium, Lead and Zinc Emissions Related to Zinc Production

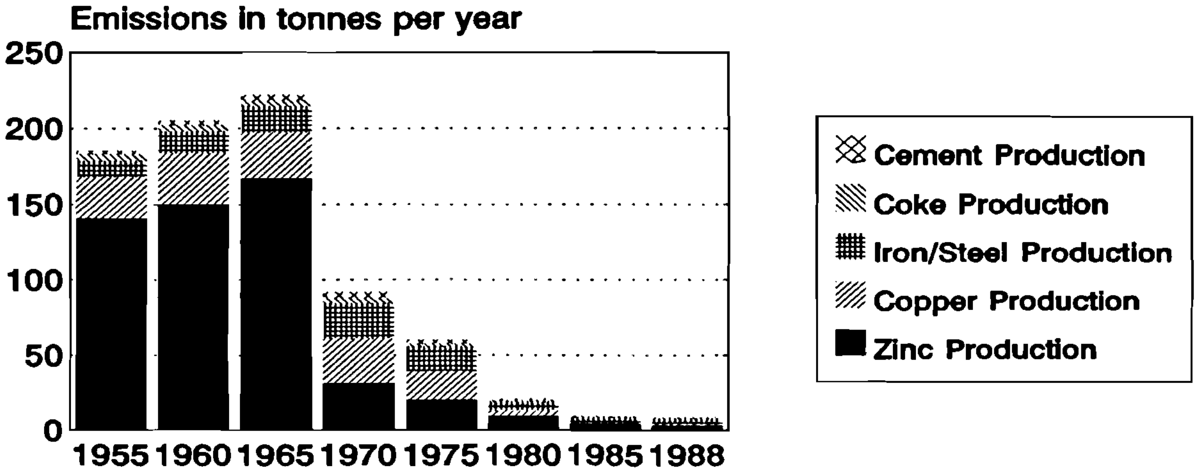


Sources: IIASA, own calculations

The development of the emissions of the three different heavy metals to be looked at (atmospheric cadmium, zinc and lead emissions) have in the most cases been rather similar for each of these productions. Differences show mainly in the level of emissions. See as an example the development of cadmium, lead and zinc emissions related to zinc production (Figure 6.1.). The obviously similar development of these emissions is to a large extent explained by the fact that they are all related to dust emissions which have been abated using filters (see for example VDI, 1984). Therefore only the results for cadmium emissions will be presented in this chapter. Evidently different emissions of other metals will be presented separately, though.

The importance of different productions for the emission of heavy metals differs significantly. Figure 6.2. shows the outstanding influence of the non-ferrous metals production, above all the zinc production, on the emission of cadmium, as well as the substantial importance of this industry for the reduction of atmospheric cadmium emissions since the mid sixties.

Figure 6.2. Atmospheric Cadmium Emissions



Sources: IIASA, own calculations

This emphasizes the need to investigate not only sectors, but also individual productions. A link between individual productions and sectors may be given by a further decomposition of changes in the sectoral emission intensities into (i) changes in the emission coefficients of productions (as given by the ratio E_k/Q_k) and (ii) changes in the physical intensities of production (as given by the ratio Q_k/Y_j). This allows a more distinct interpretation of intrasectoral changes. High reductions in the emission coefficients of production indicate a high importance of technologically induced emission reductions and energy/material substitution, whereas reductions in the physical intensity of production indicate a technological advancement of the products produced (increasing knowledge intensity) and an influence of intrasectoral structural shifts (see Chapter 5, equation 5.15).

Finally, we will in a third step describe in a preliminary way some aspects of intrasectoral change, that led to the reduction of heavy metal emissions in Northrhine-Westfalia. In this qualitative description of intrasectoral changes we will also look at amelioration programmes issued by the state government of Northrhine-Westfalia aimed at the mitigation of air pollution. In so far, a first investigation of driving forces behind industrial change is included.

In 1960 hardly any existing industrial plant was equipped with adequate air pollution control. Thus, the state government of Northrhine-Westfalia made a major effort to reduce pollution from existing plants. It set up amelioration programmes for several industrial sectors, to be completed by 1973 [Arbeits- und Sozialminister Nordrhein-Westfalen, 1969]. The decision, whether a plant had to be retrofitted depended on the amount of emissions caused by that plant[23]. Of particular interest for our investigation here are the amelioration programmes concerning Thomassteel converters, sinter plants, cement plants and coking plants. Also of interest are technological changes that took place in the non-ferrous metals industry and in the electricity production.

To characterize intrasectoral change we rely on the following classification which is directly linked to the analysis in Chapter 5:

- end-of-pipe technologies,
- substitution of inputs (including the use of recycled inputs),
- process-related technological changes
  - process modifications,
  - new processes,
  - good housekeeping by organisational-technical measures or minor technological changes (for example covers over belt conveyors),
- product related technological changes
  - changes in the spectrum of products produced in a certain industry (intrasectoral structural shifts) and
  - a reduction of the physical intensity of production (dematerialization).

The conclusions of this paragraph will be integrated with the overall conclusions in Chapter 7.

6.1. Non-Ferrous Metals

6.1.1. The Development of Emissions, Emission Intensities and Value Added Shares

The decomposition analysis showed an outstanding contribution of the non-ferrous metals production to the decline of the emission/output ratio of total industry. Between 1955 and 1988 the non-ferrous metals sectors' share in the total gross value added of industry increased by 32% while its lead emissions declined by 85% and its zinc and cadmium emissions by 96% and 97% respectively (see Table 6.1.).

This implies that the emission intensities of the non-ferrous metals sector in regard to lead, zinc and cadmium emissions declined by 95% to 99%.

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[23] That is, if a plant emitted twice as much as was permitted for new plants. Exceptions were made, however.

Table 6.1. Cumulative Components of Change in Emissions: Non-Ferrous Metals Production

	Emissions	Emission Intensity	Zinc Production	Copper Production
			Emission Coefficient	Emission Coefficient
	1955/88	1955/88	1955/70	1955/70
Cadmium Emissions	-97,0%	-99,0%	-63,5%	-29,2%
Lead Emissions	-84,8%	-94,8%	-63,5%	-27,9%
Zinc Emissions	-96,1%	-98,7%	-63,5%	-15,8%
	Value Added Share in Total Industry			
1955	0,7%			
1988	0,9%			
1955/88	32,6%			

6.1.2. The Development of Heavy Metal Emissions in Relation to Non-Ferrous Metals Production

Atmospheric heavy metal emissions in the non-ferrous metals industry originate from the production of zinc, lead and copper. Owing to missing production data on lead only the productions of zinc and copper can be investigated in this section. Furthermore data availability allows an investigation of zinc and copper production only for the years 1955 to 1970.

Zinc Production and Emissions of Cadmium

Cadmium emissions associated with the production of *zinc* seem to have developed largely independent of production[24]. Zinc production declined over the entire period of time investigated (see Figure 6.3.), from 113 thousand tonnes in 1955 to 69 thousand tonnes in 1970. Opposite to the production of zinc the emissions increased from 1955 to 1965 and only then declined rapidly. After 1970 this decline, however, slowed down.

While the reason for the increase in emissions between 1955 and 1965 is not obvious, their subsequent decline is partly explained by a decline of zinc production, but primarily by technological changes. This result of a high influence of technological change on the decline in emissions is also supported by the results of Table 6.1., where the emission coefficient of zinc production[25] declined between 1955 and 1970 by 63% for cadmium, lead and zinc emissions.

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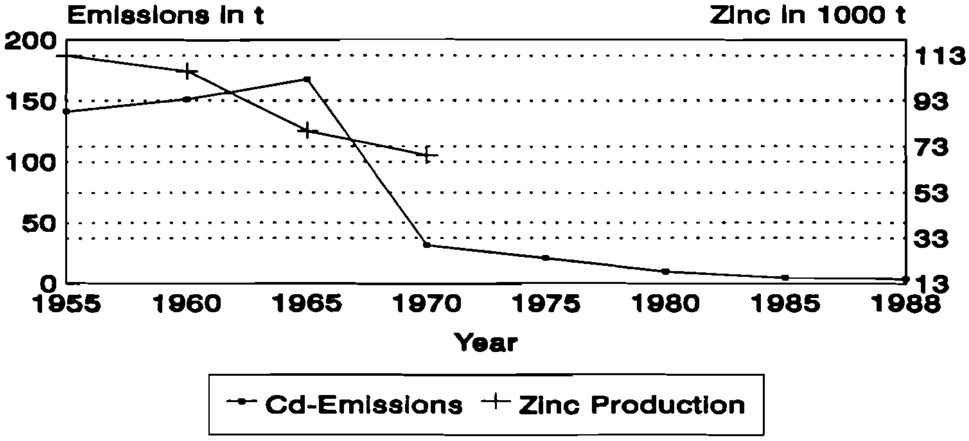
[24] This holds true for the period 1955 to 1970 for which data on zinc production are available.

[25] If we below use emission coefficient, we always refer to the emission coefficient of production, not to the emission coefficient of the inputs in production.

Figure 6.3. Zinc Production and Emissions of Cadmium

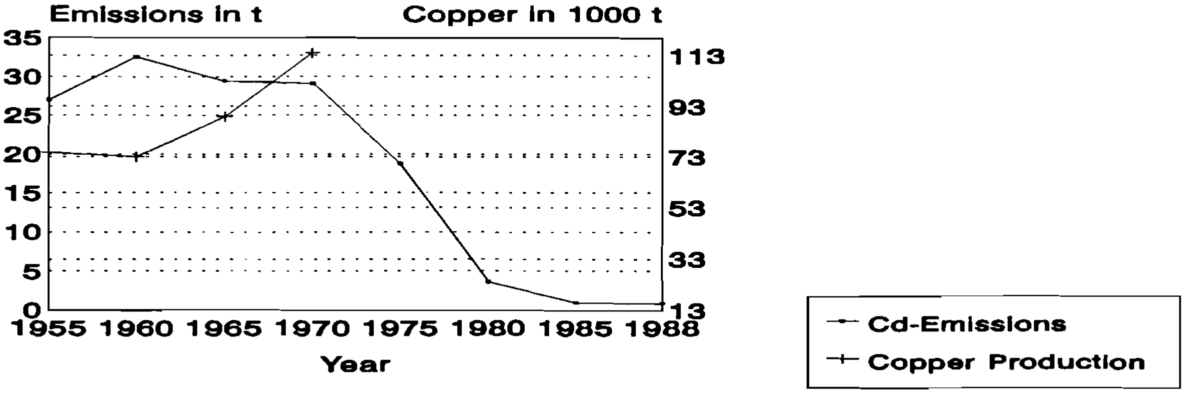


Source: IIASA, LDS, own calculations

Copper Production and Emissions of Cadmium

Figure 6.4. shows the development of *copper* production between 1955 and 1970. After a slight decrease from 1955 to 1960 the production of copper increased until 1970. Altogether there has been an increase in copper production of 56% between 1955 and 1970.

