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# Austrian Carbon Database: Production and Waste. Material Flow Based Carbon Accounting for 1990

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## Contents

## Abstract

In recent years material flow analysis (MFA) has become the main approach to develop indicators for socioeconomic pressures upon the environment as well as an information tool for environmental policy. Austria is one of the few countries that already have official material flow statistics based on MFA.

Carbon management will be the mayor issue in environmental policy for the next decades for which consistent data will be required. It has been suggested that material flow statistics could also be used for carbon accounting.

As a first step towards carbon management for Austria, material flow accounting will be used to determine the uncertainties underlying the carbon flow data for the production and waste sectors.

## Acknowledgments

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# Austrian Carbon Database:
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Klaus Kubeczko

## 1 Introduction

In the United Nations Framework Convention on Climate Change (UNFCCC) from 1994, the signatory countries have committed themselves to producing national climate reports. With the countries’ commitment on reducing greenhouse gas (GHG) emissions by ratifying the Kyoto Protocol, their reduction targets will become binding. In Austria, as in other countries, these commitments have initiated research on assessing greenhouse gas emissions. So far, most nations’ reporting systems are based on partial carbon accounting (PCA) using the Intergovernmental Panel on Climate Change (IPCC) guidelines. Two main initiatives are now using a full carbon accounting (FCA) approach, the Austrian Carbon Balance Model (ACBM) and the Austrian Carbon Database (ACDb).

Full carbon accounting is not yet used and applied in a standardized way. However, two main features are considered of paramount importance:

1. The inclusion of **all carbon flows** of the anthropogenic system and terrestrial biosphere is necessary for a consistent view of the human impact on the carbon cycle.
2. To be able to distinguish between an anthropogenic system and the biosphere, **clear boundaries** must be drawn. Therefore, on the one hand, a **consistent picture** of the anthropogenic system (not only taxonomically as under PCA) is necessary. On the other hand, biospheric carbon flows must be represented in a way that makes it possible to perceive the exchange with the anthropogenic system.

The model developed by a consortium of Austrian research institutes, ACBM, represents full carbon accounting that allows different emission scenarios to be carried out. The ACDb, developed by IIASA, focuses on the uncertainties in the data available. The ACDb is the first approach that concentrates on consistent carbon flow reporting rather than on emission oriented model design. This paper presents part of the research related to the ACDb. The established tool of material flow analysis (MFA), which balances material flows, is used as part of the FCA to balance Austria’s carbon flows relating to the production and consumption of goods, including their waste.

In this paper, emphasis is also given to problems related to the consistent picture of the anthropogenic system and its clear boundaries.

## 2 Focusing on Production and Waste: Why MFA?

The aim of the ACDb is to establish a FCA system for Austria with the goal of having a consistent database that includes uncertainties. For this purpose, it is proposed that carbon flows should be based on MFA.

This study attempts to use the material flow balance for Austria, developed by the Institute for Interdisciplinary Studies of Austrian Universities (IFF) and maintained by Statistics Austria, for those parts of the ACDb representing production (excluding process energy) and consumption of goods that were tagged according to ACBM terminology[1] as {PROD} and waste management tagged as {WASTE}. As Austria is one of the few countries that is already conducting MFA,[2] this provides the opportunity of using a methodology that is increasingly used for global environmental discussions[3] and might become a standard in national environmental reporting.[4]

To base carbon accounting on the already established MFA methodology could bring several advantages:

1. Material flow accounts are representations of a society's metabolism, which are compatible with the established economic representation of national accounting and input-output tables. This is the main advantage of using MFA-based carbon accounting as it allows for socioeconomic analysis of carbon related GHG emissions.
2. Efficiently using existing data sets where problems, such as double counting and consistency, have already been solved. Material flow data can be used for several purposes and, therefore, can realize synergies.
3. Uncertainties can be evaluated in two steps: (a) uncertainty of material flows taken from material flow accounts, and (b) uncertainties of carbon conversion factors.

The goal of the study was to show the feasibility and limits of using MFA as a basis for the anthropogenic part of FCA. Furthermore, it compares MFA-based carbon accounting to the ACBM. MFA research can profit from the ACDb approach as the quantification of uncertainties for material flows are investigated for the first time.

For this research study, the structure and the system boundaries of the ACDb were available from the beginning. It is structured the same way as the ACBM consisting of five modules: energy use and transformation {ENERGY}, forestry {FOREST},

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[1] ACBM terminology is used for the comparability of both approaches.

[2] Austria, Germany and Japan were the first countries to establish national material flow balances in the 1990s.

[3] The World Resources Institute (WRI) recently published a report based on material flow methodology to compare the environmental policies of the USA, Japan, Germany, Austria, and the Netherlands (Matthews *et al.*, 2000).

[4] When designing the ACBM project, MFA related research was not considered.

agriculture (plants and animals) {AGRO}, production and consumption {PROD}, and waste management {WASTE}. The modules exchange carbon with the systems' environment, i.e., atmosphere {ATMO}, lithosphere {LITHO}, and imports/exports {IMP/EXP} (see Figure 1).[5]

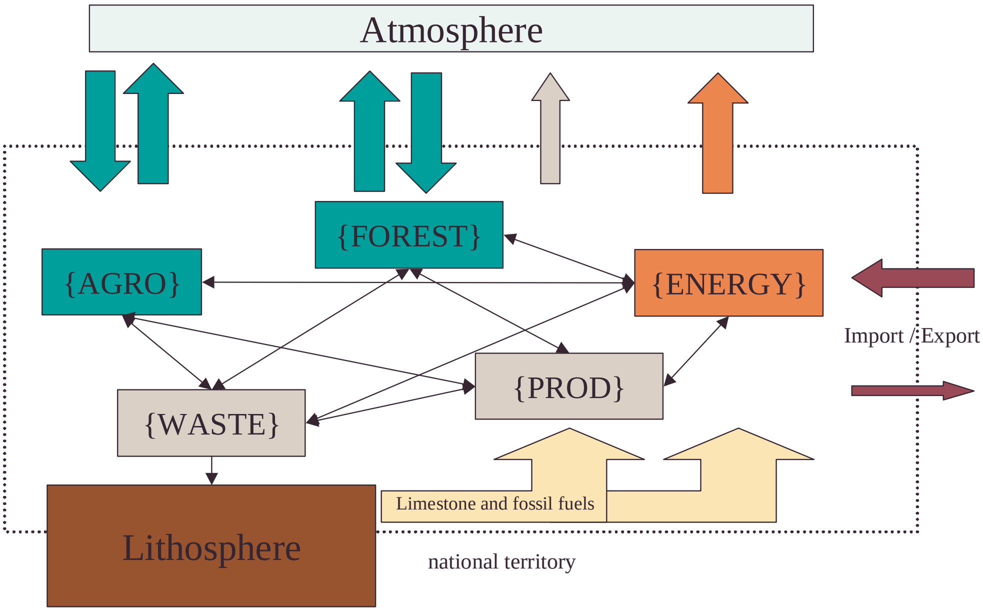

*Figure 1: Structure of ACBM.*

For the ACDb project, published data was used where applicable from the material flow balance for 1990 (Hüttler *et al.*, 1996), from the material flow time series for Austria (Schandl, 1998), and the WRI report on societies' material output (Matthews *et al.*, 2000). No unpublished background data on a lower aggregation level was used. Therefore, any results in this report can be reproduced.

Published data for MFA is only available for 1990 and 1992. It was decided to concentrate on carbon flows for 1990. At the moment, trends in uncertainties cannot be calculated for 1990 due to missing data for the years before and after that year.

Before going into the details of FCA in the form of material flow based accounting of the ACDb, some arguments in favor of FCA are presented.

## 3 Full Carbon Accounting versus Partial Carbon Accounting

The Kyoto Protocol intends to affect human behavior related to global warming, with the final goal to "*prevent dangerous anthropogenic interference with the climate system*". To reach this goal, the Kyoto targets only take into consideration what is called

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[5] Problems arose as the MFA system boundaries are not coherent with those of {PROD} and {WASTE}. This paper presents a first suggestion on how this problem can be solved.

"anthropogenic activities".[6] Proper measurement tools have to be applied in order to verify the results of human activities intended to stabilize or reduce GHG emissions. For this purpose, the IPCC provides guidelines for the measurement of emissions related to taxonomically listed activities. The IPCC takes into account the following emission source categories: energy, industrial processes, solvents and other product use, agriculture and waste. Briefly, these categories can be called "energy and industry", with its main sources of $CO_2$ emissions from fossil fuels and cement production. Land-use, land-use change and forestry (LULUCF) is a source/sink category in the IPCC guidelines. This accounting process is called partial carbon accounting (PCA), as it only considers carbon flows directly related to the activities listed.

Full carbon accounting (FCA), in contrast, includes all carbon related components of all terrestrial ecosystems. It provides a full and consistent picture of all carbon sources, flows,[7] and sinks relevant for global warming.

Different arguments for FCA can be found in recent IIASA reports (Jonas *et al.*, 2000; Obersteiner *et al.*, 2000), in the Final Project Report of the Austrian Carbon Balance Model (Orthofer *et al.*, 2000), and in CarboEurope (Valentini *et al.*, 2000).

Three arguments for FCA are:

1. ***Verification and Uncertainty***[8]

   In most cases, uncertainties are expected to be high where ecosystems are involved. How high is the sequestration of soils and forests? How high is the meteorological impact?

   The CarboEurope cluster of projects, which is a major European initiative to quantify the carbon balance of Europe, states in its report that "*[p]artial accounting of carbon sources and sinks can easily lead to a mismatch between our estimates of effects of various activities and the actual recorded signal in atmospheric* $CO_2$ *concentration*" (Valentini *et al.*, 2000). The argument concentrates on the technological means of measuring concentrations and relating them to emissions, i.e., to find the relation between flows and pools. A mismatch can also occur when dealing only with anthropogenic emissions as the flows and changes in carbon pools in consumption must also be dealt with. Typically, these flows become only verifiable when they can be checked using a top-down approach.

   By summing up flows taxonomically, PCA may result in the same emissions reported, although there will be no possibility to verify the flows in the way it is possible with MFA-based FCA.

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[6] The IPCC guidelines do not differentiate between direct human-induced and indirect human activities (Watson *et al*., 2000).

[7] Here, carbon flows include those flows that could lead to $CO_2$ emissions or $CH_4$ emissions.

[8] The term "uncertainty" is used in its broadest sense. This uncertainty reduces to the standard deviation if standard statistics can be applied. For a detailed explanation of the IIASA uncertainty concept see, Nilsson *et al*. (2000).

2. ***Leakage***

One problem that is frequently addressed deals with leakage. Trade-offs between $CO_2$ reduction projects cannot be detected when the transfer between the system in use and its environment are not considered.

As an example, reduction projects with verifiable $CO_2$ reductions in one country might lead to an even higher increase in $CO_2$ emissions in other countries. In forestry, there may be verifiable carbon absorption in old-growth forests, which is not used in Austria. As an isolated action, this makes sense. If this action leads to a reduction in harvest, the situation might be different. The compensation of harvests by imported timber can lead to higher losses in carbon sinks abroad (in the biosphere above ground, below ground biomass or in the socioeconomic system, imports/exports, trade-offs between projects). PCA does not consistently consider imports or exports, nor does it take into account trade-offs between reduction projects within one country. FCA considers imports and exports, and detects leakage, as consistency conditions do not allow for violating the law of the conservation of matter.

3. ***Action Leading Indicators***

The accounting system, be it PCA or FCA, should give a proper representation of the system allowing for policy conclusions.

In the IPCC guidelines (IPCC, 1996), activities like cement production are considered with one emission factor related to the production of cement. It does not look into the process leading to $CO_2$ emissions.

FCA, used in this study, distinguishes emissions related to process energy and those related to the chemical process. This allows the GHG emission to be traced to its source. In this example, it would be possible, *ex ante*, to estimate the reduction potential in cement production. Two-thirds of $CO_2$ emissions in cement production cannot be reduced if production is kept constant, as these emissions are consequences of the chemical process that transforms limestone into cement. Emissions, as a result of the process heat, make up only one-third of the total emissions related to the activity of cement production. FCA, in the event of inconsistencies, has to ask for reasons; PCA cannot detect them if reporting is only according to given guidelines.

# 4 From MFA to Carbon Flow Accounting

This section describes the procedure of building a carbon flow accounting system using material flow accounts. These accounts are based on the material flow analysis (MFA) approach.

## 4.1 What is MFA?

Material flow analysis is a method to represent the anthropogenic system (societies' metabolism, in MFA literature) in terms of matter, measured in tons. It balances those material flows that are activated by the economy, taking into account all inputs, outputs and accumulated stocks. When establishing a material flow balance the fundamental rule that must hold at any time is the input balances with output plus/minus changes in stock.

The MFA concept allows the creation of material balances in different forms: for countries (as used in this study), regions, fields of activities like "construction", "energy supply", "food supply" (Hüttler *et al.*, 1996), or for economic sectors such as, for example, the chemical sector (Schandl and Weisz, 1997).

The material balance is divided into five main groups: fossil fuels, mineral material, biomass, water and air. Data from the first three categories are relevant for carbon flow accounting.[9] The sub-balances of each of the categories are divided into three stages of the life cycle: primary extraction/imports, processing and final demand. All material flows activated by human economic activity are included in this balance (see Figure 2).

