Transition paths towards CO2 emission reduction in the steel Industry

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5 SimCo: Integrated Micro-economic Simulation

5.1 Introduction
This chapter gives a description of the SimCo model we developed as part of the research. It simulates the long-term development of individual iron and steel companies by successive short-term optimisations of investments and production.

The chapter starts with a description of the decision-making as implemented in SimCo and continues with a description of the overall model algorithm in section 5.3. Subsequently, section 5.4 describes the optimisation section, highlighting some important constraints. After an overview of the limitations of the model in section 5.5, the chapter concludes with some remarks on possible applications and on the data entry.

5.2 Decision-making as modelled in SimCo
Throughout its existence, a steel company faces many options to choose from. A company will generally try to guarantee the continuity of the company. The expected discounted profits over a limited foresight period are a common measure of the survival chances of the company. The policy of companies often aims at the maximisation of these discounted profits. Likewise, the optimisation section of the SimCo model maximises the discounted profits, the so called objective of the model.

SimCo includes various decision possibilities that influence the discounted profits over the foresight period. One group of decisions concerns the existence of installations including several actions which determine this. These options depend on the life-cycles of the installations. Another group concerns the material and energy consumption and production that are within reach with the operational installations. The model generates the decisions that assign the maximal value to the expected discounted profits that is attainable within the relevant constraints. The decisions of both groups are coherently optimised, in a single optimisation round.

In SimCo, the decisions with regard to the existence of installations are discrete and binary. The possible actions include construction, initialisation, upgrading, conversion and abandonment of installations. These actions determine whether an installation is operational during a certain period. The availability of technologies, the characteristics of the installation life-cycle, and the age of the present installations determine the possibilities regarding these decisions.

The decisions concerning production and consumption encompass the purchase and sale of materials and energy, and the size of flows between installations. Flows are limited by the availability and demand of materials, by the capacities and technical properties of the operational installations and by the overall configuration of the company. The model may choose any size of the flows within the limitations imposed by the constraints.

5.3 SimCo: structure and overall algorithm
SimCo has been developed in AIMMS [2], a software package designed for operations research applications. AIMMS provides a modelling language and the tools for the development of a graphical interface. It carries out the execution statements in the model, and coordinates the communication between the model and the solver, in the current case CPLEX. This solver performs the actual optimisation by maximising the model objective function, which is subject to a set of linear inequalities representing the constraints.

The database of SimCo consists of three functional groups: initialisation parameters,
technology parameters and scenario parameters, defining the technological and economic environment of the company. The overall algorithm consists of four parts, namely initialisation, execution section 1, optimisation and execution section 2. The execution and optimisation sections are placed in a conditional execution loop and return, each time after a shift by one unit period, until the final period has been reached. Figure 5.1 gives a scheme of the model structure.

SimCo works with a unit of one or more years, the unit period. Decision variables relate to a unit period. The use of the unit period instead of single years results in aggregation of the decisions of consecutive years, thereby considerably reducing matrix size and optimisation time. The previous unit period represents the point of departure for each optimisation, the current unit period represents the present, and the foresight period (one or more unit periods) represents the future included in the optimisation.

The initialisation involves the generation of the initial company situation, based on default values or values defined by the user. The initial values define the presence and age of the installations in the starting year. Another part of the initialisation is the generation of the scenario and the preprocessing of some basic technical parameters to the actual ones. This section also converts some parameters, entered as annual values, to values that refer to the unit period.

Next, the model enters the first execution section. The model evaluates the decision possibilities for the optimisation round, and prepares the fixation and elimination of some variables to reduce the matrix size and enhance the performance. After this preparation, the model enters the optimisation section.

First, AIMMS generates a matrix of linear equations representing the objective function and the constraints. The variables in these equations represent the decision possibilities,
along with some auxiliary variables. Subsequently, AIMMS transfers the matrix to the CPLEX solver, which optimises the matrix to yield the maximum value of the objective. The optimisation concerns the decisions during the current period and the foresight period, with the previous unit period representing the starting situation.