Figure 6.4. Copper Production and Emissions of Cadmium



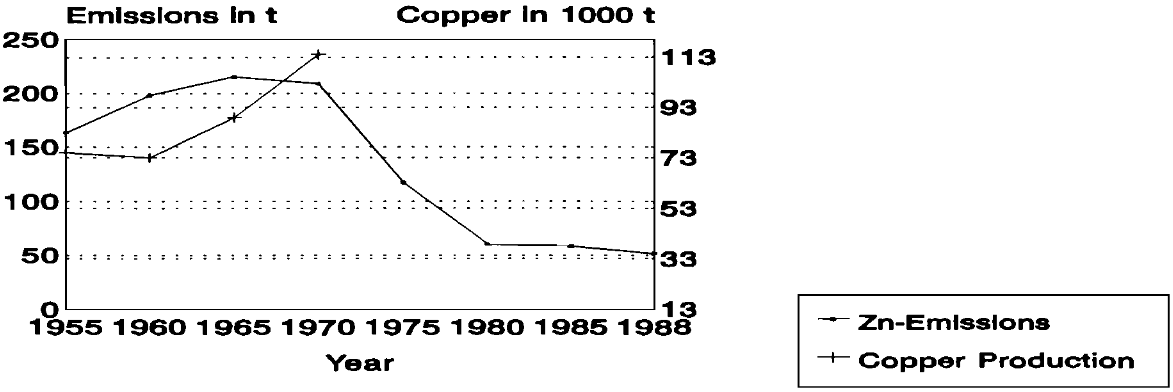
Sources: IIASA, LDS, own calculations

The cadmium emissions developed in an inverse way between 1955 and 1970. They increased from 1955 to 1960 and declined in the following years. Accordingly the emission coefficients rose until 1960 and declined afterwards. As can be seen from Table 6.1. the emission coefficients of copper production declined between 1955 and 1970 by almost 30%. Since the early sixties obviously intrasectoral change led to the decrease and later on to the stabilization in emissions, whereas the production of copper at the same time grew by increasing rates.

Copper Production and Emissions of Zinc

Unlike the cadmium emissions due to copper production the *zinc* emissions shown in Figure 6.5. increased until 1965. However, a turning point in this development can still be seen in 1960, as the increase of emissions slows down in the following years while the production of copper increases.

Figure 6.5. **Copper Production and Emissions of Zinc**



Sources: IIASA, LDS, own calculations.

After 1965 the zinc emissions caused by the production of copper declined. From 1955-1970 the zinc emission coefficient declined only by a modest 16%.

6.1.3. Aspects of Intrasectoral Change

Until 1972 mainly organisational-technical measures were taken in order to decrease dust emissions from the production of *copper*, as for example covering of storage and storing in silos and halls, wetting of slag and the installation of roofs over conveyor belts [IHK, 1973].

In the period of 1969 to 1971 one zinc refinery in Northrhine-Westfalia was closed down, each of the remaining three employed a different technology (zinc electrolyte[26], Imperial-Smelting-Plant[27], electrothermic plant) [IHK, 1973; Schackmann, 1972]. Zinc electrolytic plants are less emission intensive than electrothermic processes and meet the thresholds set for dust emissions [Metal Bulletin Ltd., 1978]. In the following years the electrothermic processes were replaced by imperial-smelting and electrolytic processes [UBA, 1982; Klepper et al., 1995].

By 1971 the newer of two lead refineries in Northrhine-Westfalia had been equipped with technologies to decrease dust emissions. For the second refinery a programme was set

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[26] The zinc electrolytic plant was built in 1968.

[27] In this plant zinc and lead are produced at the same time.

up, aimed at the reduction of dust emissions and at increasing the share of gas in energy input [IHK, 1973].

6.2. Iron and Steel

6.2.1. The Development of Emissions, Emission Intensities and Value Added Shares

In the iron and steel industry both, intra- and intersectoral changes contributed to the decline in emissions by 65% for cadmium and 75% for lead and zinc between 1955 and 1988 (Table 6.2.).

Table 6.2. Cumulative Components of Change in Emissions: Iron and Steel Production

	Emissions	Emission Intensity	Emission Coefficient	Physical Intensity
	1955/88	1955/88	1955/88	1955/88
Cadmium Emissions	-65,8%	-81,7%	-62,3%	-19,3%
Lead Emissions	-75,0%	-86,6%	-67,3%	-19,3%
Zinc Emissions	-75,0%	-86,6%	-67,3%	-19,3%
	Value Added Share in Total Industry			
1955	5,3%			
1988	4,6%			
1955/88	-14,4%			

Of greater influence, though, were changes within the sector that led to a decline in emission intensities by 82% for cadmium and 87% for lead and zinc emissions. The share of iron and steel production in relation to total industry declined by 14%.

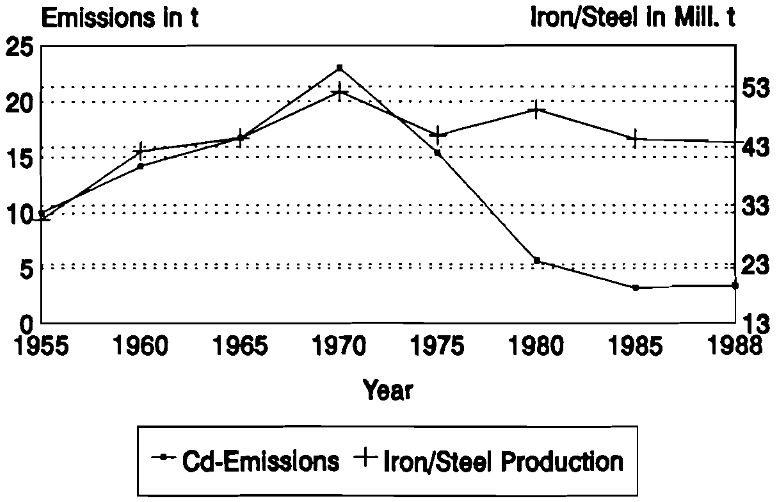
6.2.2. The Development of Heavy Metal Emissions Related to Iron and Steel Production

Iron and Steel Production and Emissions of Cadmium

The production of *iron and steel* in Northrhine-Westfalia increased from 30.6 million tonnes in 1955 to 43.8 million tonnes in 1988. Figure 6.6. shows a steady increase of production between 1955 and 1970. Except for the boom around 1980, the production stabilized around 43 million tonnes since.

Atmospheric cadmium emissions caused by iron and steel production in Northrhine-Westfalia decreased between 1955 and 1988 from 9.6 to 2.9 tonnes per year. Parallel to the development of production there has been a continuous increase of cadmium emissions until 1970. The parallel development of emissions and production continued until 1975, between 1975 and 1980 the cadmium emissions declined independently of the development of production.

Figure 6.6. Iron and Steel Production and Emissions of Cadmium



Sources: IIASA, LDS, own calculations.

This development was similar for the production of iron as well as for the production of steel. Zinc and lead emissions related to iron, as well as to steel production developed parallel to cadmium emissions.

Between 1955 and 1975 cadmium emissions related to iron and steel production seem to have been mainly influenced by the growth of production. However, between 1970 and 1975 emissions began to decline with a higher rate than production. While there was a rather stable development of production since 1975, emissions - and therefore also emission coefficients - declined. Since 1985 both, production and emissions, remained at a constant level. Since the decoupling of emissions and production started around the early 1970's, technical influences, that is intrasectoral changes, have been more important for the reductions in emissions than the development of production. Table 6.2. shows that - over the whole period of investigation - the emission coefficients of iron and steel production declined distinctly stronger than the physical intensity of production. This result allows the interpretation that in regard to intrasectoral changes the decline in emissions was mainly determined by technological change in end-of-pipe technology rather than by intrasectoral structural shifts within the iron and steel industry, or product related changes. The results shown in Figure 6.6. allow the interpretation that facilities to reduce emissions have primarily been installed between 1975 and 1985.

6.2.3. Aspects of Intrasectoral Change

Steel Converters

In 1960 54 dust emission intensive Thomas converters were in use in Northrhine-Westfalia. The aim of an amelioration programme set up by the state government of Northrhine-Westfalia in 1961 was to reduce the high dust emissions caused by these plants by retrofitting them with end-of-pipe technologies. An experimental plant was built in 1959 in order to test dedusting technologies and by 1962 a technology to keep back the dust had been developed [Arbeits- und Sozialminister Nordrhein-Westfalen, 1969]. However, by that time it was already clear that no new Thomassteel converters were to be built, but that they would be replaced by LD- and LDAC-converters (Oxygensteel) equipped with dust removing technologies [Arbeits- und Sozialminister Nordrhein-Westfalen, 1969; IHK, 1973]. The focus of the amelioration programme therefore was switched to the replacement of Thomassteel converters (process related technological change).

Though the programme was originally supposed to be completed in 1967, its accomplishment was delayed by organisational changes, that is concentration processes within the steel industry which were taken into consideration by the authorities responsible for the implementation of clean air legislation. The replacement of Thomassteel converters was also delayed by accelerated economic growth which extended the time span to economically run these plants. By 1969 only 11 out of the 54 Thomassteel converters employed in 1960 were still in use. Between 1962 and 1969 18 LD- and LDAC-converters (basic oxygen) equipped with dedusting facilities went into operation [Arbeits- und Sozialminister Nordrhein-Westfalen, 1969].

In the following years further means of dust control were installed in several enterprises, such as electro filters and covers to collect exhaust gas arising from converters and dust arresters in auxiliary facilities [IHK, 1982; Initiativkreis Ruhrgebiet, 1992].

By 1969 there had been no amelioration programmes aimed at retrofitting Siemens-Martin- and Electrosteel plants with dedusting equipment. Nevertheless, there was a trend to replace Siemens-Martin-furnaces by Oxygensteel plants since the early sixties [Arbeits- und Sozialminister Nordrhein-Westfalen, 1969]. Electrosteel plants were equipped with different kinds of filters in order to reduce dust emissions [IHK, 1973].

Sinter Plants

In order to reduce dust emissions from sinter plants the state government of Northrhine-Westfalia set up an amelioration programme in 1965. Until 1969 6 of 37 plants were closed down. In order to reduce the dust emissions of the remaining plants different kinds of filters were installed (end-of-pipe technology). In 19 out of the 31 sinter plants in operation in 1969 dust emissions had to be further reduced in order to meet the aims set up [Arbeits- und Sozialminister Nordrhein-Westfalen, 1969].

Other Activities

Being a major industrial user of energy, the iron and steel industry took significant measures to reduce energy consumption, especially coke consumption in the 1960's [Feddersen and Kruck, 1982].

6.3. Electricity Production

6.3.1. The Development of Emissions, Emission Intensities and Value Added Shares

Despite the nearly twofold growth of value added share of electricity production between 1955 and 1988 (Table 6.3.) atmospheric emissions of cadmium, zinc and lead related to electricity production declined by 52%, 62% and 63% respectively. This implies a highly decreased emission intensity of somewhat above 92% for the three heavy metals within this sector.