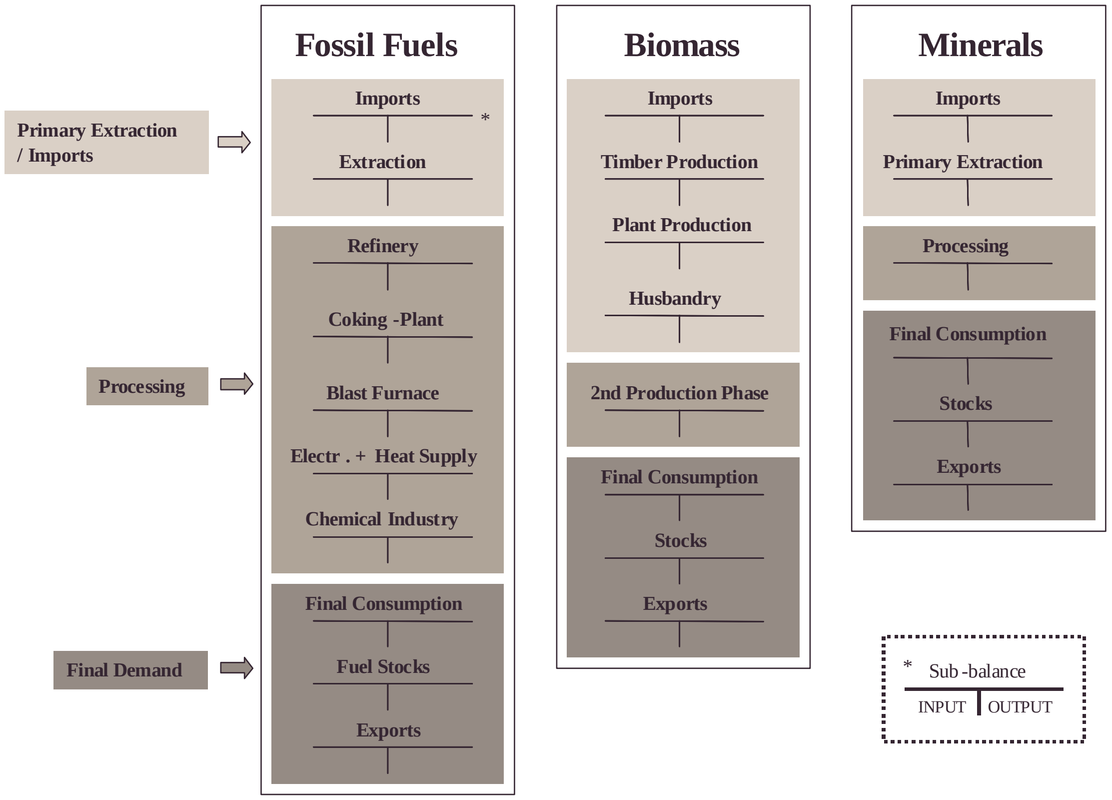

*Figure 2: Structure of material flow balance.*

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[9] The balances for water and air are accounted separately as they represent the highest material flows. These balances do not provide any carbon related information for CFA.

Austria, Germany, and Japan were the first countries to establish national material flow balances (Steurer, 1992; 1994; BMU, 1995; Schütz and Bringezu, 1993; Kuhn *et al.*, 1994). The World Resources Institute recently published a report based on material flow methodology to compare the environmental policies of the USA, Japan, Germany, Austria, and the Netherlands (Matthews *et al.*, 2000).

Austria is one of the few countries that have official statistics on material flows. The first material flow balance was established as a feasibility study in 1996 for the years 1990 and 1992 (Hüttler *et al.*, 1996).[10] A profound revision is planned for 2002 (Schandl, 2000). In the meantime, a revised material flow balance for the years 1996 and 1997 was produced by Statistics Austria.

The main characteristics of MFA relevant for FCA are:

- its consistency condition in material flow accounting. The different carbon related material flows can be aggregated in a bottom-up process and checked top-down with the law of the conservation of matter;
- its internal structure that allows for the comparison of material flows with economic activities; and
- its elaborated system boundaries, which enables a clear distinction between anthropogenic material flows and material flows to and from the biosphere.[11]

## 4.2 How to Draw System Boundaries?

The ACBM structure of FCA is shown in Figure 1. This structure does not take into account the difference between anthropogenic and biospheric flows within the different modules. The {AGRO} module not only includes harvest and livestock production but also carbon sinks in soil. The same is true for the {FOREST} module; a soil model is included in the module. This is the main structural difference that makes MFA-based carbon flows difficult to be integrated into ACBM logic. MFA only deals with the anthropogenic part of carbon flows. For FCA, a module representing the biospheric flows has to be added.

Figure 3 shows the different modules from ACBM within the MFA structure. In omitting those parts of {FOREST} and {AGRO} that have to be considered as biospheric, the ACBM modules fit into the MFA framework. Although, {PROD}, the module of main importance in this study, is split between all three main categories of MFA, i.e., fossil fuel, biomass and minerals.

During the course of the study, it became clear that mixing ACBM and MFA logic led to a major difficulty in comparability. Here and in the following paragraphs it is argued that FCA fully takes into account the MFA logic for the anthropogenic part of FCA.

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[10] The Department of Social Ecology of the Institute for Interdisciplinary Studies of Austrian Universities carried out this feasibility study (Hüttler *et al*., 1996).

[11] MFA methodology cannot be used as an information system for land-use and land-use change. This must be dealt with in a separate terrestrial biosphere module. The design of this module, as well as its links to the MFA-based carbon balance, have not been investigated in this study.

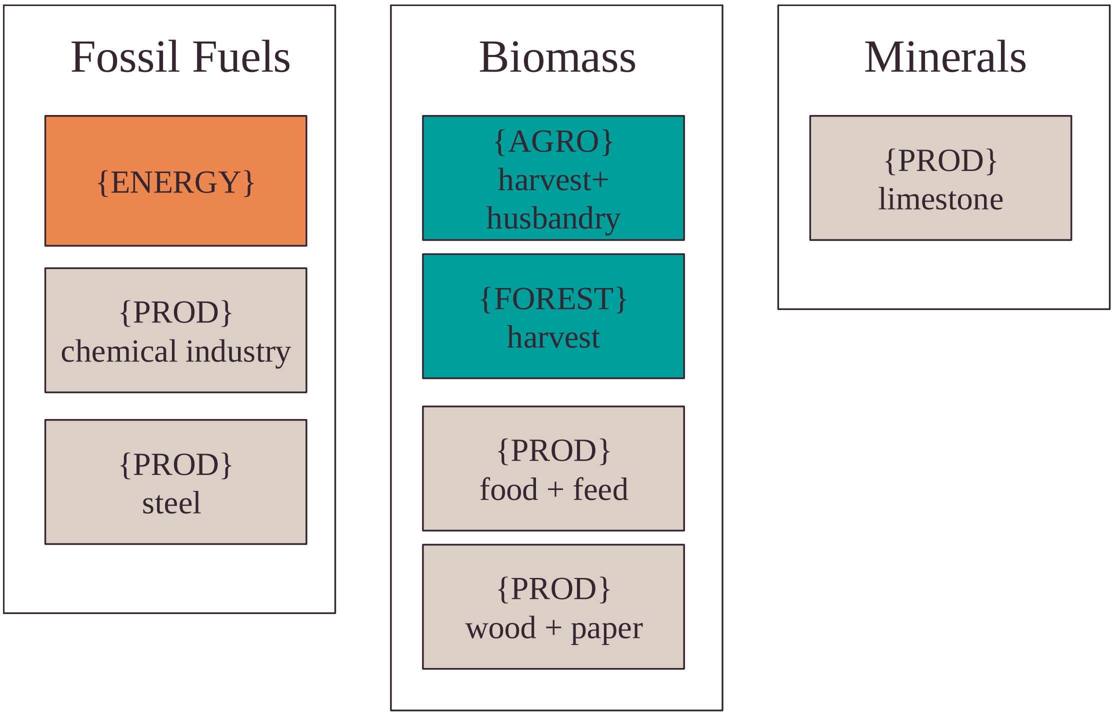

*Figure 3: ACBM and MFA categories compared.*

## 4.3 The Internal Structure of Flows Related to the Production Process, Consumption and Waste Management in the ACDb

As mentioned above, the structure and system boundaries of the ACDb were available from the beginning, as comparability with the ACBM should be given. However, the internal structure of {PROD} and {WASTE} were changed during the course of the study. The consumption of goods was part of {PROD}. In the ACDb model structure, the boundaries were drawn between {PROD} and consumption combined with waste, which was called {CONSU/WASTE}. Arguments for this are given in the following paragraphs.

### *4.3.1 Drawing Boundaries between {PROD} and {CONSU/WASTE}*

The ACBM defines the {PROD} module as a database on material and carbon flows in the production sector. The internal consumption pool plays a major role in balancing the inputs and outputs (Orthofer *et al*., 2000). For instance, the consumption of goods[12] is taken as a buffer between {PROD} and {WASTE}.

From a socioeconomic perspective, bearing in mind policy conclusions, the consideration of the consumption of goods as only a sub-category in {PROD} to buffer

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[12] Note that this does not include the more carbon relevant categories of final consumption, i.e., heating, transport, and other service related consumption.

production and waste flows, is unsatisfactory. Knowing the emissions from consumption are at least as equally important as the knowledge of emissions from waste treatment. To subsume consumption under {PROD} would therefore veil the real hierarchy of important categories.

Another problem is the inconsistency of using the structures of different modules. The {ENERGY} module is the only one that includes consumption categories (mechanical work, process heat, space heat, transport, etc.). Flows to the {WASTE} module do not occur. This might be due to the traditional view that $CO_2$ emissions are not considered part of waste management, i.e., direct outputs to air from the anthropogenic system, in contrast to output to water or land,[13] are treated differently. When interpreting data from the {CONSU/WASTE} module, it must be borne in mind that they do not include energetic consumption.

Due to the major changes in waste management (outputs to land and water plus recycling and re-use) since 1990, it is hard to model the relation between production and consumption on the one hand and waste on the other. Large uncertainties are involved in the balances. However, large uncertainties are not so obvious as data is only available from waste collection. Reliable estimates are difficult to obtain for flows from consumption to waste collection. This is mainly due to the characteristics of stock, which is highly complex. It is hard to produce reliable projections of when a product will be out of use. Therefore, no consistency checks are possible.

To avoid high uncertainties at the boundaries of the different modules, which occur when endeavoring to draw the system boundaries between consumption and waste collection, it is suggested to draw the boundaries differently to the ACBM.

The {PROD} module only represents carbon flows relating to the production process of goods, excluding process energy. The {PROD} module is divided into four sub-balances: food processing, wood processing, chemical production, and mineral processing.

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[13] See, output categories in the WRI report (Matthews *et al*., 2000).

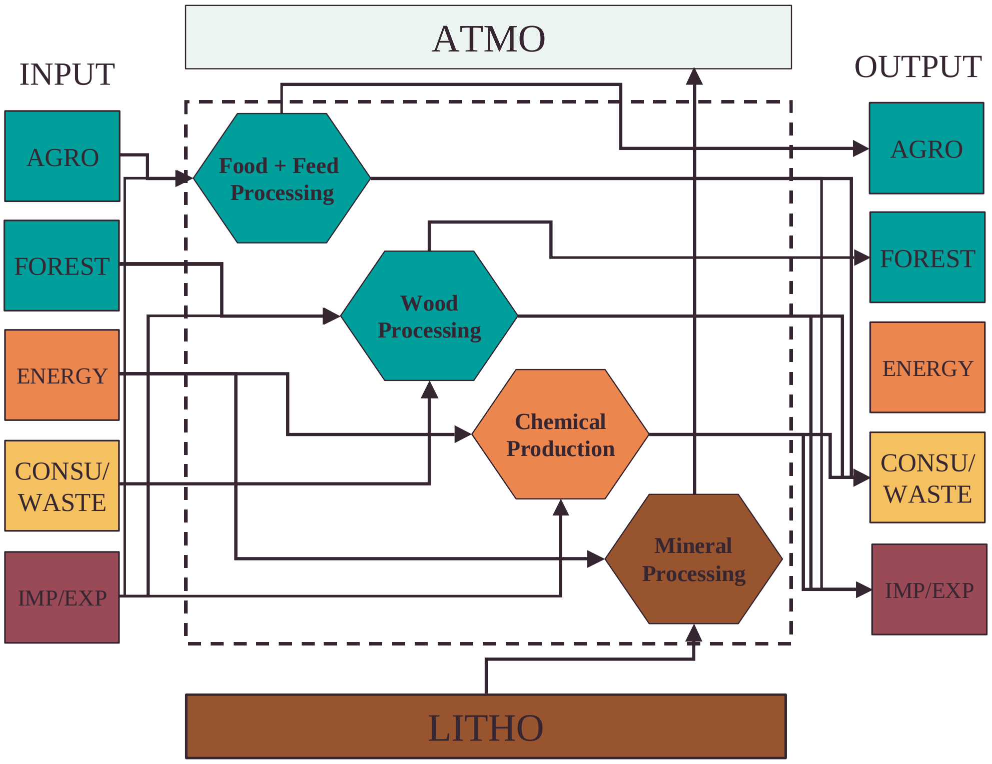

*Figure 4: Structure of the ACDb {PROD} module represented in input/output logic.*

The new module {CONSU/ WASTE} receives inputs from {PROD} in two forms: (1) flows of products for final consumption of goods, and (2) waste from industrial processes. Both flows are by far better to estimate than flows between consumption and waste. Using MFA, a methodology is available that allows a more accurate calculation of final consumption. However, MFA does not provide information about waste management, it only gives rough categories of domestic output to water, air, and land.

However, it should be borne in mind that this module still has the highest uncertainty in terms of carbon flows. This is the result of (1) the complexity of consumption and the big differences in the estimation of respiration (from 0.6–1.7 MtC[14]), and (2) the different definitions of waste in industrial production and waste management, which leads to double counting.