<table>
<thead>
<tr>
<th>round variables:</th>
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The matrix moves one unit period between two successive optimisation rounds. The current unit period in round \( n \) becomes the previous unit period in round \( n + 1 \). In round \( n + 1 \), the frozen installation variables in the previous period represent the company configuration inherited from round \( n \).

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<th>n+1</th>
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The solver applies evaluation methods to determine whether the overall optimum may be found in a certain direction, thereby limiting the number of iterations required for finding the optimum. In the optimal situation, all integer variables have integer values.[49, 55]

After the optimisation, the CPLEX solver returns the optimised values of the variables to AIMMS, which carries out the execution statements in the model. This second execution section implements a shift by one unit period, and calculates the values of display parameters, based on the relevant variables from the matrix. Then, this section freezes the values of the variables that refer to the previous unit period (which was the present period in the former optimisation round), to create a new point of departure for the next optimisation round. At this point, while it has not yet reached the final period, the model
returns to the first execution section. Figure 5.2 gives a schematic representation of the connection between two successive optimisations and of the periods included in the optimisation.

5.4 Optimisation

The optimisation model in SimCo is a \textit{mixed integer programme} (box 5.1), a variant of the \textit{linear programming model} in which a part of the variables is subject to the integer constraint, in addition to linear constraints. Optimisation concerns the minimisation or, as in SimCo, the maximisation of the objective, the value of which is determined by the \textit{objective function}. The variables in the \textit{objective function} return in the technology matrix, which defines the linear constraints. Box 5.2 gives an overview of the structure of the optimisation problem in SimCo.

<table>
<thead>
<tr>
<th>Box 5.2 Structure of the Optimisation problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>The optimisation problem aims at the maximisation of Net Present Value for the foresight period. For this purpose, it can decide on the operationality of existing and new installations, and on the size of material and energy flows. The decisions have to meet various kinds of constraints, listed below</td>
</tr>
<tr>
<td>Objective function (box 5.4)</td>
</tr>
<tr>
<td>Constraints:</td>
</tr>
<tr>
<td>Definition of link between installation capacity and maximal production by operationality</td>
</tr>
<tr>
<td>- production limited by installation capacity (box 5.5)</td>
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<tr>
<td>Definition of constraints on operationality and life-cycle of installations</td>
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<tr>
<td>- operationality definition (box 5.6)</td>
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<tr>
<td>- installation life-cycle definition (box 5.7)</td>
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<tr>
<td>Definition of physical constraints on flows in installations</td>
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<td>- input/output limitations (box 5.8)</td>
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<td>- energy constraints (box 5.9)</td>
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<td>- preservation of material characteristics (box 5.10)</td>
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<td>- constraints on material flow characteristics (box 5.11)</td>
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<tr>
<td>Definition of overall constraints on flows</td>
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<td>- CO₂ emission definitions (box 5.12)</td>
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<tr>
<td>- summation of flows through installations to total net flows</td>
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</table>

Concerning the solution of this kind of optimisation problems, it suffices to mention that software exist to find a proven optimum. The applied AIMMS version includes the CPLEX solver for linear and (mixed) integer models. Detailed information on linear and integer programming is available in several publications on operations research [49, 55]. For those unfamiliar with operation research models, it is important to realise that an mixed integer optimisation model is solely shaped by constraints and an objective. A missing constraint, however trivial, results in a model that has undesired degrees of freedom. The solver, searching for the optimum, will jump into any resulting maze to improve the value for the \textit{objective function}.

This section will highlight some important structural constraints, to give an impression of the company model. The text gives a verbal explanation of the functions of the constraints, while the equation boxes give a mathematical representation. Constraints which only serve to speed up the optimisation process, and have no specific meaning, are not included. Box 5.3 explains the equation boxes. Both text and boxes will start with the very basis of the optimisation model, the objective function.
5.4.1 Objective function

The objective function (box 5.4) includes the variables and parameters that directly determine costs and profits. The variables indicate quantities or events, the parameters indicate prices and taxes for quantities, or costs for events. The variables reappear in the constraints, which link these variables to parameters and to variables not included in the objective function.