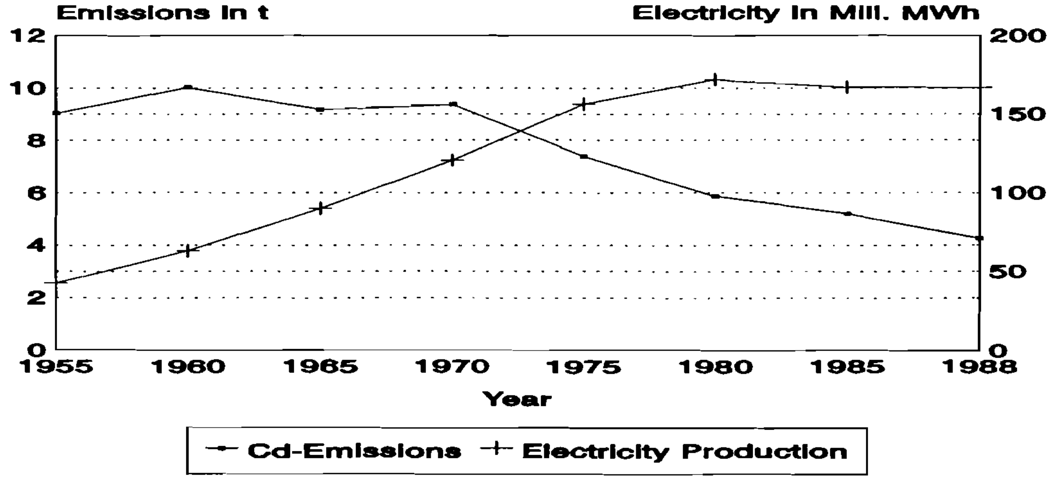
Table 6.3. Cumulative Components of Change in Emissions: Electricity Production

	Emissions	Emission Intensity
	1955/88	1955/88
Cadmium Emissions	-52,0%	-92,5%
Lead Emissions	-62,8%	-94,2%
Zinc Emissions	-62,3%	-94,1%
	Value Added Share in Total Industry	
1955	1,9%	
1988	5,5%	
1955/88	192,2%	

6.3.2. The Development of Heavy Metal Emissions Related to Electricity Production

The total electricity production in Northrhine-Westfalia increased from some 42 billion kWh to 166 billion kWh in 1988. This includes production of electricity within several industrial sectors, such as iron and steel, non-ferrous metals and chemical industry. The following figure makes clear that the emission related to the production of electricity (in all the sectors) have declined considerably.

Figure 6.7. Electricity production and emissions of cadmium



Sources: IIASA, LDS, own calculations

Figure 6.7. shows that cadmium emissions developed largely independently of electricity production. While there was a steady increase of electricity production between 1955 and 1980, the development of cadmium emissions showed a negative trend between 1960 and 1988.

These results show, that the reduction of atmospheric heavy metal emissions can be explained by intrasectoral changes, that is changes within the electricity production.

There may be several reasons for this decline. Heavy metal emissions of electricity production can be reduced by:
(1) the application of end-of-pipe technology, such as filters
(2) a switch from hardcoal and browncoal to oil and gas as fuel input
(3) improvements in the transformation efficiency of electricity production
(4) preventive measures such as the use of relatively cleaner coal (with a lower dust content) and the application of coal cleaning techniques (such as coal washing).

In order to determine the influence of each of these factors on heavy metal emissions, we can apply the nested decomposition methodology described in Chapter 5. We will look here (for data reasons) on the total electricity production in Northrhine-Westfalia[28] using the following identity:

$$\sum_i \frac{E_i}{Q} = \sum_i \frac{E_i}{I_i} \cdot \frac{I_i}{Q_i} \cdot \frac{Q_i}{Q}$$

where E_i are the emissions of heavy metals from electricity production due to the use of fuel i, I_i are the inputs of fuel i in electricity production, Q_i are the outputs in MWh of using fuel i, while Q is the total MWh electricity production in Northrhine Westfalia.

Changes in the first ratio on the right hand side determine the changes in the emissions per unit of fuel input. This is dependent on the application of end-of-pipe technology as well as preventive measures. The second ratio determines the change in the transformation efficiency as less inputs may be required to produce the same amount of electricity. Finally, the third ratio on the right hand side of (6.1) determines the change in fuel inputs for electricity production as fuels with high emission characteristics are replaced by fuels with lower emission characteristics.

Table 6.4. gives the outcome of the nested decomposition using the proportional allocation of the residual[29] for all the three pollutants. The cumulative effects show that these pollutants follow more or less similar developments. The application of end-of-pipe technology (and preventive measures) had clearly the biggest influence on the reduction of heavy metal emissions stemming from electricity production. Less important for the reduction of heavy metal emissions were the fuel switches and the increased process efficiency.

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[28] Only electricity production stemming from fossil fuels has been taken into account. This implies that the switch to nuclear power plants is not included in this decomposition analysis.

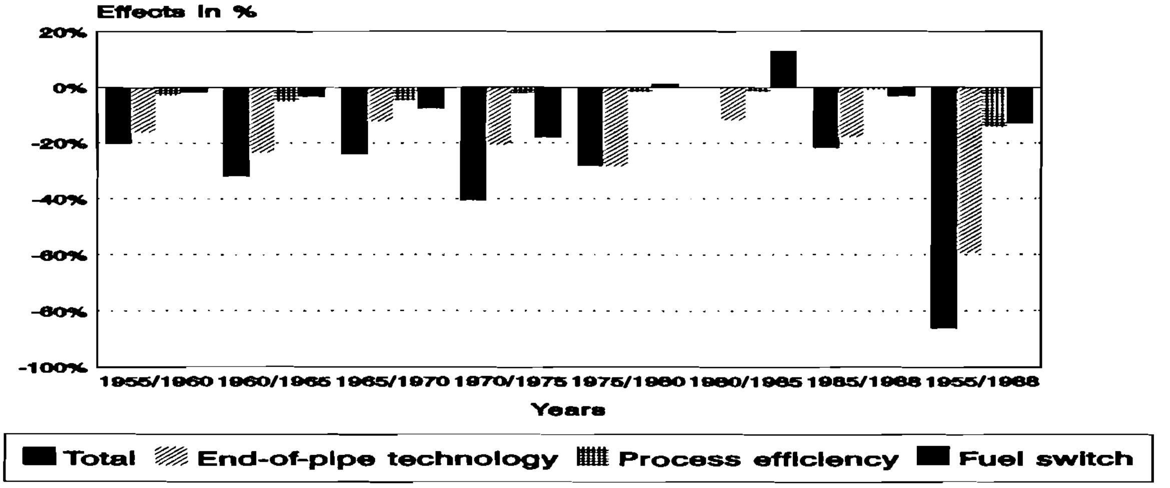
[29] As was explained in Chapter 5, the outcome of the decomposition may be influenced by the hierarchy of nesting. Here we first decompose the third ratio with the combination of the first and second ratio, and then decompose further the second and first ratio.

Table 6.4. Decomposition of Heavy Metals Emissions for Electricity Production: Cumulative Total Effects from 1955-1988

	Cadmium	Zinc	Lead
Total	-86.1%	-89.1%	-89.2%
End-of-pipe technology	-59.4%	-64.0%	-59.5%
Process efficiency	-14.0%	-14.3%	-13.5%
Fuelswitch	-12.8%	-10.8%	-16.2%

Figure 6.8. pictures the period-wise decomposition results for cadmium emissions. This figure shows that the application of end-of-pipe technology was important in all the periods considered, especially from 1960-1965 and 1970-1980. The only time when the emissions per MWh did not decline was in the period 1980-1985. As can be seen from Figure 6.8. this is due to the increase in emissions as the result of the unfavourable fuel switch. Because of the application of end-of-pipe technology and minor improvements in the process efficiency, the total emissions per MWh remained the same during this period. It emphasizes the need to include fuel shift considerations in environmental policy making.

Figure 6.8. Decomposition Results Electricity Production: Period Wise Total Effects



6.3.3. Aspects of Intrasectoral Change

In existing coal power plants different improved technologies were installed between 1969 and 1971, e.g. new or bigger electrofilters, photocells to control the combustion process to allow a well-timed cleaning of boilers from soot and dust measuring appliances [IHK, 1973]. There has also been a trend towards a fuel input change, that is a decrease of coal input and an increase of gas and oil. Nevertheless, the results from our decomposition analysis show that the biggest decrease was owing to the installation of end-of-pipe technology.

6.4. Coal Mining (Coke Production)

6.4.1. The Development of Emissions, Emission Intensities and Value Added Shares

Coke production takes place mainly within the industry of coal mining. Three quarters of the total output of coke are produced within this industry, while only one quarter is produced within the industry of iron and steel [IHK, 1973]. In the following we therefore investigate the development of the industry of coal mining.
The sector with the highest decrease in value added share (-84%) between 1955 and 1988 is coal mining (Table 6.4.). Intersectoral change therefore contributed strongly to the decline in emissions caused by this sector of around 84% for cadmium and lead and 88% for zinc emissions.

Table 6.5. Cumulative Components of Change in Emissions: Coal Mining (Coke Production)

	Emissions	Emission Intensity	Emission Coefficient	Physical Intensity
	1955/88	1955/88	1955/88	1955/88
Cadmium Emissions	-83,7%	-52,4%	-58,6%	6,2%
Lead Emissions	-84,9%	-55,7%	-61,9%	6,2%
Zinc Emissions	-88,4%	-66,2%	-72,4%	6,2%
	Value Added Share in Total Industry			
1955	20,1%			
1988	3,2%			
1955/88	-84,4%			

But also intrasectoral change contributed to this development of emissions. During the same period of time emission intensities declined by 52% for cadmium and 56% respectively 66% for lead and zinc.

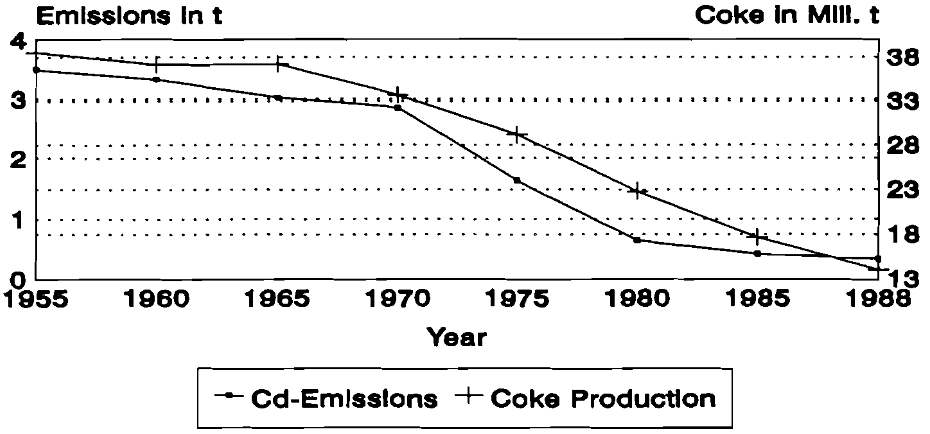
6.4.2. The Development of Heavy Metal Emissions Related to Coke Production

Coke Production and Emissions of Cadmium

Almost over the whole period of time investigated the production of coke declined. While the production of coke has been relatively stable between 1955 and 1965, it declined rapidly within the following years. Over the time period 1955 to 1988 coke production declined by approximately 65%.

Figure 6.9. shows a parallel development for the emissions of cadmium that have been caused by coke production until the early 1980's. Afterwards the decline of cadmium emissions slowed down, while the rapid decrease in coke production continued.

Figure 6.9. Coke Production and Emissions of Cadmium



Sources: IIASA, LDS, own calculations.