What seems to be a weakness in this drawing of system boundaries is of advantage for the overall view, as the uncertainties can be reduced for flows relating to the production of goods.

After having defined the internal structure of the ACDb, the procedure to calculate carbon flows is described in the next section.

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[14] MFA (Hüttler *et al.*, 1996) uses a value of 1.7 MtC (million tons of carbon) for 1992 with no data available for 1990. Using demographic data from 1992 and 1990 would result in 1.744 MtC. For the WRI report, the IFF used 0.63 MtC (2.328 Mt $CO_2$) (Matthews *et al.*, 2000). The ACBM (Orthofer *et al.*, 2000) uses a value of 1 MtC and Jonas (1997) uses 0.827 MtC.

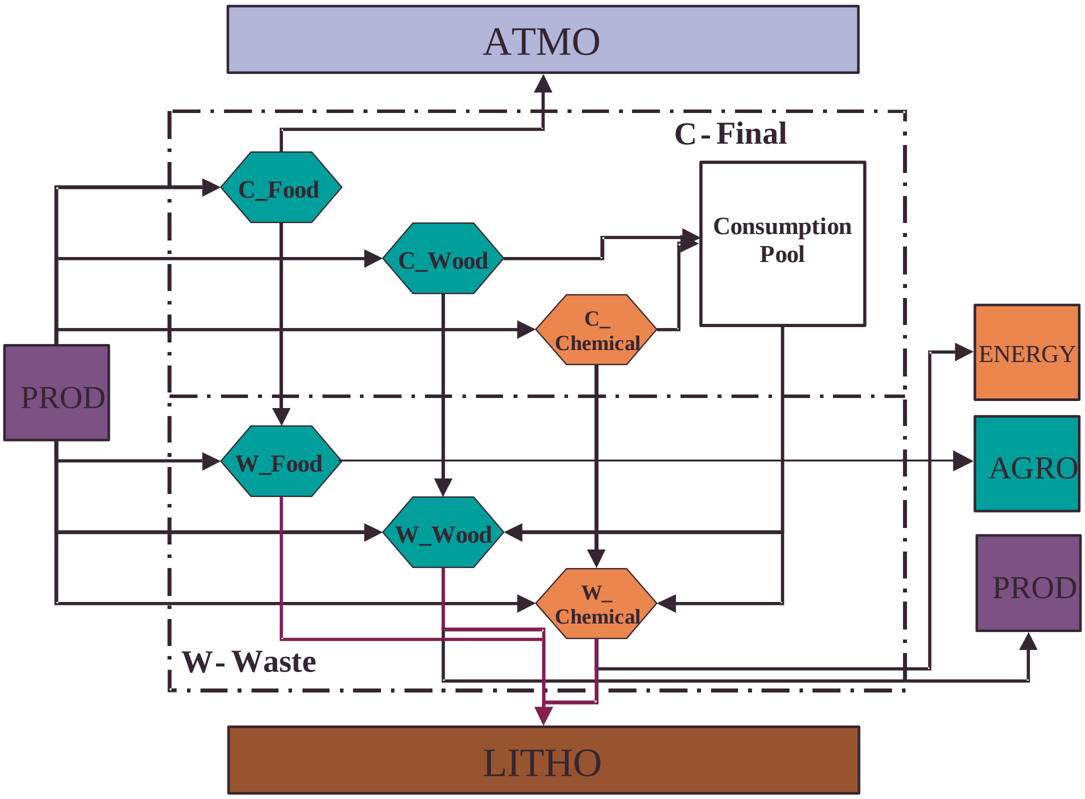

*Figure 5: Structure of the ACDb {CONSU/WASTE} module represented in input/output logic.*

## 4.4 From Material Flows to Carbon Flows

Two steps are necessary for the calculation of carbon flows from MFA. The relevant material flows must be selected and aggregated in the first step. In the second step, material flows must be multiplied by carbon conversion factors (CCF) to calculate the relevant carbon flows. Depending on the aggregation level of the material flows different CCFs have to be found.[15]

It is important to note that material and carbon flows are balanced at the same time. This assures the consistency of the flows in the system.

### *4.4.1 Step 1: Selection and Aggregation of Material Flows*

As FCA provides a full and consistent picture of all relevant carbon flows, accounting in this study includes those carbon flows which can lead to emissions (such as CO, $CO_2$ or $CH_4$, etc.) during extraction, production process or consumption within a certain

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[15] The selection of the individual CCFs is discussed in the Appendices.

range of time. For instance, carbon activated by economic activity, like gravel from limestone, which is not processed as emitting carbon, is not considered in CFA.[16]

In terms of environmental impact, those material flows that go together with high carbon flows are of relevance. To select these flows, the method of ABC analysis was used.[17]

Three types of flows have been categorized in the ACDb production, consumption and waste modules. The range that was used is based on the carbon flows and related uncertainties of the major emission sectors.

| ABC Categories (MtC) |
|---|
| **A:** > 0.5 |
| **B:** < 0.5, > 0.1 |
| **C:** < 0.1 |

Category A flows are expected to be greater than 0.5 MtC in a rough estimate. These flows are investigated in detail. Category B flows, between 0.1 and 0.5 MtC, are investigated in detail only if there is a potential for increases in these flows and time resources are available. Category C flows, below 0.1 MtC, are only considered in an accumulated way.

This follows from the relation of flows within the modules investigated and the carbon flow from {ENERGY}, the greatest anthropogenic flows to the atmosphere. Annual carbon flows from fossil energy are in the range of 16–20 MtC. Under an optimistic assumption, the related uncertainty is in the range of 2.5% or around 0.5 MtC. Category A flows in production, consumption and waste are therefore considered to be greater than the uncertainty of the most significant flow in terms of human impact in the atmosphere.

### *4.4.2 Step 2*

For each sub-balance a different CCF is used. Finding the specific carbon conversion factors and multiplying them to the relevant material flows cannot be described in a general way. CCFs are based on the carbon content of material flows. Depending upon the aggregation level of material flows a CCF has to be calculated individually and independently. The details are explained in the worksheet information in the Appendices.

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[16] Consequently, it is necessary to distinguish between limestone used for cement and lime production (as well as for soil improvement) and limestone used for other purposes.

[17] ABC analysis is also used for selecting the relevant material flows for MFA.

# 5 Uncertainty Calculations

In both steps described above, the aggregation of material flows and the definition of CCF uncertainties are involved.

The IIASA uncertainty concept was used for calculating the uncertainties of carbon flows in the ACDb {PROD} and {CONSU/WASTE} modules (Nilsson *et al*., 2000).

This concept is based on the assumption that different statistical sources might be available that is intended to represent data of the same system using the same or very similar system boundaries but having different mean values[18] and different Gauss or other forms of distributions. In some cases, these different mean values can be out of range in respect to the standard deviation of the other data sets available. Assuming that both datasets are based on expert knowledge, an accepted mean value can be produced with a standard deviation $\sigma$ representing the maximum and minimum of an uncertainty band including all available data sources. IIASA's uncertainty concept is, therefore, a first order approach for evaluating an accepted mean value and a standard deviation $\sigma$.[19]

There are different ways of dealing with uncertainties.[20] In most cases the uncertainties reported by experts, those who have collected the data, or are familiar with it due to their working experience is used. It is also possible that the statistical source already reports the uncertainties involved.

Using MFA as a basis for carbon accounting, there are three typical steps that are necessary for calculating carbon flow related uncertainties:

- Evaluation of uncertainties of the relevant aggregated material flows.
- Evaluation of uncertainties of the CCF.
- Calculation of the uncertainty of carbon flows by means of the Law of Propagation of Uncertainties (LPU).[21]

## 5.1 Law of Propagation of Uncertainties (LPU)

Typically uncertainties are calculated in two ways: addition and multiplication. The LPU applied to addition, for example, will be used to add the statistically independent material flows. The LPU applied to multiplication, for example, will be used to calculate the uncertainties for carbon flows.

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[18] For example, the statistics of Austrian pulp and paper production by Statistics Austria, the office reporting official Austrian statistics, and Austropapier, the lobbying institution of the Austrian paper industry, provide different results. The differences may be caused by different interests or by legal restrictions in reporting.

[19] The uncertainty used can be classified as type B uncertainty according to the Guidelines for Evaluating and Expressing the Uncertainty of the National Institute of Standards and Technology (NIST) Measurement Results (Taylor and Kuyatt, 1994).

[20] If knowledge of data allows, the mean uncertainty of the mean is used.

[21] To do this, the statistical independence of data is assumed, i.e., all specific data used must be based on different assumptions, stem from different series of measurements, etc.

The value $g$ is derived from the two values $x$ and $y$ for which the standard deviations $\sigma_{MX}$ and $\sigma_{MY}$ are known.

$$g = f(x, y)$$

The LPU, based on a first-order Taylor series approximation, is as follows:

$$\sigma_{MG} = \sqrt{(\frac{\partial f}{\partial x})^2 \cdot \sigma_{MX}^2 + (\frac{\partial f}{\partial y})^2 \cdot \sigma_{MY}^2}$$

In this formula $\sigma_{MG}$ is the standard deviation of the mean value of $g$.

In the case of addition $g = x \pm y$, the terms $(\frac{\partial f}{\partial x})$ and $(\frac{\partial f}{\partial y})$ become *one*.

$$\sigma_{MG} = \sqrt{\sigma_{MX}^2 + \sigma_{MY}^2} \quad \text{(addition/subtraction)}$$

In the case of multiplication $g = x \cdot y$, the terms become $y$ and $x$ respectively.

$$\sigma_{MG} = \sqrt{\bar{y}^2 \cdot \sigma_{MX}^2 + \bar{x}^2 \cdot \sigma_{MY}^2} \quad \text{(multiplication)}$$

For practical use in this study the relative standard deviation (i.e., standard deviation divided by the respective mean value) is also used.

$$\frac{\sigma_{MG}}{\bar{g}} = \sqrt{\left(\frac{\sigma_{MX}}{\bar{x}}\right)^2 + \left(\frac{\sigma_{MY}}{\bar{y}}\right)^2} \qquad \text{(multiplication)}$$

# 6 Results for 1990

The ideal procedure to come up with consistent carbon accounting would be to base the carbon accounts on the consistent material accounts provided by material flow accounting. Material flows from the consistent material accounts can be used to calculate the related carbon flows. As a second consistency check, carbon accounts have to be balanced. Based on this procedure, high quality data can be accomplished. Due to the different structure of MFA-based material accounts and the structure of the ACDb as described in section 4, additional efforts were necessary to balance material flow accounts for this research.

For the {PROD} module, material and carbon flow accounts are based on a consistent data set for 1990. For {CONSU/WASTE} material flow consistency was not achieved.

Figures 6 and 7 provide an overview of the results of the production, consumption and waste related carbon flows for 1990. For all accumulated flows relative uncertainties are reported in the form of five different classes (see table below).[22] Giving relative uncertainties in percentage would indicate an accuracy of uncertainty calculation that cannot be achieved at the present time.[23]

| **Class** | **%** |
|---|---|
| 1 | 0-5 |
| 2 | 5-10 |
| 3 | 10-20 |
| 4 | 20-40 |
| 5 | >40 |

## 6.1 Results for {PROD}

Figure 6 provides an overview of aggregated flows between {PROD} and the other modules and their related uncertainty classes. The dotted rectangle in the center represents the module. The arrows pointing towards the rectangle represent inputs; arrows pointing to other modules or to the atmosphere represent output flows. Carbon flows are given in Mt ($10^6$ tC $yr^{-1}$), with the third decimal rounded.[24]

The interpretation of carbon flows can only be done within a consistent picture of the whole carbon system. Until all modules have been balanced the results of the WRI report (Matthews *et al.*, 2000) can be used as a relevant reference point. Carbon flows from the energetic use of fossil fuels are reported to be 16 Mt. For instance, carbon emissions from {PROD} are in the range of 6% of emissions from {ENERGY}.[25]

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[22] In the final report of the ACDb project uncertainty classes will be argued in detail.

[23] Nominal values for relative uncertainties for {PROD} are reported in the Appendices.

[24] Accounts are balanced at the two decimal level.

[25] The WRI results are not directly comparable to those of the ACDb {ENERGY} module.

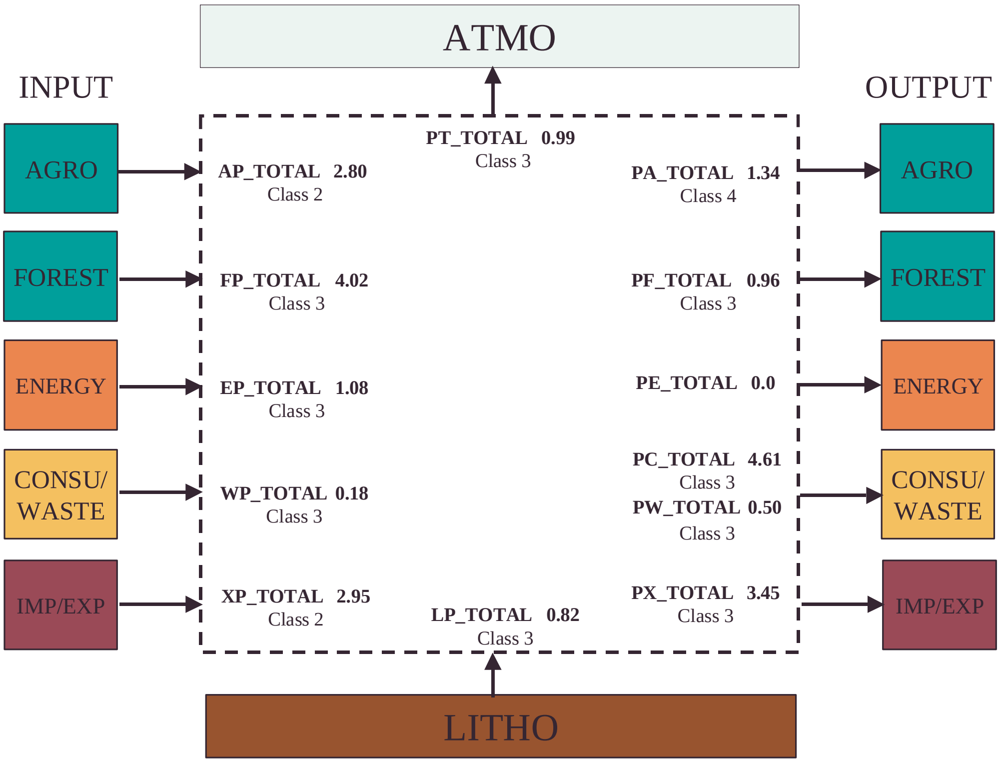

*Figure 6: {PROD} Aggregated Flows (MtC) and Uncertainties (Classes 1–5).*

Table 1 shows the four sub-balances used to represent the production of goods. For 1990, carbon flows and the related relative uncertainties are indicated. To report uncertainties, a minimal value of carbon flow is represented by a relative uncertainty value in -% and a maximum value of carbon flow is represented by a relative uncertainty value in +%. Relative uncertainties are rounded to the second decimal.