\[
NPV = \sum_{t=0}^{t_f} \text{discount-correction}_{(t)} \cdot \\
\left( \sum_{m,c} \text{price}_{(m,c,t)} \cdot \text{out}_{(m,c,t)} \right) + (\text{materials sold}) \\
- \sum_{m,c} \text{price}_{(m,c,t)} \cdot \text{in}_{(m,c,t)} \right) + (\text{materials bought}) \\
- \sum_i \text{status-costs}_{(i)} \cdot \text{installation} \cdot \text{status}_{(i)} \cdot t \right) + (\text{installation costs}) \\
- \sum_i \text{production costs}_{(i)} \cdot \text{production}_{(i)} \cdot t \right) + (\text{production costs}) \\
- \text{electricity price}_{(t)} \cdot \text{electricity-input}_{(t)} \right) + (\text{electricity costs}) \\
- \text{wage}_{(t)} \cdot \text{labour}_{(t)} \right) + (\text{labour costs}) \\
- \text{tax}_{(t)} \cdot \text{CO}_2_{(t)} \right) + (\text{carbon tax}) \\
\right)
\]

5.4.2 Constraints

There are three structural constraint groups, one to define the life-cycle constraints of installations, another to steer material and energy flows and other resources. Finally, there are some constraints that define variables at a higher aggregation level. The first two groups are connected by constraints that limit the output of products by the actual
installation capacities. These constraints (box 5.5) are a suitable starting point from which to explore both the life-cycle and the material flow constraints.

Capacity constraints
Capacity constraints ensure both that there can be no production in an installation that is not operational, and that the production cannot exceed the actual installation capacity. They include the effects on actual capacity of certain activities occurring during the life-cycle of the installation, the effects of specific inputs and the effect of the installation age.

Box 5.5 Production limited by installation capacity

\[
\text{production}_{i,0} \leq \text{capacity}_{i} \cdot \text{operationality}_{i,0} - \text{action effect}_{i} \cdot \text{action}_{i,0} + \sum_{m} \text{material effect}_{m,i} \cdot \text{input}_{m,i,0} - \text{age effect}_{i} \cdot \text{age effect counter}_{i,0}
\]

\[
\text{production}_{i,0} \leq \text{capacity}_{i} \cdot \text{operationality}_{i,0}
\]

Box 5.6 Operationality definition

\[
\text{operationality}_{i,0} = \text{operationality}_{i,1-1} + \text{initialisation}_{i,0} - \text{abandonment}_{i,1-1} + \sum_{i2} \text{conversion}_{i2,i,0} - \sum_{i3} \text{conversion}_{i3,i,1}
\]

Operationality and life-cycle
The constraint that defines the operationality of an installation (box 5.6) ensures that the operationality is the same as that in the preceding period, unless start-up, conversion or abandonment change it. Other constraints, not shown here, ensure that preceding the start-up of an installation, there is a construction period. Some other constraints regulate a proper order of actions, preventing actions from taking place simultaneously. The references to the previous unit period in the constraints represent the links between past, present, and future.

Initially, when a newly-built installation becomes operational, the abandonment counter (box 5.7) obtains its maximum value. The abandonment counter indicates the number of years that an installation can still be operational without requiring special actions. During each unit period that an installation is operational the value of the abandonment counter diminishes. The abandonment counter constraints force the model to undertake appropriate actions when the installation is worn out, and also allow these actions in an earlier stage. Operationality of an installation is not possible when the abandonment counter drops below one. Its value can be restored to the maximum by an upgrade. Otherwise, either abandonment or conversion to another installation is necessary. As in the operationality constraints, references to the foregoing unit period represent the links between past, present and future. The chosen construction of the model with regard to the abandonment counter allows the inclusion of installation life cycles in the model without the need to include the whole life-cycle in the matrix.
Flow constraints, totals and characteristics
As stated before, the output of products is limited by the installation capacities. These limitations only apply to flows representing products. Additional mass flow constraints define the links with raw materials, by-products and waste flows, by input and output limitations relative to production. The mass flows are also subjected to mass-balance constraints (both on the totals and by compounds or elements incorporated in the materials), to energy constraints, and to constraints that define overall characteristics of installation input and output.