As coke production and cadmium emissions caused by the production of coke followed the same trend of development at least until the early eighties, intersectoral change, that is the economic decline of coke production, seems to have been the main influence of the decline in emissions. However, technical changes - mainly between 1960 and 1980 - also influenced this development of emissions, as emissions declined with a higher rate than production. Since 1985 cadmium emissions remained almost constant, while there was a further decline in the production of coke[30].

The decomposition of emission intensities (see Table 6.5) shows the high importance of technological change for the emission reductions due to intrasectoral change within the coal mining sector. Emission coefficients declined between 1955 and 1988 by almost 60%. The 6% increase in physical intensity of production may imply unfavourable intrasectoral structural shifts within the coal mining sector, indicating that the production of coke has become relatively more important.

6.4.3. Aspects of Intrasectoral Change

Coking Plants

The main focus of reducing emissions of heavy metals caused by the coal mining industry lay on coking plants [IHK, 1973]. Two programmes covering different steps of the production process have been set up in order to reduce dust emissions from coking plants, one in 1965, the other in 1967 [Arbeits- und Sozialminister Nordrhein-Westfalen, 1969]. By 1971 almost all coking plants in Northrhine-Westfalia were equipped with gas cleaning technologies [IHK, 1973]. Different technologies were employed for different steps of the coking process. They comprise covers to collect the hot gases, suction fans, the wetting of the coke particulates in the steam and equipment to separate the dust with help of rotating separators or by washing of the gases [Arbeits- und Sozialminister Nordrhein-Westfalen, 1969].

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[30] Emissions of zinc and lead related to coke production developed in the same way.

Apart from technological development also a decrease in the number of coking plants combined with a development towards bigger production units improved the situation of emissions [UBA, 1977].

6.5. Stones and Clays (Cement Production)

6.5.1. The Development of Emissions, Emission Intensities and Value Added Shares

Intra-, as well as intersectoral change contributed to the decline of heavy metal emissions caused by the sector of stones and clays (Table 6.6). Between 1955 and 1988 cadmium emissions declined by 83%, lead and zinc emissions by 80%.

Table 6.6. Cumulative Components of Change in Emissions: Stones and Clays (Cement Production)

	Emissions	Emission Intensity	Emission Coefficient	Physical Intensity
	1955/88	1955/88	1955/88	1955/88
Cadmium Emissions	-82,5%	-90,5%	-68,0%	-22,5%
Lead Emissions	-80,2%	-89,3%	-66,7%	-22,5%
Zinc Emissions	-80,2%	-89,3%	-66,7%	-22,5%
	Value Added Share in Total Industry			
1955	2,4%			
1988	2,0%			
1955/88	-15,7%			

Still intrasectoral change was of higher importance, leading to a decrease in emission intensities of about 90%. The share of production of stones and clays in the production of the industry overall decreased by 16%.

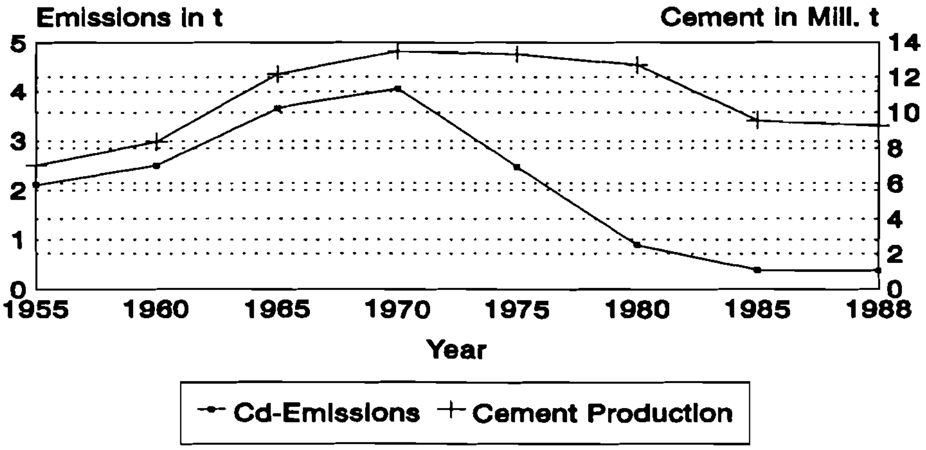
6.5.2. The Development of Heavy Metal Emissions Related to Cement Production

Cement Production and Emissions of Cadmium

From 1955 to 1988, the production of *cement* increased by 31%. The production increased rapidly between 1955 and 1970 (see Figure 6.12). Since then it decreased, first slowly between 1970 and 1980 and from 1980 more rapidly. During the last years covered by this investigation the decline in production slowed down again.

Production and emissions rose in a parallel way between 1955 and 1960. Between 1960 and 1970 the increase of cadmium emissions slowed down. In the following time emissions dropped fast until 1985 and stabilized during the last years of investigation. During the entire period emission coefficients dropped, due to technological changes. The assumption of a high influence of technical change concerning emission reductions due to intrasectoral change is also supported by the results shown in Table 6.6., as emission coefficients of the production of stones and clays declined between 1955 and 1988 by 68%.

Figure 6.10. Cement Production and Emissions of Cadmium



Sources: IIASA, LDS, own calculations.

6.5.3. Aspects of Intrasectoral Change

Cement Industry

An amelioration programme for cement plants, aimed at the reduction of dust emissions and focusing on furnaces, was set up in 1962 [Arbeits- und Sozialminister Nordrhein-Westfalen, 1969]. By 1973 all cement furnaces in Northrhine-Westfalia were equipped with electro-filters [IHK, 1973].

In order to prevent dust emissions from storage of cement clinker the programmes were directed at organisational-technical measures, as for example the storage of clinker in silos or halls [Arbeits- und Sozialminister Nordrhein-Westfalen, 1969].

Apart from technologies of air pollution control concentration within the cement industry reduced the emissions of dust, as larger plants have lower specific amounts of exhaust gas[31] and more effective pollution control technologies [IHK, 1973].

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[31] In large plants the dust emissions increase with a slower rate than the production and decline compared to the same amount of cement produced in several smaller plants [IHK, 1973]. This development is probably due to economies of scale.

Chapter 7. Conclusions and Outlook for Further Research

7.1. Conclusions

Emissions of heavy metals have declined substantially in most Western European countries. In this paper we have analysed the patterns of atmospheric heavy metal emissions (1955-1988) in Northrhine-Westfalia from the perspective of industrial transformation. The industrial point source emissions of cadmium and zinc have declined steadily since the mid 60's, with major reductions in a relatively short period: from 1965 until 1980. Emissions of lead declined since 1970, with major reductions until 1980.

We find that relatively few productions are responsible for the major part of emissions. These include copper, zinc and lead refining, iron and steel production, cement production, coke production and electricity production. The total emission reduction is hence dependent on the application of new technologies within these production processes (intrasectoral changes), changes in the relative shares of these productions in the total economy of Northrhine-Westfalia (intersectoral change) and the overall economic growth.

Decomposition methods aim at disentangling these changes from each other. It appears that the decomposition methods that have been applied so far suffer from two weaknesses. First, there seems to be no agreement on how the interaction effect between intersectoral and intrasectoral changes should be interpreted and allocated. Second, the sector classification is in an unpredictable way critical to the outcomes of decomposition analysis.

We describe how the interaction effect can be allocated proportionally to the change in the components it consists of. The advantage of this method is that the change in the emission/output ratio is completely described by the sum of intersectoral and intrasectoral effects. Moreover, this method allows the data to determine the division between intersectoral and intrasectoral effects instead of a priori assumptions set by the researcher.

While we focus in this paper mainly on intersectoral and intrasectoral effects, we outline how decomposition analysis could be further applied in a material flow context. With the aid of a simple material flow analysis, we disentangle the intrasectoral changes in: (i) the application of end-of-pipe technology; (ii) substitution of material and energy inputs in production; (iii) improvements in the efficiency of the process technology, and (iv) product related technological changes, such as increasing knowledge intensity of production (substitution of materials for labour) and shifts in relative shares of productions within an economic sector. Nested decomposition analysis could be applied in order to quantitatively disentangle these determinants of intrasectoral change. It requires however specified data that are not available in the current project.

In the empirical part of this paper, we focus on describing industrial transformation in Northrhine-Westfalia with help of decomposition and material flow analysis. First we decompose the cadmium, zinc and lead emission/output ratio into intrasectoral and intersectoral effects. Intrasectoral changes are the weighted changes in each sector's emissions per unit of monetary output, while the intersectoral changes are the weighted changes in each sector's share of total value added in Northrhine-Westfalia. We find that intrasectoral changes have been the major cause of emission reductions. This indicates the importance of technologically induced changes in Northrhine-Westfalia, leading to a reduction in emission intensities in all sectors.

The industrial basis in Northrhine-Westfalia seems to have remained unaltered to a large extent, as indicated by the absence of intersectoral changes. Intersectoral changes had a minor influence on emission reductions in the case of zinc emissions, while the shift in the structure of the economy led to increases in emission levels in the case of lead and cadmium emissions. Since the major part of the emissions is related to one sector, the non-ferrous metals sector, the development of this sector determines to a large extent the outcomes of the decomposition analysis. The value added share of the non-ferrous metals sector increased over the time period considered. Also the electricity production and the chemical industry grew at a rate above average in Northrhine-Westfalia. Declining value added shares are found in the other sectors: coal-mining, iron and steel and stones and clays.

Looking at the individual sectors (see summary in Table 7.1.), we found that high decreases in the emission intensity of sectors brought about decreases in emissions of all productions. Although for the majority of productions the decline of heavy metal emissions did not start until 1970, the highest reduction in emissions overall was achieved during the mid and end sixties. This development is due to the way above-average importance of the non-ferrous metals production (and especially zinc production) for the emission of heavy metals, which declined substantially in the mid sixties, already. The highest decreases of emissions in percentage changes took place in the non-ferrous metals production and the industries of coal-mining and stones and clays.

Analysing the reasons behind the important intrasectoral changes, we find that the reduction of emissions per unit of *physical* product (tonnes steel, cement, etc.) were most important. These reductions indicate an increased application of end-of-pipe technology, as well as process related changes in Northrhine-Westfalia. A decomposition analysis of the causes of the reduction of emissions per MWh produced electricity shows, that especially the application of end-of-pipe technology was most influential. Of less importance were the fuel switches and the improvements in process efficiency. There are reasons to believe that this holds true for the other productions as well.

Besides the reductions in the emissions per unit of physical production, also increases in the value added per unit of physical product have been a source of intrasectoral changes. These were important in cement manufacturing and in iron and steel production.

In a further step, we also looked at the different measures that were taken in Northrhine-Westfalia in order to reduce emissions. This provides a first explanation of policy programmes that induced intrasectoral change which may give an explanation on the observed developments. Between 1960 and 1973 different measures were taken within the Northrhine-Westfalian industrial sectors responsible for heavy metal emissions in order to decrease dust emissions. These measures cover organisational-technical measures, substitution of inputs and the installation of end-of-pipe technologies, as well as the introduction of new processes.