The disaggregated view shows that all carbon emissions from {PROD} come from limestone processing (cement and lime production) and steel production. $CO_2$ emissions from limestone processing comprise about 5% of all emissions.

Apart from aggregated flows from {AGRO} and {IMP/EXP} carbon flows have class 3 uncertainties. Further research to reduce uncertainties should concentrate on flows with uncertainties of class 3 or higher, as well as when absolute uncertainties are in the range of other flows reported. To give an example, the sub-balance “Food and Feed Processing” comprises the carbon flow of products harvest (AP_harvest). This flow has class 2 uncertainty. In absolute terms, the uncertainty is ±0.13 MtC, which is almost as much as the carbon in recycled paper (0.18 MtC).

Table 1 comprises the carbon flows (in MtC) and related relative and absolute uncertainties.

*Table 1: Carbon flows and related uncertainties in {PROD}.*

| | **Input** | **Output** | **Uncertainties** | | | |
|---|---|---|---|---|---|---|
| | CF | CF | σ +/- or - (%) | σ +(%) | σ +/- or - (Mt) | σ + (Mt) |
| | MtC | MtC | | | | |
| **I. Wood Processing** | | | | | | |
| XP_Pulp and Paper | 0.498 | | 16.0% | | 0.08 | |
| XP_wood products | 0.054 | | 10.0% | | 0.005 | |
| FP_roundwood | 3.062 | | 12.8% | 16.7% | 0.39 | 0.551 |
| FP_residual wood | 0.958 | | 10.2% | 16.5% | 0.097 | 0.158 |
| WP_recycling paper | 0.180 | | 15.0% | 15.0% | | |
| PF_residual wood | | 0.961 | 10.3% | 16.6% | 0.099 | 0.159 |
| PC_wood products and paper | | 2.507 | 17.3% | 24.3% | 0.432 | 0.608 |
| PX_wood products | | 0.465 | 10.0% | | 0.046 | |
| PX_pulp and paper | | 0.819 | 10.0% | | 0.082 | |
| *Total* | *4.75* | *4.75* | | | | |
| **II. Food and Feed Processing** | | | | | | |
| AP_harvest | 2.387 | | 5.5% | | 0.131 | |
| AP_husbandry | 0.413 | | 10.0% | | 0.041 | |
| XP_food and other products of biomass | 0.516 | | 11.0% | | 0.057 | |
| XP_feed | 0.149 | | 20.0% | | 0.030 | |
| PC_food and other biomass | | 1.505 | 10.0% | | 0.151 | |
| PA_feed | | 0.421 | 20.0% | | 0.084 | |
| PA_cereals for husbandry traded | | 0.918 | | | | |
| PX_feed | | 0.025 | 20.0% | | 0.005 | |
| PX_food | | 0.410 | 10.0% | | 0.041 | |
| PW_waste from Prod | | 0.099 | 20.0% | | 0.020 | |
| PX_other products | | 0.085 | 274.3% | | 0.234 | |
| *Total* | *3.46* | *3.46* | | | | |
| **III. Chemical Production** | | | | | | |
| XP_plastic and plastic products | 1.201 | | 14.1% | | 0.169 | |
| EP_fossil raw material | 0.910 | | 14.1% | | 0.128 | |
| XP_organic chemicals | 0.532 | | 14.1% | | 0.075 | |
| XP other organic chemical inputs | 0.000 | | | | | |
| PX_plastic and plastic products and other chemicals | | 1.649 | 15.0% | | 0.247 | |
| PC_plastic and other chemical products | | 0.593 | 14.1% | | 0.084 | |
| PW_waste from chemical industry | | 0.403 | 14.1% | | 0.057 | |
| *Total* | *2.64* | *2.64* | | | | |
| **IV. Steel Production** | | | | | | |
| EP_C in pig iron | 0.172 | | 6.4% | 6.1% | 0.011 | 0.010 |
| PT_pig iron to steel | | 0.172 | 6.4% | 6.1% | 0.011 | 0.010 |
| *Total* | *0.17* | *0.17* | | | | |
| **V. Cement and Lime Production** | | | | | | |
| LP_limestone for cement production | 0.623 | | 15.1% | 16.6% | 0.094 | 0.103 |
| LP_limestone for lime production and chemicals | 0.199 | | 10.0% | | 0.020 | |
| PT_$CO_2$ from cement production | | 0.623 | 15.1% | 16.6% | 0.094 | 0.103 |
| PT_$CO_2$ from limestone production | | 0.199 | 10.0% | | 0.020 | |
| *Total* | *0.82* | *0.82* | | | | |

## 6.2 Results for {CONSU/WASTE}

For the {CONSU/WASTE} module, consistency was only accomplished for the carbon balance! The sub-balances of the {CONSU/WASTE} module are only a first attempt to use material flow balance data for the calculation of consistent carbon flows. For detailed uncertainty calculations, material flow consistency has to be achieved. At the present stage, uncertainties for output flows are in classes 3 and 4.

The results for the {CONSU/WASTE} module are summarized in Figure 7.[26]

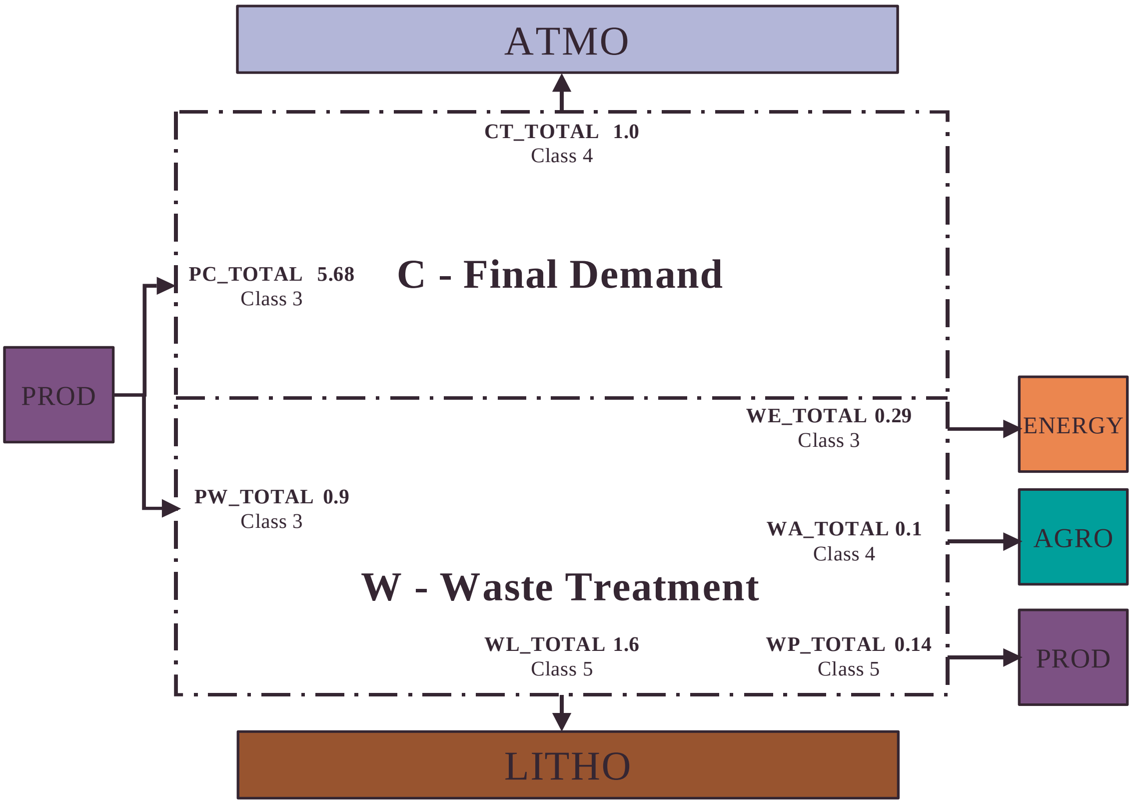

*Figure 7: {CONSU/WASTE} Aggregated Flows (MtC).*

The highest outputs of the module are from consumption to the atmosphere due to human respiration (1 MtC) and to the lithosphere as flows to landfill (1.76 MtC). To balance the accounts we have to assume that flows not recorded by waste management statistics remain in consumption building the consumption stock of artifacts in use. On the aggregated level, flows to these stocks of carbon in artifacts (2.04 MtC) make up for more than 40% of the total input. Only 3.35 MtC of 5.41 MtC coming from {PROD} leaves the system in the same accounting period of one year. Further research seems necessary to investigate this high amount of carbon remaining within society.

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[26] Outputs to water are not considered, as they only make up for 0.08 MtC according to the WRI report (Matthews *et al.*, 2000).

*Table 2: Carbon flows in {CONSU/WASTE}.*

| | **Input** | **Output** |
|---|---|---|
| | CF | CF |
| | MtC | MtC |
| **I. Wood Utilization *(non-energetic)*** | | |
| ***Consumption*** | | |
| PC_wood products and paper | 2.327 | |
| CW_from pool | | 0.315 |
| CW_waste paper | | 0.180 |
| CW_re-used waste wood | | 0.239 |
| CS_to consumption pool | | 1.593 |
| *Total* | 2.327 | 2.327 |
| ***Waste Management*** | **Input** | **Output** |
| | CF<br>MtC | CF<br>MtC |
| CW_from pool | 0.315 | |
| CW_waste paper | 0.180 | |
| CW_re-used waste wood | 0.239 | |
| PW residues from paper industry | 0.399 | |
| WP_recycling paper | | 0.180 |
| WE_wood re-use | | 0.239 |
| WL_landfill and stat. diff. | | 0.714 |
| *Total* | *1.133* | *1.133* |
| | | |
| **II. Food Supply** | **Input** | **Output** |
| ***Consumption*** | | |
| PC_food and other biomass | 1.360 | |
| CT_respiration | | 1.000 |
| CW_food residues | | 0.308 |
| CW_human excrement | | 0.052 |
| *Total* | *1.360* | *1.360* |
| ***Waste Management*** | **Input** | **Output** |
| CW_food residues | 0.308 | |
| CW_human excrement | 0.052 | |
| PW_waste from food prod. | 0.344 | |
| WA_recycling re-use | | 0.100 |
| WL_to landfill and stat. diff. | | 0.604 |
| *Total* | *0.704* | *0.704* |
| | | |
| **III. Plastic and Chemicals** | **Input** | **Output** |
| ***Consumption*** | | |
| PC_consumption | 0.578 | |
| CS_pool | | 0.449 |
| CW | | 0.129 |
| *Total* | *0.578* | *0.578* |
| ***Waste Management*** | **Input** | **Output** |
| CW | 0.129 | |
| PW_chemical production | 0.403 | |
| WP_re-use | | 0.037 |
| WE_incineration | | 0.053 |
| WL_landfill | | 0.442 |
| *Total* | *0.532* | *0.532* |

# 7 Conclusions

The goal of this study is to show the feasibility and limits of using MFA for FCA. At the same time, it should compare MFA-based carbon accounting to the ACBM.

Austria is a leading country in both, MFA research (see, e.g., the WRI report on material flows (Matthews *et al.*, 2000)) as well as in FCA research (see, the first version of the Austrian carbon balance model (Jonas, 1997) and ACBM (Orthofer *et al.*, 2000) referred to in this paper). So far, no efforts have been made of using MFA for FCA.

From the experience made, it can be concluded that MFA-based carbon accounting is feasible. To be more precise, MFA is suggested to build a basis for the anthropogenic part of FCA.

MFA is a representation of the anthropogenic system in terms of matter, measured in tons. It balances those material flows that are activated by the economy, taking into account all inputs, outputs and accumulated stocks. MFA makes a clear distinction between anthropogenic and biospheric flows. It has been developed to be able to relate it to economic national accounting and be able to work with consistent time series data. Double counting of flows can be avoided due to its consideration in MFA methodology. These characteristics, the well defined system boundaries and the level of accumulation of material flows in respect to monetary flows allows the use of MFA-based carbon accounting to directly relate GHG reduction to socioeconomic consequences. The time series allows for the building of scenarios and projections. Even the comparison with monetary input-output tables would be possible, which could be of interest to European Union countries, as there will be bi-annual input-output tables available in future.