The most straightforward mass flow constraints concern the total throughput definition, the definition of product output, and the minimal and maximal input and output relative to product output (box 5.8). The throughput is the sum of both all inputs and outputs. Together these definitions guarantee that the overall mass balance is correct. Furthermore, some materials are designated as products of certain installations. The product output of these installations equals the output of these materials. Minima and maxima relative to product-output, link other material flows to the product output. For example, this allows the determination of minimal and maximal output of blast furnace slag in relation to the pig iron production.

In addition to these straightforward flow constraints, there are constraints concerned with specific properties of mass flows and installations. Energy balances, CO₂ equivalent balances, balances of important compounds and chemical elements contained in the
materials, and minima and maxima on element inputs are among these, along with the
definition of the labour required.

The general energy balance defines the installation energy input and output. In addition
to the energy contained in the material flows, it defines the electricity input and output
linked to the total product output, and, optionally, linked to the specific products and to the
material input. An example of the latter is the electric arc furnace, in which input of coal
reduces the demand for electricity. The energy loss from the installation may depend on
total production, on the throughput and on the specific outputs. For most installations,
however, both electricity demand and energy loss depend on product output only, as
represented in the simplified energy balance (box 5.9).

### Box 5.9 Energy constraints (simplified)

$$\sum_{m} \text{energy value}_{m} \cdot \text{input}_{m, \text{in}, \text{i}, \text{t}} + \text{electricity factor}_{m} \cdot \text{production}_{m, \text{in}, \text{i}, \text{t}} \geq \sum_{m} \text{energy value}_{m} \cdot \text{output}_{m, \text{in}, \text{i}, \text{t}} + \text{energy loss}_{m, \text{in}, \text{i}, \text{t}} \cdot \text{production}_{m, \text{in}, \text{i}, \text{t}}$$

Compared with the general energy constraint, the CO$_2$ constraints are rather simple. The
constraints guarantee that the CO$_2$ equivalent of the input equals that of the output. In a few
installations, other constraints prohibit perfect matching of the CO$_2$ input and output. In
such cases, there is a slack parameter slightly above zero.

Some constraints concern the overall characteristics of the input and output flows of an
installation. For these constraints, the model uses an additional index, $c$, of category. The
category constraints are especially important to provide installations with the right
flexibility in the mass flows. For example, possible iron sources for the blast furnace are
sintered ore, pellets and lump ore. There is no lower limit to the consumption of each of
these individually, but the iron content of each material and of the produced pig iron
determine the minimal consumption of the three materials together.

### Box 5.10 Preservation of material characteristics

$$\sum_{n} \text{category factor}_{n, c} \cdot \text{output}_{n, \text{in}, \text{i}, \text{t}} - \text{slack}_{n, c} \cdot \text{throughput}_{n, \text{in}, \text{i}, \text{t}} \leq \sum_{n} \text{category factor}_{n, c} \cdot \text{input}_{n, \text{in}, \text{i}, \text{t}} \leq \sum_{n} \text{category factor}_{n, c} \cdot \text{output}_{n, \text{in}, \text{i}, \text{t}} + \text{slack}_{n, c} \cdot \text{throughput}_{n, \text{in}, \text{i}, \text{t}}$$

The first two category constraints are balance constraints (box 5.10). They assure that the
characteristics of input and output, when relevant, do not diverge more than the slack
parameter allows. These constraints are structurally very similar to the CO$_2$ constraints. An
example concerns the iron contained in the installation input and output.
Another pair of category constraints control characteristics of the input flow (box 5.11). An example is the amount of oxygen required in combustion processes. The input of specific fuels and other materials combined with the characteristics of the combustion process determine the amount of oxygen required. It is possible to attribute an oxygen consumption factor to each fuel for the specific process and a negative oxygen consumption factor to air and oxygen. By determining a minimum and maximum category level for the input flow, the model guarantees that the right amount of air or oxygen accompanies each consumed fuel mix.