Table 7.1. Summary of Findings in this Study on the Sectoral Level

Sectors (Productions)	Development Emissions	Causes: Intra/Intersectoral. Developments of Intensities and Value Added Shares.	Causes of Intrasectoral Change	Explanations
Non-ferrous metals	85%-97% decreases.	Intrasectoral change, but increasing production. Emission intensity declines by 95-99%.	End-of-pipe technology and probably intrasectoral structural shifts.	
o.w. Zinc	Decreases mainly between 1965-1970.	Mainly intrasectoral change.	Major improvements of 62-67% in emission coefficient (1955-1970).	Around 1970, 1 zinc refinery was closed down. In 1968, a cleaner electrolytic plant was built.
o.w. Copper	Decreases mainly between 1970-1980.	Intrasectoral change. Increasing production.	Minor improvements of 15-30% in emission coefficient (1955-1970).	Until 1972 mainly organizational-technical measures were taken in order to reduce dust emissions.
o.w. Lead			1971: equipment of one of two lead refineries with end-of-pipe technology. For the other refineries a programme was set up aimed at the reduction of dust emissions and fuel switches towards more natural gas.	
Iron and Steel	65%-75% decreases, mainly between 1970-1980.	Intrasectoral change, but increasing production. Emission intensity declines by 82-87%.	62-67% improvement in emission coefficient. 20% decreases in physical intensity of production (more knowledge intensive products).	1961: The set-up of an amelioration programme for steel converters aimed at reduction of dust emissions through end-of-pipe technology, in 1962 the focus of this program switched to a replacement of Thomassteel converters by Oxygensteel converters. 1960-1969: 43 Thomassteel converters were closed down. 1962-1969, 18 Oxygensteel plants went into operation.
Electricity Production	52-62% decreases in public power plants. Steady reduction since 1970.	Strong intrasectoral change. Decline in emission intensity of 92-94%. Increasing production	86-89% improvement in emission coefficients. 60-64% of these were due to application of end-of-pipe technology, 14% to improvements in process efficiency (mainly between 1960-1970) and 11-16% to fuel switches (mainly between 1970-1975). Programme for electrofilters and combustion control between 1969-1971.	
Coal Mining (Coke)	84-88% reduction in emissions, steadily declining after 1965.	Mainly intersectoral change. Also a decline in emission intensity of 52-66%.	Declining emission coefficients of 59-72%. Increases in physical intensity of product, probably due to intrasectoral structural shifts.	Two programmes were set up in 1965 and 1967 in order to reduce dust emissions from coking plants. By 1971 almost all coking plants were equipped with gas cleaning technologies.
Stones and Clays (Cement)	80-82% reduction in emissions, mainly between 1970-1985.	Mainly intrasectoral change, also intersectoral change. 90% reduction in emission intensity.	67% reduction in emission coefficient. 23% decreases in physical intensity of products, probably due to intrasectoral structural shifts.	An amelioration programme to reduce dust emissions from furnaces was set up in 1962. By 1973 all cement furnaces were equipped with end-of-pipe technologies. Organisational changes led to larger production units and declining dust emissions.
Other Industry	No emissions of heavy metals (assumed).	Decreasing production share in the case of lead and cadmium emissions. Increasing production share with respect to zinc emissions.		

While minor technological changes and the installation of different kinds of filters took place in almost all sectors, an introduction of new processes can be found within the non-ferrous metals industry and the iron and steel industry. The programmes that were set up are also summarized in Table 7.1.

In further studies on Northrhine-Westfalia/the Ruhr Area more emphasis will be placed on technological changes that took place after 1972. Additionally the costs related to the application of new technologies, driving forces of intersectoral change, as well as legal and administrative developments will be investigated. Hopefully this historical analysis together with an investigation of conditions for a clean-up in the Katowice-Area will allow to develop criteria for an evaluation of plans and proposals for a clean-up in the Katowice voivodship.

From this investigation, we would suggest the following recommendations for future research on environmental policy in the Katowice area:
- The developments of the non-ferrous metals sector determine to a large extent the emissions of heavy metals. Special attention in the Katowice area need to be paid to this sector.
- Our decomposition results show that the reductions in heavy metal emissions are almost entirely explained by intrasectoral changes. Intersectoral changes were either absent, or resulted in a slight increase in emissions. This may indicate that substantial reductions can be achieved by technological measures only, leaving little scope for 'structural industrial policy' orientated at the relative importance of certain sectors for the total industrial structure in the Katowice area. This needs to be investigated in more detail.
- The intrasectoral changes seem to be especially induced by the application of end-of-pipe technology. Programmes in the Katowice area should take these technologies explicitly into consideration.

7.2. Outlook for Further Research

Missing parts in this study are in the first place due to data availability. Concerning e.g. the non-ferrous metals sector it would have been desirable to investigate zinc, copper and lead production separately. Owing to lacking value added data for these productions, the decomposition analysis in Chapter 4 could only be applied to the non-ferrous metals sector as a whole. Concerning the sectoral analysis in Chapter 6 reliable production data were only available for zinc and copper production and also only for the period from 1955 to 1970. Also due to lacking data it was possible to apply nested decomposition analysis to the electricity production only. As a consequence, the sectoral investigation in Chapter 6 had to be conducted to a large extent as a qualitatively descriptive analysis.

These problems are on the one hand due to an insufficiently disaggregated availability of economic data, on the other hand to the fact, that the emission data were set up for a classification of productions differing from the classification of national or regional statistics of economic data. For further research, and especially for the investigation of the Katowice voivodship/the Black Triangle it would be necessary to put emphasis on setting up integrated data, in order to avoid the difficulties encountered in this investigation.

The investigation of intrasectoral change in this chapter has to be regarded as preliminary. Especially technological changes that took place after 1972 have to be further analysed[32].
In this respect the influence of the development in legal framework, as for example the Northrhine-Westfalian clean air planning (Luftreinhaltepläne) set up since 1978 [see for example Lanesentwicklungsbericht, 1980], as well as the ordinance concerning large combustion plants (Großfeuerungsanlagenverordnung), on changes in the technologies employed are to be investigated.

Also of interest are sectoral and regional orientated programmes set up by the Northrhine-Westfalian government. Examples are different technology programmes and the "Action Programme Ruhr" (Aktionsprogramm Ruhr), which provided between 1980 and 1984 financial aid for the restoration of heavily polluting plants, such as refineries, iron and steel plants, power plants and coking plants. Complementary financial aid for measures aiming at the reduction of dust emissions in plants not covered by the "Action Programme Ruhr" was provided by the Immission[33] Improvement Programme (Immissionsschutzförderprogramm) since 1978 [Luftreinhalteplan, 1985]. Also the programme "Labour and Environment" (Arbeit und Umwelt) set up by the state government of Northrhine-Westfalia in 1984 supported measures regarding air pollution control in industrial and power plants [Bußmann, 1988]. Additionally, the Northrhine-Westfalian environmental programmes and reports of 1974, 1983, 1984 and 1993 might give hints on planned, as well as on already pursued technological change. These programmes are subject of further study [Schucht 1995, forthcoming].

The here developed methodology, decomposition in combination with material flow analysis, could be applied in scenario analysis, either for Northrhine-Westfalia or some other regions. Simple extrapolation of emissions have often led to wrong forecasting. Since decomposition analysis can distinguish between several components of emissions reductions, analysing the patterns of these components and extrapolating them its application may already deliver more reliable results. This could be combined with 'technological frontiers' that can be given by experts. For example, the purification efficiency of flue gasses for dust emissions can hardly exceed the 99%. Once this technological frontier has been reached, it can be expected that further reductions of emissions have to be realised by structural changes, material substitution and an increasing knowledge intensity of production. These forecasts should be combined with forecasts on the future developments of the economy in the region. The main advantage of this approach is that emission levels are made dependent on economic developments and hence represent a good example of environmental-economic modelling.

Acknowledgements

The authors would like to thank Dr. Jürgen Blazejczak for the many useful comments he has made during this study.

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[32] This question will be further investigated in ongoing research [Schucht, 1995 forthcoming].

[33] The term "immission" comprises ambient air concentrations and depositions.

References

Allen, R.G.D., 1975. Indexnumbers in theory and practice. MacMillan Press, London.

Ang, B.W., 1993. Sector Disaggregation, Structural Effect and Industrial Energy Use: An Approach to Analyze the Interrelationships. *Energy*, Vol 8: 1033-1044.

Ang, B.W., 1994. Decomposition of industrial energy consumption: The energy intensity approach. *Energy Economics*, 1994, p163-174.

Ang, B.W., Lee, S.Y., 1994. Decomposition of industrial energy consumption. Some methodological and application issues. *Energy Economics*, 1994, p83-92.

Arbeits- und Sozialminister Nordrhein-Westfalen, 1969: Reinhaltung der Luft in Nordrhein-Westfalen. Bericht zum Kongress Reinhaltung der Luft in Düsseldorf vom 13. bis 17. Oktober 1969. Düsseldorf.

Auty, R., 1985. Materials intensity of GDP: Research issues on the measurement and explanation of change. *Resources Policy*, vol11: p275-283.

Ayres, R.U., 1989. Industrial Metabolism. In: J.H. Ausubel and H.E. Sladovich (Editors): Technology and Environment. National Academy Press, Washington, D.C., p23-50.

Ayres, R.U., Kneese, A.V., 1969. Production, Consumption and Externalities. *American Economic Review*, Vol 59: 282-297.

Baumol, W.J., Oates, W.E. The theory of environmental policy, Cambridge 1988.

Binder, M., 1993. Energieverbrach der OECD: Eine kommentierte Datenübersicht. Forschungsstelle für Umweltpolitik, FFU rep 93-2.

Blazejczak, 1995: Rhine/Black Triangle Policy Comparison Workshop. March 2-3, 1995. Workshop Report. International Institute for Applied Systems Analysis. Laxenburg, Austria.

Boyd, G.A., Hanson, D.A., Sterner, T., 1988. Decomposition of changes in energy intensity: A comparison of the Divisia index and other methods. *Energy Economics*, p309-314.

Bruyn, S.M. de, Opschoor, J.B., 1994. Is the Economy Ecologising?. Tinbergen Institute Discussion Paper, TI 94-65, 27pp.

Bruyn, S.M. de, J.C.J.M. van den Bergh, 1995. Decomposition of energy intensities: the proportional approach. Free University Amsterdam, Research Memorandum.

Bruyn, S.M. de, J.C.J.M. van den Bergh, J.B. Opschoor, 1996. Structural Change and Dematerialisation: an empirical analysis. To be published in: J. van der Straaten, J.C.J.M. van den Bergh (Editors). Economies and Ecosystems in Change, Island Press, Washington D.C.

Bußmann, L., 1988: Die Wirtschaft des Landes Nordrhein-Westfalen. Ludwig Bußmann (Editor). Landeszentrale für politische Bildung Nordrhein-Westfalen. Köln.

Cleveland, C.J., 1991. Natural Resource Scarcity and Economic Growth Revisited: Economic and Biophysical Perspectives. In: Constanza, R. (Editor). Ecological Economics: The Science and Management of Sustainability. Columbia University Press, New York.

Dasgupta, P., Heal, G.M., 1979. Economic Theory and Exhaustible Resources. Cambridge University Press, Welwyn.