Major efforts were made in adapting MFA sub-balances to be comparable to the ACBM logic. From the experiences made, it appears necessary to draw more attention to the system boundaries between the anthropogenic carbon flows and those of the terrestrial biosphere. This would lead to a much more efficient use of existing material flow data. The following structure of full carbon accounting for Austria is therefore suggested (see Figure 8). This would be the right way to design a FCA.

The anthropogenic part of carbon accounting should be based on the structure and the system boundaries developed for MFA. This would allow the use of existing material flow data that is available from Statistics Austria. Emissions to the atmosphere, imports, exports, domestic extraction of biomass, output to nature, and the extraction of minerals and fossil fuels from the lithosphere would be the relevant flows related to this module.

The terrestrial biosphere module would then represent carbon sinks and sources that were included in the {FOREST} and {AGRO} modules.

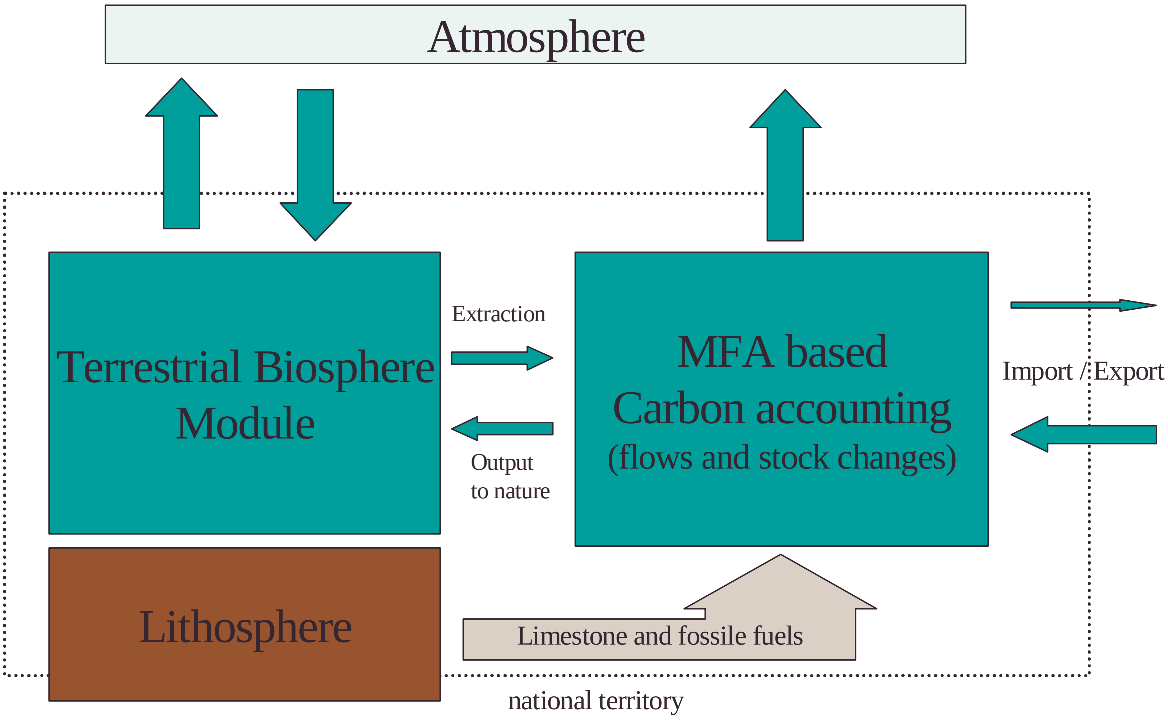

*Figure 8: The concept for future work — FCA using MFA methodology.*

## 7.1 Advantages and Disadvantages of MFA-based FCA and ACBM in Comparison

The following table lists the advantages and disadvantages of the ACBM methodology and FCA that is based on MFA-based full carbon accounting plus a terrestrial biosphere module, as described in Figure 8.

| | Advantages | Disadvantages |
|---|---|---|
| **ACBM** | • ACBM is detailed in terms of categories of flows considered as it concentrates on carbon flows from the beginning.<br>• A wide range of flows of all sizes is considered due to a bottom-up approach. | • The output categories (consumption, exports) are not used consistently. For example, consumption categories in {ENERGY} are included in the structure of the module, whereas all other flows to consumption are collected in {PROD}.<br>• In terms of aggregated output to the atmosphere, no distinction is made between production and consumption. For instance, $CO_2$ emissions from {PROD} include those of consumption.<br>• The definition of modules as “sectors” is misleading as the energy sector, in economic terminology, does not include firms using process energy. |
| **FCA using MFA** | • MFA is based on existing and widely consistent methodology in material flow analysis.<br>• To distinguish between MFA-based carbon accounting and a terrestrial biosphere module allows for a clear distinction between societies’ metabolism and the biosphere.<br>• The system boundaries used are understandable for social scientists. This helps to derive policy conclusions more readily.<br>• MFA-based carbon flows can be linked to economic national accounting and input-output methodology.<br>• It is possible to distinguish emissions from production and consumption.<br>• The problem of double counting is already handled before specifying the carbon flows in FCA. | • MFA does not give information about waste management; it only gives rough categories of domestic output to water, air and land.<br>• The aggregation of flows in a material flow balance is according to importance in terms of material weight. For FCA, a new way of aggregation might be necessary.<br>• MFA is not designed to give reports on small flows. |

## 7.2 Consequences for MFA and Carbon Accounting

Apart from any adaptations that are necessary within the ACDb, material flows in national MFA should, where possible, be aggregated in a way that further reduces uncertainties. As MFA aggregation is based on material flow and not carbon flow quantities, a compromise must be found. And, where necessary, disaggregation must be investigated.

As carbon flows in waste management are considered to be of importance for FCA, the output categories of national MFA must be discussed and specified.

## 7.3 Further Research

Additional work is still necessary to discuss system boundaries of (and within) FCA. MFA-based FCA that fully takes into account the MFA logic can use the results presented in the Appendices. Nevertheless, improvements to the material flow accounts accomplished in recent years have to be taken into account when time series are set up. More work will also be required to find a more appropriate aggregation of flows, based on the necessities of carbon accounting.

MFA methodology leads to carbon emissions from production and energy reported, which are 16 MtC (author's calculations from Matthews *et al.* (2000)), the ACBM reports 19.0 MtC. The difference of 3 MtC by far outweighs all of the other uncertainties in absolute terms. Such a high amount also influences all of the other flows related to fossil fuels, e.g., all flows related to the chemical industry must be investigated as consistency requirements might influence the mean values and the uncertainty of flows related to plastic processing.

From the 1990 results, it becomes clear that uncertainties are still too high. For accumulated flows, no data with class 1 uncertainties are available. Only data for flows from {AGRO} have class 2 quality, all others have class 3. Further improvements can be expected when material flow accounts for 1990 are available in a revised version. Research on appropriate aggregation, as well as improvements in CCFs, can further improve data quality.

## 7.4 Policy Recommendations

Articles 5, 7 and 8 of the Kyoto Protocol require industrialized countries to have a verifiable national system for estimating emissions and sinks by 2007 in the form of an annual inventory of emissions and sinks. Basing carbon reporting for anthropogenic carbon flows on the consistent methodology of MFA allows the reporting country to report verifiable anthropogenic carbon flows. The example of the WRI report on material flows (Matthews *et al.*, 2000) shows how far the national comparison of material flows has developed. Carbon accounting based on MFA would be a small step further that pays off.

To establish FCA that is accepted by all nations involved in the Kyoto process will be a necessary part of the transaction cost involved in trading emission certificates. Building on MFA would help to lower these costs. To use MFA as an international standard to build on, a strong effort would be required to implement MFA in all countries committed to the UNFCCC. Austria, as one of the leading countries in MFA and FCA research, should concentrate its effort to make significant progress in the standardization of FCA.

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# Appendix 1: Worksheet Information on {PROD}

The following worksheet information reflects the results using the MFA approach. Worksheet information provides detailed information on material and carbon flows and the related uncertainties in the sub-accounts on the single flow levels between modules.

## Sub-balance: Food and Feed Processing

### System Boundaries

The system boundaries between {AGRO} and {PROD} are specifically difficult to draw, if using material flow data. Flows considered in {AGRO} are considered under the main group of “Biomass” in “Primary Extraction/Imports” of the material flow account (see Figure 2). In {PROD}, those flows are considered that are part of the “Second Production Phase” of material flow accounts (Hüttler *et al*., 1996). Differently from Hüttler *et al*. (1966), imports and exports are dealt with in {PROD}. What is considered as harvest and husbandry is dealt with in {AGRO}.

### Carbon Conversion Factor (CCF)

Three different conversion factors are used in this module, two for produce and one for products from animals. The conversion factor for harvest is a weighted average of two different conversion factors, basically defined by the difference in the water content of produce.

Conversion factors consist of the conversion factor from produce or meat to dry material multiplied by the carbon content of dry matter.

*Produce:* The carbon content of produce is in the range of 40–45%. The water content of produce is in the range of 9–15% for corn, dry fodder and oil seeds and 87–77% for other produce.

For cereal harvest the average value carbon conversion factor $CCF_{produce\_1} = 0.385$ was used, which is a weighted average derived from Schidler *et al*. (1998). The standard deviation is 2%, which is determined by the difference in MFA data and data from Schidler *et al*. (1998). For all other produce the $CCF_{produce\_2} = 0.092$ was used, which is the carbon content of potatoes and sugar beet.[27] The standard deviation of 12.5% is determined by the variation of carbon content from 0.115 to 0.068 tC/t produce. Not taking the uncertainty in the material flows into consideration, the weighted $CCF_{produce\_1}$ and $CCF_{produce\_2}$ to $CFF_{produce} = 0.253$ tC / t produce are added with a related $\sigma = 2.4\%$.[28]

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[27] The CCF is roughly estimated from accumulated material flows for 1990 by means of accumulated carbon flows in the ACBM. The CCF for different flows between {AGRO} and {PROD} within the ACBM are in the range of 0.152 to 0.388.

[28] The calculation is as follows: $\sigma_{produce\_1} = CCF_{produce\_1} \cdot 5.3t \cdot 0.02 = 0.004$ $\sigma_{produce\_2} = CCF_{produce\_2} \cdot 4.3t \cdot 0.005 = 0.005$

$$\sigma_{produce} = \sqrt{0.004^2 + 0.005^2} = 0.006 \mathrel{\widehat{=}} 2.4\%.$$

$CCF_{produce\_1}$ = 0.385 tC/t cereal harvest σ = 2%
$CCF_{produce\_2}$ = 0.092 tC/t non-cereal produce σ = 12.5%
$CCF_{produce}$ = 0.253 tC/t produce σ = 2.4%

*Animal products*: The carbon content for meat is 0.162 tC/t meat. This is calculated the same way as for produce, by multiplying the 30% of dry substance with a carbon content of 54%. The carbon content of milk is 0.069 tC/t milk.

The carbon conversion factor for animal products is a weighted average for 1990 of milk and meat (including eggs). The σ of 8.3% takes into account the different carbon contents of meat, eggs and milk between 0.115 and 0.068 tC/t animal products calculated by Schidler *et al*. (1998), which represents a range of ±25%.[29] It was assumed that the change in the relation between meat and milk production does not increase the uncertainty above that which is determined by the different material flows reported.

$CCF_{animal\text{-}products}$ = 0.088 tC/t animal products σ = 8.3%

*Food and other Biomass*: For the import/export of food and other biomass only one aggregated value is given in the material flow balance. Therefore, a carbon conversion factor was needed based on the carbon contents of all products imported or exported. The weighted CCF is 0.179 based on domestic agricultural production (excluding feed used in {AGRO}). This factor neither reflects the different composition of imports and exports nor the consumption pattern. A standard deviation of 10% was therefore assumed.

$CCF_{food\ and\ other\ biomass}$ = 0.179 tC/t animal products σ = 10%

**AP_harvest**

| | |
|---|---|
| Carbon Flow (Mt) | 2.387 |
| Uncertainty (%) (Mt) | ±5.5%; ±0.131 Mt |
| Material Flow (Mt) | 2.387 |

Based on material flow. Source: Schandl (1998).

The material flow that was used for the biomass flows from harvest in the MFA of Hüttler *et al*. (1996), which was a feasibility study, was corrected in the latest time series in Schandl (1998). This value is 5% higher than the one reported by Schidler *et al*. (1998). The difference between these values is taken as σ. Due to multiplication with the carbon conversion factor CCF = 0.253 and the related σ = 2.4%, the total carbon flow is 2.44 MtC with a standard deviation of σ = 5.5% or 0.135 MtC.

---

[29] 25% is interpreted as 3σ. The material flow value of 4.7 Mt in MFA is overestimated, as it is 15% higher than the value for 1992. Using material flows to weigh the CCF creates some problems with statistical dependencies; nevertheless the higher variance of the carbon contents determines the outcome of the multiplication of uncertainties in the law of error propagation.

**AP_husbandry**

| | |
|---|---|
| Carbon Flow (Mt) | 0.413 |
| Uncertainty (%) (Mt) | ±10%; ±0.041 Mt |
| Material Flow (Mt) | 4.700 |

Based on material flow. Source: Hüttler *et al.* (1996).

The material flow, behind AP_husbandry is an accumulation of meat, milk and eggs. The sources differ from 4.7 Mt (Hüttler *et al.*, 1996) to 4.25 Mt (Schidler *et al.*, 1998). The related standard deviation is 5.6%, taking 4.7 Mt as the mean value and 4.25 Mt as the absolute value at $-\sigma$. Due to multiplication with the carbon conversion factor CCF = 0.088 and the related $\sigma = 8.3\%$, the total is $\sigma = 10\%$.