The labour required depends on the general characteristics of the installation, on the development of labour efficiency, on the age of the installations and, for some installations, on the specific products. The labour parameters incorporate the improvement of labour efficiency, while the effect of installation age ensures that only after an upgrade, when labour saving measures may be implemented, the improvement of labour efficiency has its full effect.

Finally, there are the constraints that define variables at a higher aggregation level. Examples of these include the definition of net production and consumption of materials and electricity and the definition of the CO$_2$ emissions at the company level. The definition of both total material and total electricity input and output is at the level of net output. Output minus input equals total production minus total consumption.

The emitted CO$_2$, emissions as calculated in the model, represent the net emissions (box 5.12). They are similar to the system emissions in the static analysis of chapter 4, as defined in paragraph 4.4.3. The emissions are the overall result of the CO$_2$ incorporated in ingoing materials, of carbon fixation in outgoing flows, the CO$_2$ emitted in the production of the ingoing materials and electricity, and the emissions prevented by using excess energy for electricity generation. Carbon fixation is the CO$_2$ withdrawn from the carbon cycle, for example by storing CO$_2$ in oil fields, depleted natural gas fields or aquifers.
5.4.3 The execution sections between two optimisation rounds

The intermediate execution section mainly serves an administrative function. It generates display parameters that provide insight in the model results, and prepares the data for the following optimisation section. But in addition, it also has an important function in the evaluation of the freedom of the model for the next round.

The execution section contains routines that evaluate the extent to which the previous model results limit the freedom of the model. In the next optimisation round, the results of this routine prevent the initialisation of variables that represent events that cannot happen anyway. This routine reduces the matrix size and increases the calculation speed. An example concerns the elimination of variables that represent abandonment, construction and upgrade for a brand-new installation.

The routine also results in the fixation of variables for which the value is determined already. To return to the example of a brand new installation, the variable operationality will not change anyhow for a number of years to come.

5.5 Boundaries

A model has to strike a balance between reality and manageability. The aim of SimCo is to simulate as good as possible the long-term development of a company by successive short-term optimisations. As all models, SimCo is a simplified representation of reality, with all the limitations involved. This section gives an overview of the main structural limitations of SimCo and the implications for the results. Moreover, it mentions possibilities to deal with limitations of SimCo.

It is important to note that many limitations of SimCo result from the input parameters, rather than from the model structure. For the reason of speed, and to allow an easier overview and faster analysis of the model results, data input is less comprehensive and detailed than it might be. This section is confined to the limitations resulting from the model structure itself.

The modelling method for the optimisation section, mixed integer programming, does not allow non-linear constraints. In practice, nearly all constraints are in reality more or less non-linear. However, there are various ways of approximating non-linear phenomena with linear equations.

Material characteristics are invariable in the model, while they may be highly variable in reality. An example is blast furnace gas, of which the composition varies with the fuel input and the oxygen-air ratio. In this case, the definition of two kinds of blast furnace gas largely overcomes such a limitation. The model can choose the ratio between the two kinds of blast furnace gas. The same solution holds for the combustion of waste gases. In some other cases, the introduction of a slack parameter provides the model with the required degree of freedom. In general however, the variability of material characteristics causes no large problems, and material characteristics can be assumed constant.

The model includes only the main events in the life-cycle of installations. The intermediate adaptation of an installation is not possible in the model, unlike in reality. However, intermediate adaptations are not likely to have important consequences; upgrades are generally better occasions to introduce changes.

Not all installation characteristics are time-dependent. Labour efficiency and energy loss do vary with time, but the material input and output constraints are the same for all periods. In some cases this might introduce problems. For example, the gradual decrease of energy loss would sometimes allow for lower fuel inputs, while the material constraints
prohibit this. The model may avoid this problem by conversion to a variant of the installation with different material input-output characteristics. However, here again the problem of calculation speed looms due to the many conversion possibilities. Input of all installation characteristics for each period would render the data input virtually unmanageable. In general, the fuel consumption has been made dependent on the energy loss as much as possible, to prevent problems of this nature.