ECE, 1994: Task Force on Heavy Metal Emissions. State-of-the-Art Report. Economic Commission for Europe. Executive Body for the Convention on Long-range Transboundary Air Pollution. Working Group on Technology. Prague.

Enders, W., 1995. Applied Econometric Time-Series. John Wiley and Sons, New York.

Feddersen, F., Kruck, R., 1982: Der Einfluß der Umweltpolitik auf die wirtschaftliche Entwicklung in den Ballungsräumen und die Möglichkeit einer ballungsraumspezifischen Umweltpolitik. Gesellschaft für Regionale Strukturentwicklung Bonn.

Guthmann, K., 1961: Das Problem "Reinhaltung der Luft" unter besonderer Berücksichtigung der Eisenhütten-, insbesondere Stahlwerksbetriebe, IV. Radex-Rundschau. Heft 4. Düsseldorf.

Herman, R., Ardekani, S.A., Ausubel, J.H., 1989. Dematerialization, in: J.H. Ausubel and H.E. Sladovich (Editors): Technology and Environment. National Academy Press, Washington, D.C., p50-69.
Howarth, R.B., Schipper, L., Duerr, P.A., Strøm, S., 1991. Manufacturing energy use in eight OECD countries: Decomposing the impacts of changes in output, industry structure and energy intensity. *Energy Economics*, p135-142.

IHK, 1973: Reinhaltung der Luft. Finanzielle und technische Leistungen der Industrie des Landes Nordrhein-Westfalen. Wirtschaftliche Mitteilungen der Niederrheinischen Industrie- und Handelskammer Duisburg-Wesel zu Duisburg.

IHK, 1982: Umweltschutz im östlichen Ruhrgebiet. Industrie- und Handelskammer zu Dortmund. Dortmund.

Initiativkreis Ruhrgebiet, 1992: Die Rolle der Mitgliedsunternehmen im Umweltschutz der Region. Kommunalverband Ruhrgebiet. Essen.

Jänicke M., Mönch, H., Ranneberg, T., Simonis, U.E., 1989. Economic Structure and Environmental Impacts: East-West Comparisons. *The Environmentalist*, vol9, p171-182.

Jänicke, M., Mönch, H., Binder, M., 1992: Umweltentlastung durch industriellen Strukturwandel? - Eine explorative Studie über 32 Industrieländer (1970 bis 1990). Berlin.

Jenne, C.A., R.K. Catell, 1983. Structural change and energy efficiency in industry. *Energy Economics*, Vol

Klepper, G., Michaelis, P., Mahlau, G., 1995: Industrial Metabolism. A Case Study of the Economics of Cadmium Control. Kieler Studien. Institut für Weltwirtschaft an der Universität Kiel.

Landesentwicklungsbericht: Landesentwicklung Nordrhein-Westfalen. Bericht der Landesregierung Nordrhein-Westfalen. Several volumes. Düsseldorf.

LDS: Bergbau und Verarbeitendes Gewerbe in Nordrhein-Westfalen. Produktion ausgewählter Erzeugnisse. Ergebnisse der vierteljährlichen Produktionserhebung. Several volumes. Landesamt für Datenverarbeitung und Statistik Nordrhein-Westfalen. Düsseldorf.

LDS: Volkswirtschaftliche Gesamtrechnung der Länder. Bruttowertschöpfung des Produzierenden Gewerbes in Nordrhein-Westfalen. 1970 bis 1988. Landesamt für Datenverarbeitung und Statistik Nordrhein-Westfalen. Düsseldorf.

LDS: Energiebilanz des Landes Nordrhein-Westfalen. 1978 bis 1988. Landesamt für Datenverarbeitung und Statistik Nordrhein-Westfalen. Düsseldorf.

LDS: Statistisches Jahrbuch Nordrhein-Westfalen. Several Volumes. Landesamt für Datenverarbeitung und Statistik Nordrhein-Westfalen. Düsseldorf.

Liu, X.Q., Ang, B.W., Ong, H.L., 1992. The Application of the Divisia Index to the Decomposition of Changes in Industrial Energy Consumption. *The Energy Journal*, Vol 13: 161-177.

Luftreinhalteplan, 1985: Luftreinhalteplan Ruhrgebiet West - 1. Fortschreibung - 1984 bis 1988. Minister für Arbeit, Gesundheit und Soziales des Landes Nordrhein-Westfalen. Düsseldorf.

Mannaerts, H.J.B.M., 1993. 'Het verbruik van non-energetische grondstoffen op lange termijn'. Onderzoeksmemorandum, 109. Centraal Planbureau, Den Haag, 43pp.

Metal Bulletin Ltd.: Cadmium. Edited Proceedings. Cadmium Conference. Several volumes. London.

Olendrzynski, K., Anderberg, S., Bartnicki, J., Pacyna, J., Stigliani, W.M., 1995: Atmospheric Emissions and Deposition of Cadmium, Lead and Zinc in Europe During the Period 1955-1987. WP-95-35. International Institute for Applied Systems Analysis. Laxenburg/Austria.

Opschoor J.B., Reijnders, L., 1991. 'Towards Sustainable Development Indicators'. in: H. Verbruggen and O. Kuik (Editors): 'In Search of Indicators for Sustainable Development' Kluwer Academic Press, Dordrecht: p7-29

Pacyna, J.M., 1991: Emission Factors of Atmospheric Cd, Pb and Zn for Major Source Categories in Europe in 1950 through 1985. Norsk Institutt for Luftforskning. Lillestrøm.

Park, S., 1992. Decomposition of industrial energy consumption: An alternative method. *Energy Economics*, :265-269.

Pearce, D.W., 1993. 'Blueprint 3: Measuring sustainable development'. Earthscan Publications, London, 224pp.

Rose, A., Chen, C.Y., 1991. Sources of change in energy use in the U.S. economy, 1972-1982: A structural decomposition analysis. *Resources and Energy*, Vol 13: 1-21.

Schackmann, H., 1972: Umwelt und Wirtschaft im Ruhrgebiet. Schriften der Volks- und Betriebswirtschaftlichen Vereinigung im Rheinisch-Westfälischen Industriegebiet. Düsseldorf.

Schucht, S., 1993: Ökologische Aspekte des Strukturwandels im Bergbau und Verarbeitenden Gewerbe von Nordrhein-Westfalen. Diplomarbeit. Forschungsstelle für Umweltpolitik, Freie Universität Berlin.

Selden, T.M., Song, D.S. 1994. Environmental Quality and Development: Is There a Kuznets Curve for Air Pollution Emissions?. *Journal of Environmental Economics and Management*, vol27, p147-162.

Shafik, N. and Bandyopadhyay. S., 1992. Economic Growth and Environmental Quality: Time-Series and Cross-Country Evidence, World Bank Working Papers WPS 904, Washington.

Skolka, J., 1989. Input-Output Structural Decomposition Analysis for Austria. *Journal of Policy Modelling*, Vol 11: 45-66.

Statistisches Bundesamt: Statistisches Jahrbuch für die Bundesrepublik Deutschland. Several volumes. Wiebaden.

Stigliani, W.M., Anderberg, S., 1992: Industrial Metabolism at the Regional Level: The Rhine Basin. WP-92-10. International Institute for Applied Systems Analysis. Laxenburg/Austria.

Stigliani, W.M., Jaffé, P.R., 1993: Industrial Metabolism and River Basin Studies: A New Approach for the Analysis of Chemical Pollution. IIASA-Working Paper.

Stigliani, W.M., Jaffé, P.R., Anderberg, S., 1993: Pollution in the Rhine Basin. *Environmental Science & Technology*. Vol. 27, No. 5, pp. 786-793.

McSweeney, C., Hirosako, M., 1991. Understanding crude steel consumption: The perils of ignoring the role of technological change. *Resources Policy*, vol15, p258-270.

Torvanger, A., 1991. Manufacturing sector carbon dioxide emissions in nine OECD countries, 1973-1987: A Divisia index decomposition to changes in fuel mix, emission coefficients, industry structure, energy intensities and international structure. *Energy Economics*, : 168-186.

UBA, 1977: Materialien zum Immissionsschutzbericht 1977 der Bundesregierung an den Deutschen Bundestag. Umweltbundesamt. Berlin.

UBA, 1982: Anhörung zu Cadmium. Protokoll der Sachverständigenanhörung Berlin, 2. bis 4. November 1981. Umweltbundesamt (Editor). Berlin.

Umweltbericht, 1974: Umweltbericht Nordrhein-Westfalen. Landesregierung Nordrhein-Westfalen (Editor). Düsseldorf.

Umweltprogramm, 1983: Umweltprogramm Nordrhein-Westfalen. Landesregierung Nordrhein-Westfalen (Editor). Düsseldorf.

Umweltprogramm, 1993: Zehn Jahre Umweltprogramm Northrhine-Westfalia und Reformperspektiven für die 90er Jahre. Ministerium für Umwelt, Raumordnung und Landwirtschaft Nordrhein-Westfalen. Düsseldorf.

Umweltprogramm Maßnahmen, 1983: Maßnahmenkatalog zum Umweltprogramm Nordrhein-Westfalen. Landesregierung Nordrhein-Westfalen (Editor). Düsseldorf.

Umweltprogramm Zwischenbericht, 1984: Umweltprogramm Nordrhein-Westfalen - Zwischenbericht. Landesregierung Nordrhein-Westfalen (Editor). Düsseldorf.

VDI, 1984: Schwermetalle in der Umwelt. UFOPLAN-Nr. 10403186. VDI-Kommission Reinhaltung der Luft. Berlin.

Vogt, A., 1978. Divisia Indices on Different Paths. In: Eichorn, W. (Editor). Theory and application of economic indices: proceedings of an international symposium held at the University of Karlsruhe, April-June 1976. Physical Verlag, Wurzburg: 297-305.

Wadell, L.M. and Labys, W.C., 1988. Transmaterialization: Technology and Materials Demand Cycles. *Materials and Society*, vol12: 59-85.

Wyckoff, C., 1992. Structural Change and Industrial Performance: A Seven Country Growth Decomposition Study. OECD, Paris.

Annex A: Three Decomposition Methods Based on Measurement of Discrete Changes

Decomposition methods have normally been derived from Divisia integrals [Liu et al., 1992]. This linkage of decomposition methods to the theory of index numbers is sometimes confusing and leads us to numerous combinations of possible decomposition methods. In this annex, we derive decomposition methods differently: depending on the way change in economic variables can be measured. This singles out three decomposition methods.

A.1. Measuring Change

Over time, all economic variables are subject to changes. Despite the importance of "change" in economic studies, amazingly little has been written on the *measurement* of change. The reason must be that in economic theory all variables are continuously changing over time. In such a continuous world, the concept of derivative explains all changes, both in the margins as over longer periods of time. However, with discrete time this similarity no longer holds.

Between a certain time interval <0,T>, change in any positive variable y(t) can then be measured in three interrelated ways:
(1) Exponential growth rates: $\ln(y_T) - \ln(y_0)$
(2) Absolute changes: $y_T - y_0$
(3) Percentage changes: $(y_T - y_0)/y_0$ (*100%)

Each of these expressions gives different figures for the change in y(t). It could be argued that they serve basically different purposes, but in decomposition analysis they also differ in their ability of segregation: to distinguish the change in one composite variable as the sum of changes in each component. We will argue that in that respect decomposition with absolute or percentage changes has some advantages over decomposition with exponential growth rates.