**XP_food and other products of biomass**

| | |
|---|---|
| Carbon Flow (Mt) | 0.516 |
| Uncertainty (%) (Mt) | ±11%; ±0.057 Mt |
| Material Flow (Mt) | 2.640 |

Based on material flow. Source: Hüttler *et al.* (1996).

This flow is derived from material flow data for biomass imports. Material flow "*Sonstige Produkte*" (other products) in the material flow accounting sub-balance for biomass, includes paper. Reducing the paper imports from this flow and adding up the "food and other products of biomass" we derive 2.640 Mt material flow.

For the calculation of the carbon flows the division between husbandry and agricultural products was made according to the relation of AP_harvest and AP_husbandry.

For import/export data a relatively low standard deviation was assumed of 5% for material imports/exports. Until Austria joined the European Union the importing and exporting of trucks were weighted at the borders to Germany and Italy. Imports and exports to these countries account for a great portion of the total imports and exports of agricultural products. It was that the trucks were always fully loaded.[30]

The uncertainty of carbon flows is mainly determined by the carbon conversion factor, which is 10%.

**XP_feed**

| | |
|---|---|
| Carbon Flow (Mt) | 0.149 |
| Uncertainty (%) (Mt) | ±20%; ±0.030 Mt |
| Material Flow (Mt) | 0.600 |

Based on material flow. Source: Hüttler *et al.* (1996).

---

[30] The uncertainty might be higher for data after of the free transportation of goods within the European Union is implemented, as controls are less feasible, with a tendency towards underreporting.

Uncertainty is dominated by the deviation of the carbon conversion factor. For calculating the carbon flow the CCF for produce was used, although the composition of feed is not the same as the composition of harvest. As a first rough estimate a standard deviation of 20% was assumed.

**PC_food and other biomass**

| | |
|---|---|
| Carbon Flow (Mt) | 1.505 |
| Uncertainty (%) (Mt) | ±10%; ±0.151 Mt |
| Material Flow (Mt) | 8.398 |

Based on material flow. Source: Hüttler *et al*. (1996).

The unrealistic value in the material flow balance for 1990 of 12 Mt is replaced by a value of 8.398 Mt derived from the 1992 value for "*Lebensmittel und sonstige Produkte*" (food and other products) and "*Eigenverbrauch, Direktvermarktung*" (consumption in the primary sector and direct marketed products) and weighed with the difference of sums of the sub-balance "final consumption" (see Figure 2) (Hüttler *et al*. 1996).

Uncertainty is dominated by the deviation of the carbon conversion factor.

**PA_feed**

| | |
|---|---|
| Carbon Flow (Mt) | 0.421 |
| Uncertainty (%) (Mt) | ±20%; ±0.086 Mt |
| Material Flow (Mt) | 1.700 |

Based on material flow. Source: Hüttler *et al*. (1996).

See the arguments for XP_feed.

**PA_cereals for husbandry traded**

| | |
|---|---|
| Carbon Flow (Mt) | 0.918 |
| Uncertainty (%) (Mt) | ±10%; ±0.092 Mt |
| Material Flow (Mt) | 2.382 |

Based on material flow. Source: Schandl (1998).

This flow represents flows related to the trading of cereals used as feed in {AGRO}. Cereals for feed make up for 45% of the total harvest (Hüttler *et al*. 1996).

**PX_feed**

| | |
|---|---|
| Carbon Flow (Mt) | 0.025 |
| Uncertainty (%) (Mt) | ±20%; ±0.005 Mt |
| Material Flow (Mt) | 0.100 |

Based on material flow. Source: Hüttler *et al*. (1996).

See the arguments for **XP_feed**.

**PX_food**

| | |
|---|---|
| Carbon Flow (Mt) | 0.410 |
| Uncertainty (%) (Mt) | ±10%; ±0.041 Mt |
| Material Flow (Mt) | 2.100 |

Based on material flow. Source: Hüttler *et al.* (1996).

Uncertainty is dominated by the deviation of the carbon conversion factor.

**PW_waste from production**

| | |
|---|---|
| Carbon Flow (Mt) | 0.099 |
| Uncertainty (%) (Mt) | ±20%; ±0.020 Mt |
| Material Flow (Mt) | 0.400 |

Based on material flow. Source: Hüttler *et al.* (1996).

The material flow value from the 1992 balance is used, as no value for 1990 was available. Uncertainty is dominated by the deviation of the carbon conversion factor. For calculating the carbon flow the CCF for food and other biomass was used, although the composition of waste from production is not the same as the composition of harvest. As a first rough estimate a standard deviation of 20% was assumed.

**PX_other products**

| | |
|---|---|
| Carbon Flow (Mt) | 0.085 |
| Uncertainty (%) (Mt) | ±274%; ±0.234 Mt |
| Material Flow (Mt) | 2.486 |

Based on the author’s own calculations.

This flow is used to balance the accounts. From material flow accounts (Hüttler *et al.*, 1996) it is not clear which portion of the account “other products” is coming from the agricultural sector and how much from the forest sector.

To balance the material flows 2.486 Mt are calculated. The value for exports of other products in Hüttler *et al.* (1996) is 3.1 Mt.

The standard deviation of this flow is calculated by adding up, according to the law of error propagation, all $\sigma$ necessary to balance the account.

## Sub-balance: Wood Processing

Detailed data record on the harvesting of forests has been done for the ACDb's {FOREST} module. Data from the {FOREST} module are available for FP_roundwood, FP_residual wood, and PF_residual wood.

### System boundaries

Fuel wood is considered to go directly from {FOREST} into {ENERGY}. The imports and exports of roundwood and residual wood are accounted for in the {FOREST} module. The imports/exports of pulp and paper are considered in this balance together with wood and wood products, as they are closely related to wood production.

### Carbon conversion factor (CCF)

Making a combined material and carbon flow balance for wood and paper makes it necessary to use at least two different conversion factors; one for paper and pulp and another for wood and wood products.

*Paper*: According to Holzforschung Austria (Lee-Mueller, 2000) the carbon content of cellulose is 0.44 tC/t cellulose. The content of cellulose in paper ranges from 48% to 90%.

Chemical wood pulp (*Zellstoff*) consists mainly of cellulose; the lignin part from wood has been withdrawn in a chemical process. Mechanical wood pulp (*Holzstoff*) still includes lignin. The import/export data are assumed to have 10% water content.

The carbon content of paper and pulp is therefore between 0.21[31] and 0.39[32] tC/t pulp or paper. It was not possible to go into the details of the composition of different types of paper in imports, exports and consumption, nor was it possible to consider the differences in the different relations between pulp and paper in imports and exports. For pragmatic reasons, an unweighted average carbon content of 0.3 tC/t pulp and paper was assumed.[33] Considering the deviation of the minimum and maximum carbon content as 2σ, the standard deviation is σ = 0.045 or 15%.

$$\boxed{CCF_{pulp+paper} = 0.3 \text{ tC/t pulp and paper} \quad \sigma = \pm 0.045 \text{ or } \pm 15\%}$$

*Wood*: A single carbon conversion factor was assumed for all wood and wood products. The average value is based on the composition of Austrian harvest, assuming that imported and exported materials and products have the same composition of timber.

Material flows of wood and wood products are those of dry matter, i.e., 12% less water content than for harvested wood (like in {FOREST}).

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[31] Lowest wood content in paper.

[32] The carbon content of pulp with 10% water content (0.44*0.9).

[33] This conversion factor is the same as the unweighted average between conversion factors (from 0.253 to 0.349) used by the ACBM.

|  |
|---|
| CCF = 0.44 tC/t wood after harvest |
| $CCF_{wood}$ = 0.5 tC/t wood dry |

### XP_pulp and paper

|  |  |
|---|---|
| Carbon Flow (Mt) | 0.498 |
| Uncertainty (%) (Mt) | ±16%; ±0.08 Mt |
| Material Flow (Mt) | 0.1.660 |

Based on material flow. Source: Statistics Austria (2000).

Material flows for imports of pulp and paper are taken from the ISIS database of Statistics Austria. Carbon flows are calculated by using $CCF_{paper}$. The imports consist of 60% pulp and waste paper (0.99 Mt) and 40% paper, paperboard and articles thereof (0.67 Mt). Assuming the carbon content is the same, the uncertainties of this carbon flow are high as there is no information available about the water content of pulp imported. The related carbon flow is 0.5 Mt.

The uncertainties $\sigma$ = ±0.08 Mt ±16% arise due to statistical uncertainties in the ISIS import/export database and due to the differences in carbon conversion factors for paper and pulp as well as for different paper qualities.

### XP_wood products

|  |  |
|---|---|
| Carbon Flow (Mt) | 0.054 |
| Uncertainty (%) (Mt) | ±10 %; ±0.005 Mt |
| Material Flow (Mt) | 0.260 |

Based on material flow. Source: Statistics Austria (2000).[34]

Uncertainties for imported wood products have to consider the weight that includes non-wood materials.

### FP_roundwood

|  |  |
|---|---|
| Carbon Flow (Mt) | 3.062 |
| Uncertainty (%) (Mt) | -123 +17%; -0.39 +0.551 Mt |
| Material Flow (Mt) | 6.124 |

Based on carbon flow. Source: Jonas (2000).

Carbon flows are taken from the {FOREST} module. The imports and exports of roundwood are also accounted for in the {FOREST} module.

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[34] Due to the common market within the European Union, the uncertainties in material flows reported are increasing for Austria after 1992.

**FP_residual wood**

| | |
|---|---|
| Carbon Flow (Mt) | 0.958 |
| Uncertainty (%) (Mt) | -10 +17%; -0.097 +0.158 Mt |
| Material Flow (Mt) | 1.686 |

Based on carbon flow. Source: Jonas (2000).

As for the flow, FP_roundwood, carbon flows are taken from the {FOREST} module. The imports and exports of roundwood are also accounted for in the {FOREST} module.

**PF_residual wood**

| | |
|---|---|
| Carbon Flow (Mt) | 0.961 |
| Uncertainty (%) (Mt) | -10 +17%; -0.099 +0.159Mt |
| Material Flow (Mt) | 1.691 |

Based on carbon flow. Source: Jonas (2000).

**PC_wood products and paper**

| | |
|---|---|
| Carbon Flow (Mt) | 2.507 |
| Uncertainty (%) (Mt) | -17 +24%; -0.432 +0.608 Mt |
| Material Flow (Mt) | 5.794 |

Based on carbon flow. Source: Author’s own calculations.

This flow is derived by balancing the carbon flows. To countercheck the results, the material flow from the carbon flow was calculated. This value can be compared to the flow calculated for the material flow balance for 1990 (Hüttler *et al*., 1996), which is 5.00 Mt. It was assumed that consumption consists of 65% dry wood and 35% paper. This relation is derived from the relation in the ACBM.

The standard deviation of this flow is calculated by adding up, according to the law of error propagation, all σ necessary to balance the account.

**PX_wood products**

| | |
|---|---|
| Carbon Flow (Mt) | 0.465 |
| Uncertainty (%) (Mt) | ±10%; ±0.046 Mt |
| Material Flow (Mt) | 0.930 |

Based on material flow. Source: Statistics Austria (2000).

**PX_pulp and paper**

| | |
|---|---|
| Carbon Flow (Mt) | 0.819 |
| Uncertainty (%) (Mt) | ±10%; ±0.082 |
| Material Flow (Mt) | 2.730 |

Based on material flow. Source: Statistics Austria (2000).

The imports consist of 12% pulp and waste paper (0.32 Mt) and 88% paper, paperboard and articles thereof (2.41 Mt). Assuming that the carbon content is the same as used for imports, the related carbon flow is 0.82 Mt, with the uncertainties mainly due to the different composition of imports and exports.

**Other material**

This flow is only used to balance the material flow due to the fact that paper production needs additional material to wood.

| | |
|---|---|
| Carbon Flow (Mt) | 0.0 |
| Uncertainty (%) (Mt) | -; - |
| Material Flow (Mt) | 1.415 |

Based on material flow. Source: Author's own calculations.

## Sub-balance: Chemical Production

The main relevant carbon flow in the chemical industry is caused by plastic production. Further flows are related to the production of paints, solvents, bitumen and other chemicals. One balance was established for all chemical products based on the material flow balance account on fossil fuels (Hüttler *et al*., 1996).[35]

### Plastic and Other Chemical Flows

**System boundaries**

In the material flow balance chemical production is part of the fossil fuel accounts. Most raw materials for chemical products are joint products in the refinery process; therefore it would be appropriate to include it in the {ENERGY} module. To remain comparable to the ACBM, it is dealt with in the {PROD} module. The flow to the {PROD} module from the {ENERGY} module consists of the flows of raw material (crude oil derivatives, coal and gas). Imports consist of plastic, plastic products and organic chemicals (semi-finished products). Plastic recycling, which makes up only 0.049 Mt of plastic (Fehringer *et al.*, 1997) and 0.036 Mt of carbon respectively, is not considered due to the relatively small flow, which is less than the uncertainties involved.

**Carbon conversion factor (CCF)**

The carbon content of plastic is 760g carbon/kg plastic, i.e., 76% with a variation from 81–72% (Fehringer *et al.*, 1997:152, A10).

$$\boxed{CC_{plastic} = 0.76 \text{ tC/t plastic} \qquad \sigma = +7/-5\% \ (+0.05/-0.04 \text{ tC/t plastic})}$$

---

[35] Under the current aggregation of the accounts, solvents are not reported separately as requested by the IPCC guidelines.