<table>
<thead>
<tr>
<th>Box 5.13 Overview of model boundaries</th>
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<tbody>
<tr>
<td>All constraints are linear</td>
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<tr>
<td>Material characteristics are invariable</td>
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<tr>
<td>Only main events in installation life-cycle are included</td>
</tr>
<tr>
<td>Only part of installation characteristics is time-dependent</td>
</tr>
<tr>
<td>The characteristics of existing installations are invariable</td>
</tr>
<tr>
<td>The model cannot influence the maximum demand for products</td>
</tr>
<tr>
<td>Future developments are certain in the model: perfect foresight in a limited period</td>
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</tbody>
</table>

In the model, the company has no possibility to change the characteristics of an installation, while in practice, each upgrade presents an opportunity to improve installations. Conversion of an installation to an installation with different characteristics, which is possible within the model structure, might circumvent this problem. In practice, the increase in calculation time is an important obstacle. Fortunately, the differences within one installation over time are generally much smaller than the differences between different types of installations. Therefore, this simplification generally has a limited impact.

In the SimCo model, the company has no influence on the maximum demand for products. In practice, marketing and price policies may have an important influence on the realised sales. However, variability of both prices and sales would introduce non-linearity. In the model, prices are fixed. The sales of products have an upper bound and, optionally, a lower bound, to confine the production to a predetermined range.

The model has a deterministic nature, which means that in the model the expected values of future parameters will come true. Uncertainty is left out in the optimisation of investment decisions. The effect of this uncertainty on the decisions is probably relatively limited, as short-term fluctuations in price and demand hardly influence major investment decisions. Uncertainty analysis, by varying scenario parameters, is of course possible, but is very time-consuming. Another possibility is to calculate the performance of a certain run under different scenarios, by fixation of the investment decisions, while varying the scenario parameters.

The implications of the model boundaries for the results are probably restricted, and some uncertainty analysis will largely overcome these. However, it is important to be aware of the model imperfections in the analysis of the results, especially as small changes in the point of departure may sometimes have large effects on the long-term results.

### 5.6 Other applications of SimCo

The current application of SimCo involves a study on the long-term development of iron and steel companies, by repetitive short-term optimisation. This application requires a wide range of available installations, and allows for a relatively rough definition of installation life-cycles and material flows.

SimCo may serve other purposes as well. With the appropriate data input, the model
may serve as a decision support tool, providing optimal decision schemes for possible future developments in specific cases. This application requires very detailed company specific information, but the decision possibilities are generally limited, as they are tuned to the specific situation. For this specialistic application, uncertainty analysis is imperative.

5.7 Data entry

As will be clear from the equations listed in the section on optimisation, the data definition for SimCo differs substantially from that in the other analysis methods. Rather than fixed installation characteristics, SimCo requires upper and lower boundaries on flows and characteristics of flows. These ensure that the behaviour of the model remains within a realistic range. Of course, it is possible, by giving upper and lower boundaries the same values, to have fixed installation characteristics. Yet, allowing the material flows to vary increases the realism of the model in an important way.

Paradoxically, sometimes data input not directly derived from literature sources plays an important role in forcing the model to choose realistic values for input and output flows. The parameters that determine the flow of materials have been chosen such that the possible ranges of material flows encompass the input characteristics assumed in the other analyses. The parameters available for determining the range of material flows are the upper and lower input and output limits, the energy loss of the installation, the definition of category constraints and the CO\(_2\) balances.