A.1.1. Interrelations Between the Three Ways to Measure Change

The three ways to measure change in discrete time-intervals can all be derived from the continuous growth-rates. Growth is by its very nature the addition of a flow to a stock variable. The basic property of a function that exhibits a constant rate of growth is that the addition of the flow to the stock is constant at each point in time. Thus a constant rate of growth has the effect of an exponential increase in the stock variable, a phenomenon that was already investigated by Malthus. For a differentiable function $y = f(t)$, where y can for example be income, this will give the following growth rate r(y):

$$r(y) = \frac{dy/dt}{y} = \frac{f'(t)}{f(t)} \qquad \text{(A.1)}$$

Imposing the initial condition that at $t=0$, $y(0) = y_0$, the function that satisfies equation (A.1) is the exponential function:

$$y(t) = y_0 e^{rt} \qquad \text{(A.2)}$$

The discrete growth rate over a time interval 0 and T is then found by integrating (A.1) over the time interval, which results in:

$$r(y)_{0,T}=\int_0^T \frac{f'(t)}{f(t)}dt = \int_0^T \frac{d(\ln(y))}{dt}dt = \ln(y_T)-\ln(y_0) \tag{A.3}$$

Since the derivative of the natural logarithm of f(y) is by definition equal to (A.1) the rate of growth between 0 and T can simply be calculated by taking the logarithmic difference. This gives the discrete growth rate.

The absolute changes are simply defined by the numerator of (A.1), which is being identified as the addition of the flow to the stock. Integrating f'(t) over a time interval 0 and T gives then simply the absolute changes in variable y(t):

$$\int_0^T f'(t)dt = \int_0^T \frac{dy}{dt}dt = y_T-y_0 \tag{A.4}$$

Percentage changes are some kind of hybrid forms. A percentage is the ratio of a variable y(t) over two moments in time, 0 and T, and can be given as: $(y_T/y_0)\cdot 100\%$. Percentage *change* is then defined by subtracting 100% from this percentage: it gives the relative increase compared to the base year. The percentage change can be expressed as:

$$\tilde{y}_{0,T} = \frac{y_T-y_0}{y_0} = \frac{y_T}{y_0}-1 \tag{A.5}$$

which gives a percentile that can be multiplied by 100%.

It can be shown that the percentage change is a special discrete type of exponential growth rates, as defined by equation (A.1). Notice that (A.3) can be written differently as:

$$r(y)_{0,T} = \int_0^T \frac{f'(t)}{f(t)}dt = \int_0^T \frac{dy/dt}{y}dt \tag{A.6}$$

By (A.4) we have for the integration of the numerator *dy/dt* the discrete expression y_T-y_0. It is only with the denominator that we cannot say which value we should choose for y. Over the time interval considered, y takes the values between y_0 and y_T. Basically we can choose either y_0, y_T or some weighted combination of both. By choosing y_0 (base year weighting), (A.6) reduces to (A.5).

A.2. Decomposition Analysis

Many economic variables are composite variables. Changes in nominal income consist of the changes in prices and quantities. However, changes in prices are simply inflation and do not add to economic welfare. The question is how to disentangle the influence of price changes from quantity changes in order to correct the nominal income for price changes. Price movements occur in a wide variety of consumer goods and there seems no real prescription how we could add them up in order to get an aggregate index of consumer price changes [Allen, 1975]. This relates decomposition to the statistical economic theory of index numbers: the consumer price index is just one example. So our variable income y is made up by the sum of expenditures on a number of j goods (y_j) where each of the expenditures on good j is made up by the multiplication of prices and quantities: $y=\Sigma y_j=\Sigma p_j q_j$. Decomposition aims to disentangle the price changes from quantity changes. We will do that in two steps. First we will decompose the income spent on good j (y_j) into price and quantity changes. Then we will add up all the price and quantity changes for all goods in order to correct nominal income for price changes. So our first step is to decompose a *multiplicative* term ($y_j=p_j q_j$), while our second step is to implement this in an *additive* framework ($y=\Sigma y_j$).

A.2.1. Exponential Growth

The decomposition of expenditures on y_j into a price and quantity component is straightforward since taking the logarithm of a product is similar to the sum of the two logarithms. So the growth rate $r(y_j)$ can be obtained as:

$$r(y_j)_{0,T} = \int_0^T \frac{f_j(t)}{f_j(t)} dt = \int_0^T \frac{d(\ln(y_j))}{dt} dt = \ln(p_{j,T}) - \ln(p_{j,0}) + \ln(q_{j,T}) - \ln(q_{j,0}) \qquad \text{(A.7)}$$

The growth rate of a multiplicative term can be given as the growth rates of their components. However, the *sum* of the growth rates on the expenditure of every product j does not add up to the total growth rates ($\ln(y)$ is not equivalent to the sum of $\ln(y_j)$):

$$r(y) \neq \sum_j r(y_j) \qquad \text{(A.8)}$$

Therefore we cannot add up the growth rates of the prices and quantities of every good j in order to construct price and growth quantities.
The way to do this starts from the continuous case by rewriting total income in (A.3) as the sum of expenditures on j goods (y_j):

$$r(y) = \frac{d(\ln(\Sigma y_j))}{dt} = \frac{1}{\Sigma y_j} \frac{d}{dt}(\Sigma y_j) = \frac{\Sigma f_j'}{\Sigma y_j} \qquad \text{(A.9)}$$

Analogous to (A.1), f'_j equals $f_j r(y_j)$ so that (A.9) can be expressed as:

$$r(y) = \sum_j \frac{y_j}{y} \cdot r(y_j) \qquad \text{(A.10)}$$

So the growth rate of income is the sum of weighted growth rates of the expenditures on every j product where the ratio y_j/y reveals how we should weight the growth rates of the components in order to match them with the growth rate of the total. This ratio can be seen as the structural variable (s_j), since it reveals something of the structure of expenditures in an economy. Using (A.8) it follows that (A.10) can be rewritten in the discrete case as:

$$r(y)_{0,T} = \sum_j \int_0^T s_j(t) r(y_j) dt = \sum_j s_j(t)\{\ln(p_{j,T}) - \ln(p_{j,0})\} + \sum_j s_j(t)\{\ln(q_{j,T}) - \ln(q_{j,0})\} \qquad \text{(A.11)}$$

It is here that we encounter a well-known difficulty [Vogt, 1979]: we do not know the time path of the structural variable $s_j(t)$. Between the time-interval 0 and T, s_j will change because the structure of the economy is not likely to remain constant. Over the time interval considered, s_j takes the values between $s_{j,0}$ and $s_{j,T}$. So we could use either $s_{j,0}$ (base year) or $s_{j,T}$ (current year) or some combination of both in order to weight the growth in prices or quantities.

It has been proposed by Liu et al. [1992] to transform this path problem into a parameter estimation problem through the following linear weighting function:

$$w_{s_j} = s_{j,0}+\theta_j(s_{j,T}-s_{j,0}), \qquad 0 \leq \theta_j \leq 1 \tag{A.12}$$

where Θ_j is the weighting factor between year 0 and T. Choosing values for Θ_j then defines the time path of the structural variable $s_j(t)$ that is used in decomposition analysis. Choosing $\Theta_j = 0$ results in a weighting of the price and quantity growth rates with the structure of the expenditures in year 0, while $\Theta_j = 1$ results in a weighting with the structure in year T. The parameter values of 0 and 1 represent the boundaries for the choice since the assumption with integration is that the variables are monotonically increasing or decreasing over the time interval [Liu et al., 1992][34]:

Applying this weighting function in the decomposition method returns the following parametric decomposition method (PDM) based on exponential growth rates[35]:

$$\ln(y_T-y_0) = \sum_j w_{s_j} \cdot \ln(p_{j,T}-p_{j,0}) + \sum_j w_{s_j} \cdot \ln(q_{j,T}-q_{j,0}) + \sum_j \ln(R_j) \tag{A.13}$$

The growth of income is then decomposed into a *price effect* and a *quantity effect*. This decomposition method contains a residual R_j. This residual term is added here since we do not know the time path of the structural variable y_j/y. So if we took $\Theta_j = 0$ for every j, the sum of the "price-effect" and "quantity-effect" would probably not match the total growth in income because of changes in the structural variable over the time period considered (see also A.2.4.).

A.2.2. Absolute Change Decomposition

Decomposition based on absolute changes aims to disentangle the absolute change in prices from the absolute change in quantities. Starting with decomposition of the multiplicative term $y_j=p_jq_j$ and assuming that all the variables are a function of time $(f_j(t)=g_j(t)h_j(t))$, we get analogous to (A.4):

$$y_{j,T}-y_{j,0} = \int_0^T g_j(t)h_j'(t)dt+\int_0^T h_j(t)g_j'(t)dt \tag{A.14}$$

which is simply the product-rule of differentiation. Over a time interval <0,T>, $g'_j(t)$ and $h'_j(t)$ are defined as the absolute changes in p_j and q_j respectively (see also equation (A.4)). This would yield the following decomposition method based on absolute change:

$$y_{j,T}-y_{j,0} = q_j(t)(p_{j,T}-p_{j,0})+p_j(t)(q_{j,T}-q_{j,0}) \tag{A.15}$$

Similar to the decomposition of exponential growth rates, the variables $p_j(t)$ and $q_j(t)$ that are used as weights for the absolute change in the other variable, are not defined over the time interval <0,T>. We can set up now two weighting functions: one for the change in price and one for the change in quantity for every good j:

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[34] This means that s_j cannot exceed the values of year 0 and T.

[35] This parametric decomposition method is similar to the decomposition method PDM1 that was proposed in Ang [1994] (no formal derivation). Decomposition with $\Theta_j = 0.5$ for all j was performed by Boyd et al. [1988] and Torvanger [1991], while decomposition with $\Theta_j = 0$ for all j was performed by Howarth et al. [1991].

$$w_{p_j} = p_{j,0}+\alpha_j(p_{j,T}-p_{j,0}) \tag{A.16}$$

$$w_{q_j} = q_{j,0}+\beta_j(q_{j,T}-q_{j,0}) \tag{A.17}$$

Unlike the exponential growth rates, the sum of absolute changes in the expenditure on each good j, equals the absolute change in the total:

$$y_t-y_0 = \sum_j (y_{j,T}-y_{j,0}) \tag{A.18}$$

Combining (A.15), (A.16), (A.17) and (A.18) yields then the following parametric decomposition method based on absolute changes:

$$y_T-y_0 = \sum_j w_{q_j}(p_{j,T}-p_{j,0})+\sum_j w_{p_j}(q_{j,T}-q_{j,0})+\sum_j R_j \tag{A.19}$$

This equals PDM2 as given in Ang [1994]. Again a residual term is added since the price and quantity-effects do not add up to the total change in income for the same reasons as have been mentioned above.