We use the mean value of the $CC_{plastic}$ as $CCF_{chemicals}$ for all material flows in the chemical industry balance except for *EP_fossil raw material*. As we are also using the CCF for flows of plastic products with less then 100% plastic content and semi-finished products consisting of more than the average $CC_{plastic}$, the standard deviation must be higher than that for $CC_{plastic}$. A standard deviation of ±10% was assumed.

| $CCF_{chemicals}$ = 0.76 tC/t plastic and other chemicals | $\sigma = \pm 10\%$ (±0.076 tC/t) |
|---|---|

For fossil raw material from the {ENERGY} module (crude oil derivatives, coal and gas) a CCF of 0.85 tC/t fossil raw material was assumed. This low CCF is necessary due to the inclusion of process energy in the balance, which is missing in the output as carbon emission to the atmosphere.[36] At the time of writing this paper the ACDb {ENERGY} module was not completed and detailed information not available. Therefore, the standard deviation was assumed to be about ±10%.

| $CCF_{fossil\ raw\ material}$ = 0.85 tC/t fossil raw material | $\sigma = \pm 10\%$ (±0.085 tC/t) |
|---|---|

### Uncertainties of the material flows

All material flows used in this balance are taken or calculated from the MFA fossil fuel account of Hüttler *et al*. (1996) except for imports and exports of products with low plastic content.

The total output of carbon to the atmosphere in the account for 1990 is reported with 14.46 Mt,[37] which is 24% less than the 19 Mt reported by the ACBM.[38] As uncertainty in the carbon emission affects all input and output values reported, including those used for presenting accounting, a $\sigma = \pm 10\%$ was assumed.

**XP_plastic and plastic products**

| | |
|---|---|
| Carbon Flow (Mt) | 1.201 |
| Uncertainty (%) (Mt) | ±1%; ±0.169 Mt |
| Material Flow (Mt) | 1.580 |

Based on material flow. Source: Hüttler *et al*. (1996); Fehringer *et al*. (1997).

The material flow balance reports 1.19 Mt of plastic and plastic products imported. This does not include products imported that only partly consist of plastic, like cars, machinery, etc. An average content of 17% of plastic in products imported (only

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[36] Here, more accuracy would be required in material flow accounts.

[37] The latest data for carbon flows to the atmosphere based on MFA are reported by the World Resources Institute Report on material flows. For 1990, the WRI reports 17.62 Mt of carbon emitted as CO and $CO_2$ from combustion of fossils and industrial processes (Matthews *et al.*, 2000). Reduced by the emissions from industrial processes, calculated in this report, 16.62 Mt would be emitted from fossils.

[38] The compatibility of the material flow balance of the fossil fuel account and the {ENERGY} module has not been investigated in detail. It was not possible to identify the cause of the different carbon emission values in the present report. One reason for the different values might lay in the drawing of system boundaries. Further research would be necessary to get a detailed view on the compatibility.

products that partially consist of plastic[39]) is estimated by Fehringer *et al.* (1997:44) for 1994. Adding the plastic used for wrapping (29,400 t[40]) of all imported products 444,200 t of plastic was imported. Taking into account the increase in imports by 11% (Statistics Austria, 2000) from 1990 to 1994 (it was assumed that this increase over all products is the same as for those containing plastics) 392,000 t were imported in 1990.

**EP_fossil raw material**

| | |
|---|---|
| Carbon Flow (Mt) | 0.910 |
| Uncertainty (%) (Mt) | ±14%; ±0.128 Mt |
| Material Flow (Mt) | 1.070 |

Based on material flow.  Source: Hüttler *et al.* (1996).

The material flow consists of 0.70 Mt crude oil derivatives, 0.06 Mt coal and 0.31 Mt of gas.

**XP_organic chemicals**

| | |
|---|---|
| Carbon Flow (Mt) | 0.532 |
| Uncertainty (%) (Mt) | ±14.1%; ±0.075 Mt |
| Material Flow (Mt) | 0.700 |

Based on material flow.  Source: Hüttler *et al.* (1996).

According to MFA, all organic chemicals used for the chemical industry are imported.

**XP_other non fossil inputs**

| | |
|---|---|
| Carbon Flow (Mt) | 0.00 |
| Uncertainty (%) (Mt) | -; - |
| Material Flow (Mt) | 0.130 |

Based on material flow.  Source: Hüttler *et al.* (1996).

This flow is used to balance the account in terms of material.

**PX_plastic, plastic products and other chemicals**

| | |
|---|---|
| Carbon Flow (Mt) | 1.649 |
| Uncertainty (%) (Mt) | ±15%; ±0.247 Mt |
| Material Flow (Mt) | 2.170 |

Based on carbon flow.  Source: Author's own calculations.

This flow is used to balance the carbon account. Apart from material flows considered in MFA, it also includes products exported that only partly consist of plastic, like cars, machinery etc. An average content of 20% of plastic in products exported (only

---

[39] Fehringer *et al.* (1997) use only part of the products listed in the import/export statistics of Statistics Austria.

[40] Estimation of undeclared wrapping $\sigma = \pm 10\%$.

products that partially consist of plastic[41]) is estimated by Fehringer *et al.* (1997:42) for 1994. Adding the plastic used for wrapping (14,300 t) of all exported products 0.417 Mt of plastic was imported. Taking into account the increase in imports by 12% (Statistics Austria, 2000) from 1990 to 1994[42] 0.367 Mt were exported in 1990, making up for 0.28 Mt of carbon exported.

**PC_plastic and other chemical products**

| | |
|---|---|
| Carbon Flow (Mt) | 0.593 |
| Uncertainty (%) (Mt) | ±14%; ±0.083 Mt |
| Material Flow (Mt) | 0.780 |

Based on material flow. Source: Hüttler *et al.* (1996).

The carbon flow of 0.593 Mt[43] is calculated from the material flow from the chemical industry to final demand (0.76Mt) and the difference between imports and exports of products with low plastic content (0.39–0.37 Mt) reported by Fehringer *et al.* (1997).

**PW_waste from chemical industry**

| | |
|---|---|
| Carbon Flow (Mt) | 0.403 |
| Uncertainty (%) (Mt) | ±14%; ±0.057 Mt |
| Material Flow (Mt) | 0.530 |

Based on material flow. Source: Hüttler *et al.* (1996).

The same CCF as for plastic was assumed.

## Sub-balance: Cement and Lime Production

1. **Cement Production**
   Basic process: Limestone or dolomite is reduced to lime and $CO_2$ by high temperatures in a calcining process.

   Limestone: CaCO3 → CaO + CO2
   Dolomite: CaCO3*MgO3 → CaO*MgO

   About two-thirds of $CO_2$ emissions from cement production are due to the chemical process. One-third of the emissions are a result of fuel use for process heat in the production of cement clinker (Reiter and Stroh, 1995). The raw material for the production of cement clinker consists of 78% of CaO3 and CaCO3*MgO3 (a maximum of 5%) of which 34.6% of the mass are $CO_2$. The limestone used must be at least 75% pure (Reiter and Stroh, 1995). The IPCC guidelines indicate that the purity of limestone might range between 85–95%.

---

[41] Fehringer *et al.* (1997) use only part of the products listed in the import/export statistics of Statistics Austria.

[42] It was assumed that this increase over all products is the same as those containing plastics.

[43] For comparison, the ACBM modellers report a carbon flow of 0.535 Mt for plastic.

2. **Lime Production**
   The same calcining process is used as in cement production (but only limestone is used).

3. **Pig Iron Production**
   In pig iron production limestone is used to liquefy the blast-furnace slag. Approximately 100kg (±10%) of limestone are used to produce one ton of pig iron. The statistics of pig iron have an accuracy of ±10% due to the reporting only up to the level of 10*E5 t (Schützenhöfer, 2000).

4. **Soil Fertilization**
   In soil fertilization, limestone and lime is used in different forms. The $CO_2$ emissions from lime produced for fertilizers are considered in "Chemical Production" (see below). The limestone portion of fertilizers is converted to CaO and $CO_2$ by chemical processes in the soil. This emission should be considered in {AGRO}. As the related carbon content is only about 10,000t, the flow is neglected and added to "Chemical Production".

5. **Chemical Production**
   In the chemical industry limestone is used for the production of soda ash and fertilizers.

### System boundaries

Emissions, as a result of fuel use for process heat,[44] are dealt with in the {ENERGY} module. Only those emissions related to the chemical process are considered for the {PROD} module. All carbon flows considered are flows from {ENERGY} or the lithosphere to the atmosphere. No flows to the {WASTE} module occur.

### Carbon conversion factor (CCF)

Two conversion calculations are considered.

***1. Stoichiometric relation***

| Chemical formula | Process | Emission Factor (EF) | Carbon Content |
|---|---|---|---|
| Limestone | | kg $CO_2$/t high calcium lime | kg C/t CaCO3 |
| CaCO3[a] | CaCO3 → CaO + CO2 | **439.7** | **120** |
| Dolomite | | kg $CO_2$/t dolomite lime | |
| CaCO3*MgO3[b] | CaCO3*MgO3 → CaO*MgO | **477.3** | **130** |

[a] CaCO3 consists of 44.01 g/mole $CO_2$/56,08 g/mole CaO (IPCC, 1996).
[b] CaCO3.MgCO3 consists of 2*44.01 g/mole $CO_2$/96.39 g/mole CaO*MgO (IPCC, 1996).

---

[44] In 1990, the emissions of $CO_2$ were 1.05Mt (Reiter and Stroh, 1995).

For cement production, less than 5% of raw material can be dolomite (Reiter and Stroh, 1995). This leads to a weighted carbon content of $CC_{weighted}$ = 120.5 5kg C / t CaCO3.[45] The related uncertainty band of ±2.5% (3σ) is reflected in a standard deviation for the dolomite portion in cement raw material of σ = 0.83%.

This assumes pure limestone. As noted above, the IPCC guidelines indicate that purity might range between 85–95% and Reiter and Stroh (1995) give a minimum of 75%. This uncertainty band if ±10% (3σ) is reflected in a standard deviation for the purity of limestone of σ = 3.3%.

The total uncertainty σ = ±3.4% (±0.0035) is derived by means of the law of propagation of uncertainty.[46]

$$\boxed{CCF_{stoich} = 0.1205 \text{ tC/t CaCO3} * 0.85 = 0.1024 \qquad \sigma = \pm 3.4\,\% \ (\pm 0.0035)}$$

## 2. *Calculation from $CO_2$ content of raw dust for clinker*

Raw material for clinker consists of 78% of limestone and dolomite (43.1% CaO, 0.5% MgO and 34.6% $CO_2$) (Reiter and Stroh, 1995:7). It was assumed that 100% of $CO_2$ is emitted during the production process. The standard deviation is determined by the composition of raw material, which was estimated to be in the range of 3%.

$$\boxed{CCF_{clinker} = 0.346 * 12 \text{ (g/mole)}/44 \text{ (g/mole)} = 0.0944 \text{ tC/t clinker raw dust} \quad \sigma = \pm 3\% \ (\pm 0.003)}$$

**LP_/PT_limestone for cement production**

| | |
|---|---|
| Carbon Flow (Mt) | 0.623 |
| Uncertainty (%) (Mt) | -15% +17%; -0.094 +0.104Mt |
| Material Flow (Mt) | 6.086 |

Based on material flow.  Source: Schandl (1998); Reiter and Stroh (1995).

The carbon flow calculated is based on two different methods of calculation: (A) on the available material flow for limestone extraction, and (B) on the data for cement clinker raw material.

The carbon flow based on the first method defines the upper limit of the uncertainty band. The carbon flow based on the second method defines the lower limit. A combination of both was used to define the mean value and the total uncertainty band of the carbon flow related to cement production.

Method (A). The only available material flow for limestone extraction for cement is taken from a material flow time series in Schandl (1998). This flow amounts to 6.86 Mt. Using the $CCF_{stoich}$ a carbon flow was calculated of 0.703 MtC, based on the

---

[45] $CC_{weighed} = 120 \cdot 0.95 + 130 \cdot 0.05 = 120.5.$

[46] $\sigma = \sqrt{0.033^2 + 0.0083^2} = 0.034.$

stoichiometric relation. It was assumed that all limestone is converted into CaO and all $CO_2$ is emitted.

Method (B). Raw material for the production of cement clinker is reported by the Austrian Environmental Agency (UBA) (Reiter and Stroh, 1995:105, 108). Using linearly interpolated data from 1991 to 1993 provides a raw material consumption of 5.78 Mt and emissions of 2.005 Mt $CO_2$, i.e., 0.546 MtC in 1990.

Combining Methods (A) and (B). The difference between the carbon flow calculations is based on different values for pure CaCO3 used for cement production in the range of 5.83–4.51 Mt. Taking an unweighted average between these values the CaCO2 flow is 5.17 Mt. The related carbon content, based on the stoichiometric calculation, is 0.623 MtC.

The standard deviation $\sigma$ is determined by the higher value plus the related $\sigma$ of +3.4% and the lower value minus the related $\sigma$ of -3.4%. The new standard deviation for the mean value 0.623 is -28.1% +16.6%.

A factor that was expected to influence the uncertainty calculation was the recarbonization of limestone. This is considered to be in the range of 11.3% of all $CO_2$ emitted during the production of cement (Harmuth, 2000).[47] As the potential absorption capacity of cement is within the present uncertainty band, this uncertainty factor will not be considered any further.

The Oak Ridge National Laboratory (ORNL) Internet database reports an emission of 0.666 MtC in 1990 (Marland *et al.*, 2000). The data is taken from the US Bureau of Mines. This is within the uncertainty calculated by using the methods above.

### LP_/PA_limestone for mineral fertilizers (not considered separately)

Originally *LP_/PA_limestone for mineral fertilizers* was considered as a separate flow. Due to the negligible size of this flow, which should go from lithosphere directly to {AGRO}, it is included in {PROD}, as if the emission would take place during production.