The specific data format of SimCo results in a considerable increase in data input detail compared to that in the other analyses. Moreover, in some cases it is very difficult to determine \textit{a priori} whether the chosen constraints and parameter values confine the model to a realistic range. In addition, not all data required, for example on energy balances or categories, are available. In many cases, reconstruction of these data from other information is possible. In some cases, the model itself has been the tool for this reconstruction: Trial and error adaptations of specific constraints and parameter values finally yielded the values that result in realistic performance of the installations, according to the available data on installation characteristics. It is possible to check whether adequate values have been chosen, by comparing the resulting input-output ranges in the model with input and output ranges found in the literature. However, as much as possible the input data originate from literature values, or from values obtained by direct calculations on literature values. The basic characteristics of the processes in SimCo are similar to those assumed for the analysis of chapter 4.
5.8 Legend of equations

Variables italic font, parameters normal font

*abandonment*<sub>(i,t)</sub> abandonment (0 or 1)

*action effect*<sub>(i)</sub> effect of an activity (start-up, upgrade, conversion) on actual capacity

*action*<sub>(i,t)</sub> specific activity (0 or 1)

*age effect counter*<sub>(i,t)</sub> age effect counter (linked to abandonment counter)

*age effect*<sub>(i)</sub> age effect

*bonus factor*<sub>(m)</sub> CO₂ bonus for excess energy in outgoing materials

*capacity*<sub>(i)</sub> capacity

*carbon equivalent*<sub>(m)</sub> CO₂ equivalent of material

*carbon equivalent*<sub>(e,t)</sub> CO₂ emitted per GJ electricity

*carbon embodied*<sub>(m)</sub> CO₂ embodied (emissions for material)

*category min*<sub>(i,c)</sub> minimum category input relative to production

*category max*<sub>(i,c)</sub> maximum category input relative to production

*category factor*<sub>(m,c)</sub> category equivalent of a tonne material

*CO₂*<sub>(t)</sub> CO₂ emissions

*conversion*<sub>(i2,i,t)</sub> conversion from other installations (0 or 1)

*conversion*<sub>(i,i3,t)</sub> conversion to other installations (0 or 1)

*counter*<sub>(i,t)</sub> abandonment counter

*dcf* discounted cash flow

*discount correction*<sub>(t)</sub> discount correction for future years

*down*<sub>(i,t)</sub> downgrade of counter (0 or maximum age)

*electricity in*<sub>(i,t)</sub> electricity consumption

*electricity factor*<sub>(i)</sub> electricity required per tonne product

*energy loss*<sub>(i,t)</sub> minimal energy loss relative to product output

*energy value*<sub>(m)</sub> energy in material

*fixation valid*<sub>(m)</sub> CO₂ fixation valid (0 or 1)

*in*<sub>(m,i,t)</sub> net material inflow

*initialisation*<sub>(i0)</sub> start-up (0 or 1)

*input*<sub>(m,a0)</sub> material input

*input*<sub>(m,a2)</sub> material input in installation

*material effect*<sub>(m,i0)</sub> effect of material input on maximum production

*maximum age*<sub>(i)</sub> maximum age before special actions are required

*maxin*<sub>(m,i0)</sub> maximum material input relative to production

*maxout*<sub>(m,i0)</sub> maximum material output relative to production

*minin*<sub>(m,i0)</sub> minimum material input relative to production

*minout*<sub>(m,i0)</sub> minimum material output relative to production

*operationality*<sub>(i,t)</sub> state of installation in which production is possible (0 or 1)

*out*<sub>(m,i)</sub> net material outflow

*outp*<sub>(m,i2)</sub> material output
price_{m,t} \quad \text{material price}

price_{e} \quad \text{electricity price}

production \text{ factor}_{m,i} \quad \text{production factor (0 or 1), defines whether a material is a product}

production \text{ costs}_{p(i,t)} \quad \text{various costs per tonne product}

production_{(i,t)} \quad \text{production}

slack\text{ }_{c(t)} \quad \text{category slack parameter}

status \text{ costs}_{n(i,t)} \quad \text{costs of installation status}

status_{s(i,t)} \quad \text{installation status: construction, start-up, operational, upgrade, conversion, abandonment}

tax_{(t)} \quad \text{CO}_2 \text{ emission tax}

throughput_{(i,t)} \quad \text{installation throughput}

up_{n(i,t)} \quad \text{upgrade of counter (0 or maximum age)}

upgrade_{n(i,t)} \quad \text{occurrence of upgrade (0 or 1)}

wage_{(t)} \quad \text{labour hour price}

wear_{(i)} \quad \text{wear factor (decrease of abandonment counter by year)}