A.2.3. Percentage Change Decomposition

Percentage change decomposition can now simply be derived from the absolute change decomposition. Notice that a percentage change of a variable y is simply the absolute change divided by the base year value of this variable (see equation (A.5)). The absolute change decomposition method is simply transformed into its percentage change equivalent by dividing every term in (A.19) by y_0. Filling in the weighting functions (A.16) and (A.17) into (A.19) and using the fact that $y_0 = (y_0/y_{j,0})p_{j,0}q_{j,0}$, gives the following percentage decomposition method:

$$\tilde{y} = \sum_j s_{j,0}(1+\alpha_j\tilde{q}_j)\tilde{p}_j+\sum_j s_{j,0}(1+\beta_j\tilde{p}_j)\tilde{q}_j+\sum_j R_j \tag{A.20}$$

The weighting functions are now integrated into the decomposition method, though the restrictions on the parameter values for α_j and β_j remain the same.

Notice furthermore that the percentage change of *observed* variables must per definition fall between the range of <-100%, +∞%>. Percentage changes can by definition not result in values lower than -100%. But since decomposition analysis uses *constructed* variables (i.e. price-effects and quantity-effects), their values can be lower than -100%. The total change in income can, however, never be lower than -100%, but the change in its components can exceed these ranges.

A.2.4. Allocation Schemes for the Residual Term

Every decomposition method includes a residual term. This residual term is the variation in income that could not be explained by either the change in prices or the change in quantities. The residual term will become larger (i) the more the variables in the weighting functions have been changed between period 0 and T, and (ii) if one of the extreme values of 0 or 1 for the parameters in the weighting functions has been chosen. While the first cause may emphasize the need to get more data and conduct decomposition in smaller periods of time, the second cause implies a sensible choice for the parameters in the weighting function. We will focus here on the latter aspect.

In order to more fully understand the residual term, we need first to give it a mathematical expression. For decomposition with exponential growth rates, we can solve R_j from (A.13) which gives the following expression:

$$\sum_j \ln(R_j) = \ln\left(\frac{y_T/y_0}{\prod_j \{y_{j,T}/y_{j,0}\}^{w_{*j}}}\right) \tag{A.21}$$

Notice that to obtain a zero residual the numerator and denominator of (A.20) must equal. So if we could find parameter values for Θ_j in the weighting function that make the numerator and denominator equal, we would obtain decomposition with a zero residual. The resulting parameter value for Θ_j can be given as:

$$\alpha_j = \frac{\ln(y_T/y_0)}{n(s_{j,T}-s_{j,0})\ln(y_{j,T}/y_{j,0})} - \frac{s_{j,0}}{s_{j,T}-s_{j,0}} \tag{A.22}$$

where n equals the amount of sectors. However, in general there is no guarantee that the values for Θ_j will lie inside the range of 0 and 1 and therefore this solution is of no value. Numerical examples can make clear that a value for Θ_j of 500 is no exception. This would violate the assumption of integration and render meaningless results. Therefore, it appears that decomposition with exponential growth rates cannot be performed without residual terms. As mentioned by Boyd et al. [1991], choosing parameter values of 0.5 for Θ_j will give a small residual. However, the arguments for these values are only based on the aim to minimize the residual. As mentioned in Howarth et al. [1991] and Park [1992], there is hardly an argument for these values if the interpretation of decomposition results is important.

For the absolute change decomposition, we can perform the same kind of analysis. Solving the residual from (A.19) using the weighting functions (A.16) and (A.17) will give the following expression:

$$\sum_j R_j = \sum_j (1-\alpha_j-\beta_j)(p_{j,T}-p_{j,0})(q_{j,T}-q_{j,0}) \tag{A.23}$$

It becomes clear that with absolute change decomposition, the residual term is defined as an interaction term between the change in price and the change in quantities for every sector j. This expression clarifies that any combination that fulfils $\alpha_j + \beta_j = 1$ will result in decomposition with a zero residual.

The question which values we should take for α_j and β_j becomes now quite important. We could take $\alpha_j = \beta_j = 0.5$ as proposed by Ang [1994]. Notice that this solution is equivalent to adding half of the residual term to the price changes and half of it to the quantity changes compared to decomposition with either $\alpha_j = \beta_j = 0$ or $\alpha_j = \beta_j = 1$. But the question that can be put forward is: why is this decomposition scheme more favourable over for example $\alpha_j = 0.3$ and $\beta_j = 0.7$? De Bruyn and Van den Bergh [1995] argue that since the interaction term itself is made up by the absolute change in prices and quantities, it is clear that the *size* of the interaction term will depend on the relative size of both the price and the quantity changes. We can use the relative size of each effect in order to split the interaction term *proportionally* to both price changes and quantity changes. What is proposed in De Bruyn and Van den Bergh [1995] is to add an α-share of the interaction term to the price changes and a β-share to the quantity changes, so that $\alpha_j + \beta_j = 1$ and that the share of the added residual is equal for both effects. This can be set up as:

$$\frac{\alpha_j(p_{j,T}-p_{j,0})(q_{j,T}-q_{j,0})}{|q_{j,0}(p_{j,T}-p_{j,0})|} = \frac{\beta_j(p_{j,T}-p_{j,0})(q_{j,T}-q_{j,0})}{|p_{j,0}(q_{j,T}-q_{j,0})|} \tag{A.24}$$

Condition (A.24) assures that the share of the added interaction term is proportional to the absolute percentages of both effects. It should be emphasized that only the size of the denominator is important (which is therefore taken in absolute values). If the absolute changes in p or q differ in sign, the interaction term will be negative. Without absolute values either α or ß must be negative in order to fulfil condition (24). This means that one positive part of the interaction term is allocated to one effect and a negative part to the other effect. This can be quite substantial if the growth rates of p and q differ in sign but are in size almost equal: values for α of -200 and ß 201 are then no exception. This does not make much sense of course; we are interested in splitting the interaction term completely and not in adding multitudes of the interaction term to one effect and subtracting multitudes of the interaction term from the other effect.

The values for α and ß that result from (A.13) together with the additional condition that α_j + $ß_j$ = 1, are:

$$\alpha = \frac{|\tilde{p}|}{|\tilde{p}| + |\tilde{q}|} \qquad \text{(A.25)}$$

$$\beta = \frac{|\tilde{q}|}{|\tilde{p}| + |\tilde{q}|} \qquad \text{(A.26)}$$

These values can be filled in (A.19) and the absolute change in income is then completely specified by the change in prices and the change in quantities. The interaction term is zero by definition. The solution for percentage changes is mathematically equivalent and will give the same solution for α_j and $ß_j$: this will not be shown here.

ANNEX B Data Description

B.1. Emission Data

B.1.1. Emission Data Supplied by IIASA

The emission data supplied by IIASA is based on a calculation of production in physical units of the sectors relevant for heavy metal emissions in the Northrhine-Westfalia part of the Rhine Basin. Known was the production of these sectors for Germany as a whole. With help of the capacity share of the Northrhine-Westfalia part of the Rhine Basin and Germany as a whole for each of these sectors the production in physical units was calculated. By multiplying this data with emission factors for Germany, published by Pacyna [Pacyna, 1991; Olendrzynski et al., 1995] the emissions for each sector were calculated.

B.1.2. Emission Data Used in this Paper

As we match emission data with economic data (gross value added, production data) which is only available for Northrhine-Westfalia as a whole, we upgraded the emission data for those sectors where a relevant part of production takes place outside the Rhine Basin part of Northrhine-Westfalia. This holds true for the non-ferrous metals production and the cement production.

Emissions Related to NF-Metals Production

Concerning the non-ferrous metals production we upgraded the emissions by dividing them by the capacity share of the non-ferrous metals production of the Northrhine-Westfalia part of the Rhine Basin and the total of Northrhine-Westfalia.

These shares are:

	1955	1960	1965	1970	1975	1980	1985	1988
Zinc production	0.63	0.63	0.69	1.00	1.00	1.00	1.00	1.00
Lead production	0.33	0,33	0.31	0.46	0.44	0.45	0.45	0.45
Copper production	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Emissions Related to Cement Production

No information on capacity shares of cement production in the Northrhine-Westfalia part of the Rhine Basin and Northrhine-Westfalia as a whole was available. In order to upgrade the data of emissions caused by cement production we, therefore, multiplied the emissions with the share of cement production in physical units in Northrhine-Westfalia as a whole[36] and the Northrhine-Westfalia part of the Rhine Basin[37].

These shares are:

	1955	1960	1965	1970	1975	1980	1985	1988
Cement Production	1.63	1.55	1.73	1.69	1.85	1.82	1.66	1.68

Emissions Related to Electricity Production

The data on emissions due to the production of electricity included emissions of public and industrial plants. In order to match this emission data with economic data (GVA) we split the emissions into those caused by public power plants and those caused within other sectors. For this purpose we used the shares in electricity production of the public power plants and the sectors mining, iron and steel, non-ferrous metals and the chemical industry, as the most important sectors for electricity production, according to their contribution published in the energy balances of Northrhine-Westfalia. According to these shares we split up the emissions for electricity production published by IIASA and added them to the emissions of the relevant sectors.
As the energy balances have only been published since 1978 we assumed, that for the years 1955, 1960, 1965, 1970 and 1975 the sectoral shares were the same as in 1978.

In Chapter 6, however, when we match the emission data with production data in physical terms, we do not add the emissions due to electricity production within industrial plants, as we investigate here the specific productions of coke, non-ferrous metals and iron and steel.

B.2. Data on Gross Value Added in Real Terms

Data on industrial gross value added in real terms (price base 1991) was obtained from the statistical office in Northrhine-Westfalia on sectoral level for the period from 1970 to 1988 but it was not available for the years before. Concerning electricity production, no data on gross value added was available for the years of 1970 to 1979, however, data for the whole utility sector was available for these years. In order to match this economic data as accurately as possible with the emission data two different adjustments of data were necessary.

B.2.1. Data on Gross Value Added for Electricity Production from 1970 to 1979

For the years of 1980 to 1988 data on gross value added was available for both, electricity production and the total utilities sector. In order to calculate data on gross value added for

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[36] Data published by the statistical office of Northrhine-Westfalia (LDS - Landesamt fuer Datenverarbeitung und Statistik Nordrhein-Westfalen).

[37] Data calculated by IIASA as stated above.

electricity production for the years 1970 to 1979 we assumed, that the share of electricity production in the total utilities sector was the same for 1970 to 1979 as in 1980.

B.2.2. Data on Gross Value Added for Sectors and the Total Industry Before 1970

In order to calculate data on gross value added for the sectors and the total industry of Northrhine-Westfalia for the period of 1955 to 1969 we created in a first step series of industrial production indices standardized on 1962=100 for the years of 1955 to 1970. In a second step we calculated the sectoral respectively industrial gross value added for each year t by dividing the production index of year t by the production index of 1970 and multiplying this share by the statistical office data on gross value added for 1970.

That is:

a) for the specific sectors
$GVA_{j,t} = Index_{j,t}/Index_{j,1970}*GVA_{j,1970}$,
where
j: sectors,
t: years (1955 to 1969)
and
b) for the total industry
$GVA_{i,t} = Index_{i,t}/Index_{i,1970}*GVA_{i,1970}$,
where
i: total industry,
t: years (1955 to 1969).

B.3. Production Data in Physical Terms

Sectoral production data in physical terms (tonnes) for the years 1955 to 1988 was obtained for the whole of Northrhine-Westfalia from the statistical office in Northrhine-Westfalia, and for the Rhine Basin part of Northrhine-Westfalia from IIASA.