Part of the limestone used for soil fertilization is used without being processed to lime. This limestone portion of fertilizers is converted to CaO and $CO_2$ by the bicarbonate equilibrium reaction processes in the soil (IPCC, 1996). Limestone, amounting to 0.187 Mt (Hintermeier, 2000), is used for soil fertilization of which 0.081 Mt are directly used as limestone. Only this portion would have to be considered in {AGRO}.[48]

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[47] A layer of about 2cm on the surface of concrete can partly carbonize. Harmuth (2000) estimates that this layer can be carbonized absorbing 43% of $CO_2$ emitted in cement clinker production. This process of carbonization is a slow process lasting for decades, i.e., that after hydration of concrete, 43% of the concrete in a layer of 2cm at the surface of concrete-components, consists of CaCO3 after a decade long diffusion process.

[48] Data for soil fertilization by lime in Austria (Dachler and Kernmayer, 1997) are based on estimates of traders (this data is not publicly available (Dachler, 2000)). Traditionally, the liming of soils is reported in terms of CaO to emphasize the portion of fertilizers, which is a base. The actual liming is mainly done with a mixture of both, CaCO3 and CaOH. Apart from these, other mineral fertilizers also include some

For a consistent carbon balance it was assumed that $CO_2$ emissions by the bicarbonate equilibrium reaction processes in the soil are included in *LP_/PT_limestone for lime production and chemical production* flow (making up 0.01 Mt) below.

**LP_/PT_limestone for lime-production and chemical production**

| | |
|---|---|
| Carbon Flow (Mt) | 0.199 |
| Uncertainty (%) (Mt) | ±10%; ±0.02 Mt |
| Material Flow (Mt) | 1.949 |

Based on material flow.  Source: Schandl (1998).

The data for limestone extraction, 1.949 Mt, is the sum of extraction for lime production (1.666 Mt[49]) and chemical production (0.282 Mt).[50] Assuming that the limestone used consists of 85% CaCO3, the carbon flow equals to 0.199 Mt, based on the stoichiometric relation.

Lime used for construction, in contrast to cement,[51] is 100% re-carbonated (Harmuth, 2000), i.e., Ca(OH)2 reacts with air to CaCO3 in the long run. After an unspecifiable time, talking in dimensions of decades, all $CO_2$ emitted during production is reabsorbed by the construction material. It was assumed that the absorption of $CO_2$ by recarbonation could be neglected, as the annual growth rates of lime production of +5% since the 1960s (Schandl, 1998) cannot be outweighed by far.

Taking into account the low value of carbon flow involved only a rough estimate was made of the standard deviation. Based on uncertainties in the purity of limestone recarbonization the $\sigma$ was estimated to be in the range of ±10%.

## Sub-balance: Steel Production

In the production process of pig iron, coke is used to reduce the ore from FeO3 by coke oxidation. In this process some carbon is absorbed by pig iron (from 4.2–4.8% of pig iron). The carbon content is reduced during the steel production from 0.08 to 0.8%, i.e., carbon is emitted as $CO_2$ during this process.

In 1990, Austria produced 3.45 Mt of pig iron and 4.29 Mt of steel (Verein Deutscher Eisenhüttenleute, 1996). In the ACDb, it was assumed that all pig iron produced in Austria is used for steel production. For steel production a fairly high amount of scrap metal is used, making up the difference between iron and steel production. It was assumed that the scrap metal used is mainly steel.

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limestone and dolomite respectively. For emissions from the {AGRO} module all parts, except CaOH, would have to be considered (Dachler, 2000).

[49] This figure contains limestone and dolomite used in iron melting.

[50] The figures are taken from a time series in (Schandl, 1998).

[51] Cement, in contrast to lime, hardens in a hydraulic process resulting in stable chemical structures, e.g., with aluminium.

### System boundaries

Generally pig iron production is considered in the {ENERGY} module due to the high percentage of energetic use of the process heat after the production process.

The {PROD} module only considers the flow of carbon incorporated in pig iron. Only those $CO_2$ emissions caused in the steel processing were considered.

### Carbon conversion factor (CCF)

Carbon in pig iron and steel.
The carbon content of pig iron is approximately 0.45 tC/t pig iron, in the range of 0.42 and 0.48.[52]

$$\boxed{CC_{\text{pig iron}} = 0.45 \text{ tC/t of pig iron} \qquad \sigma = \pm 2\% \; (\pm 0.01 \text{ tC/t of pig iron})}$$

An average carbon content of 0.05 tC t of steel, based on the great spread of carbon content of steel was assumed. Steel is produced with 0.008 tC/t of steel up to 0.08 tC/t of steel (Schützenhöfer, 2000).[53] Others give a range between 0.1% and 1% (Gara and Schrimpf, 1998:17).

$$\boxed{CC_{\text{steel}} = 0.05 \text{ tC/t of steel} \qquad \sigma = +20\% \; -28\% \; (+0.01/-0.014 \text{ tC/t of steel})}$$

$CCF_{\text{steel-production}}$
For the carbon conversion factor, a difference of the average values was used for carbon contents in pig iron and steel of 0.04 tC/t of pig iron produced.

$$\boxed{CCF_{\text{steel-production}} = 0.04 \text{ tC/t of pig iron} \qquad \sigma = +3\% \; -4\% \; (+0.014/-0.017 \text{ tC/t of pig iron})}$$

### EP_pig iron

| | |
|---|---|
| Carbon Flow (Mt) | 0.172 |
| Uncertainty (%) (Mt) | +-6/%; +-0.010 Mt |
| Material Flow (Mt) | 0.172 |

Based on material flow. Source: Verein Deutscher Eisenhüttenleute (1996).

The carbon incorporated in pig iron is considered as carbon flow from {ENERGY}. In Austria, 4.29 Mt of steel was produced from 3.452 Mt of pig iron produced domestically and the rest imported. A standard deviation of the reported value for pig iron of ±5% was assumed. For the uncertainty of the carbon flow the law of propagation of uncertainties was used for multiplying the $CCF_{\text{steel-production}}$ with the material flow.[54]

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[52] Represented as $3\sigma = \pm 0.03$ tC t of pig iron.

[53] Represented as $3\sigma = +0.03/-0.043$ tC/t of pig iron.

[54] The calculation is as follows: $\begin{array}{l} + \;= \sqrt{0.035^2 + 0.05^2} = 0.061 \\ - \;= \sqrt{0.043^2 + 0.05^2} = 0.066 \end{array}$.

### WP_scrap metal

The carbon incorporated in scrap metal used in steel production is considered to have the average carbon content of steel. Therefore, it is not considered, as there will be no additional significant carbon flow from its use.

### PT_pig iron to steel

| | |
|---|---|
| Carbon Flow (Mt) | 0.172 |
| Uncertainty (%) (Mt) | +-6/%; +-0.010 Mt |
| Material Flow (Mt) | 0.172 |

Based on material flow.  Source: Verein Deutscher Eisenhüttenleute (1996).

The carbon released in steel production is emitted as $CO_2$ to the atmosphere. The carbon remaining in steel is neglected.

# Appendix 2: Worksheet Information on {CONSU/WASTE}

## BALANCE — CONSUMPTION/WASTE MANAGEMENT

### System boundaries

The system boundaries between {PROD} and {CONSU/WASTE} are drawn according to the sub-balances "Final consumption" of the material flow balance (see Figure 1). Only three sub-balances of the {PROD} module include carbon flows to consumption, as "Steel Production" and "Cement and Lime Production" do not cause significant carbon emissions in consumption or waste treatment. Therefore, we distinguish three categories for consumption and waste management: "Wood Utilization (non-energetic)", "Food Supply" and "Plastic and Chemicals Use". Each category consists of two sub-balances, one for consumption and one for waste management.

Inputs come from {PROD} in the form of carbon flows to consumption or as flows from production to waste management. The outputs of carbon flows considered are to the atmosphere {ATMO}, lithosphere {LITHO},[55] {ENERGY}, {AGRO}, and {PROD}. Outputs to water are not considered, as they only make up for 0.08 MtC according to the WRI report (Matthews *et al.*, 2000).

### Carbon conversion factor

Carbon conversion factors are mainly based on factors used in the {PROD} module.

### Sub-Balances

Tables A1 to A3 list the material and carbon flows to and from the module, including information on the source and the origin of the data.

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[55] Landfills are considered as Lithosphere.

Table A1: Sub-balance **I. Wood Utilization (non-energetic)**.

| | **INPUT** | | **OUPUT** | | **Based on** | **Source** |
|---|---|---|---|---|---|---|
| | MF | CF | MF | CF | | |
| | Mt Material Flow | MtC | Mt Material Flow | MtC | | |
| **I. Wood Utilization (non-energetic)** | | | | | | |
| **CONSUMPTION** | | | | | | |
| PC_wood products and paper | 5.378 | 2.327 | | | {PROD} | |
| CW_from pool | | | 0.700 | 0.315 | Material flow | Hüttler *et al*. (1996) |
| CW_waste paper | | | 0.600 | 0.180 | Material flow | Hüttler *et al*. (1996) |
| CW_re-used waste wood | | | 0.421 | 0.239 | {FOREST} | |
| CS_to consumption pool | | | 3.657 | 1.593 | Author's calculation | |
| *Total* | *5.378* | *2.327* | *5.378* | *2.327* | | |
| **WASTE MANAGEMENT** | | | | | | |
| CW_from pool | 0.700[a] | 0.315 | | | Material flow | Hüttler *et al*. (1996) |
| CW_waste paper | 0.600 | 0.180 | | | Material flow | Hüttler *et al*. (1996) |
| CW_re-used waste wood | 0.421 | 0.239 | | | {FOREST} | |
| PW_residues from paper industry | 1.330 | 0.399 | | | Material flow | Krammer *et al*. (1995) |
| WP_recycling paper | | | 0.600 | 0.180 | Material flow | Hüttler *et al*. (1996) |
| WE_wood re-use | | | 0.421 | 0.239 | {FOREST} | |
| WL_landfill and stat. diff. | | | 2.030 | 0.714 | Author's calculation | |
| *Total* | *3.051* | *1.133* | *3.051* | *1.133* | | |

[a] This flow is based on the material flow for construction wood from deconstructed houses.

Table A2: Sub-balance **II. Food Supply**.

| | **INPUT** | | **OUPUT** | | **Based on** | **Source** |
|---|---|---|---|---|---|---|
| | MF | CF | MF | CF | | |
| | Mt Material Flow | MtC | Mt Material Flow | MtC | | |
| **II. Food Supply** | | | | | | |
| **CONSUMPTION** | | | | | | |
| PC_food and other biomass | 8.398 | 1.360 | | | {PROD} | |
| CT_human respiration | | | 1.000 | 1.000[a] | Material flow | Matthews *et al*. (2000) |
| water from food and human respiration | | | 5.098 | | Author's calculation | |
| CW_food residues | | | 1.900[b] | 0.308[c] | Material flow | Hüttler *et al*. (1996) |
| CW_human excrement | | | 0.400 | 0.052 | Author's calculation | |
| *Total* | *8.398* | *1.360* | *8.398* | *1.360* | | |
| **WASTE MANAGEMENT** | | | | | | |
| CW_food residues | 1.900 | 0.308 | | | Material flow | Hüttler *et al*. (1996) |
| CW_human excrement | 0.400 | 0.052 | | | Material flow | Hüttler *et al*. (1996) |
| PW_waste from food prod. | 1.404 | 0.344 | | | Material flow | Krammer *et al*. (1995) |
| WA_recycling re-use | | | 0.325 | 0.100 | Material flow | Krammer *et al*. (1995) |
| WL_to landfill and stat. diff. | | | 3.379 | 0.604 | Author's calculation | |
| *Total* | *3.704* | *0.704* | *3.704* | *0.704* | | |

[a] Hüttler *et al.* (1996) use a value of 1.7 MtC for 1992, with no data available for 1990. Using demographic data from 1992 and 1990 this would result in 1.744 MtC for 1990. ACBM reports 1 MtC and Jonas (1997) reports 0.827 MtC.

[b] 1.9 Mt of dry matter are reported for 1992, with no value for 1990 available. ACBM reports 0.199 MtC.

[c] The same carbon conversion factor is used as for PC_food and other biomass. The value is in the range of values calculated for 1993 from Krammer *et al.* (1995).

Table A3: Sub-balance **III. Plastic and Chemicals Use**.

| | INPUT | | OUPUT | | Based on | Source |
|---|---|---|---|---|---|---|
| | MF | CF | MF | CF | | |
| | Mt Material Flow | MtC | Mt Material Flow | MtC | | |
| **III. Plastic and Chemicals Use** | | | | | | |
| **CONSUMPTION** | | | | | | |
| PC_consumption | 0.760 | 0.578 | | | {PROD} | |
| CS_pool | | | 0.588 | 0.449 | Author's calculation | |
| CW_plastic and chemicals | | | 0.172 | 0.129 | Author's calculation | |
| *Total* | *0.760* | *0.578* | *0.760* | *0.578* | | |
| **WASTE MANAGEMENT** | | | | | | |
| CW_plastic and chemicals | 0.172 | 0.129 | | | Author's calculation | |
| PW_chemical production | 0.530 | 0.403 | | | {PROD} | |
| WP_re-use | | | 0.049[a] | 0.037 | Material flow | Fehringer *et al*. (1997) |
| WE_incineration | | | 0.071 | 0.053 | Material flow | Fehringer *et al*. (1997) |
| WL_landfill | | | 0.589 | 0.442 | Material flow | Krammer *et al*. (1995) |
| *Total* | *0.702* | *0.532* | *0.709* | *0.532* | | |

[a] Material flow values reported for 1994 from Fehringer *et al.* (1997) was used.