

## MATERIAL FLOW ANALYSIS WITH SOFTWARE STAN

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### ABSTRACT

The software STAN (subSTance flow ANalysis) is a new user-friendly freeware that supports performing material flow analysis (MFA) according to the Austrian standard ÖNORM S 2096 (MFA- Application in waste management) under consideration of data uncertainties.

After building a graphical model with predefined components (flows, processes, subsystems, system boundaries and text fields), known data (mass flows, stocks, concentrations and transfer coefficients) with corresponding physical units can be either entered or imported for different hierarchical layers (good, substance, energy) and time periods. A graph of the model with flows displayed as Sankey arrows (i.e. the width of a flow is proportional to its value) can be printed or exported into various graphical formats. If sufficient data are given calculation algorithms can be used to reconcile uncertain data and to compute unknown variables including their uncertainties (error propagation). Statistical tests are used to detect gross errors in a given data set.

The features of STAN are demonstrated on the example of a fictitious waste management company.

### INTRODUCTION

During the last 20 years Material Flow Analysis (MFA) has become a reliable instrument to describe material flows and stocks within various systems. In the meantime a few books in English and German are available on this topic [1-3]. In 2005 terms and methodology of MFA were standardized by the Austrian Standard ÖNORM S 2096 (MFA - Application in Waste Management).

But there are still some problems with regard to the application of MFA that have to be pointed out:

1. Usually more than one software product is used during an MFA. While the model is often iteratively designed with pencil and paper, data management and calculations are performed with spreadsheet software like Microsoft Excel. The final results are then converted into a graph with the help of graphical software. This procedure has turned out to be laborious and error prone.
2. Another major problem of many MFA studies is how to handle uncertain or inconsistent data. Often only mean values are employed. So far it is not state-of-the-art to consider uncertainties and their consequences on the results. In this way valuable

information for decision making gets lost.

In order to overcome these deficiencies STAN (subSTance flow ANalysis) was developed. STAN is a freeware for MFA that has been produced by the Vienna University of Technology (Institute for Water Quality, Resources and Waste Management) in cooperation with INKA software. It supports MFA according to the Austrian Standard ÖNORM S 2096 and allows consideration of data uncertainties. The development of the software was funded by the Austrian Ministry of Agriculture, Forestry, Water and Environment, by the nine Austrian states and by voestalpine, the largest steelmaker in Austria. Since October 2006 STAN is available for download under [www.iwa.tuwien.ac.at](http://www.iwa.tuwien.ac.at).

### SHORT PROGRAM DESCRIPTION

The following descriptions refer to STAN version 1.1.3.

#### 1. Graphical User Interface (GUI)

The GUI consists of windows that can be arranged arbitrarily. A few tool bars enable fast access

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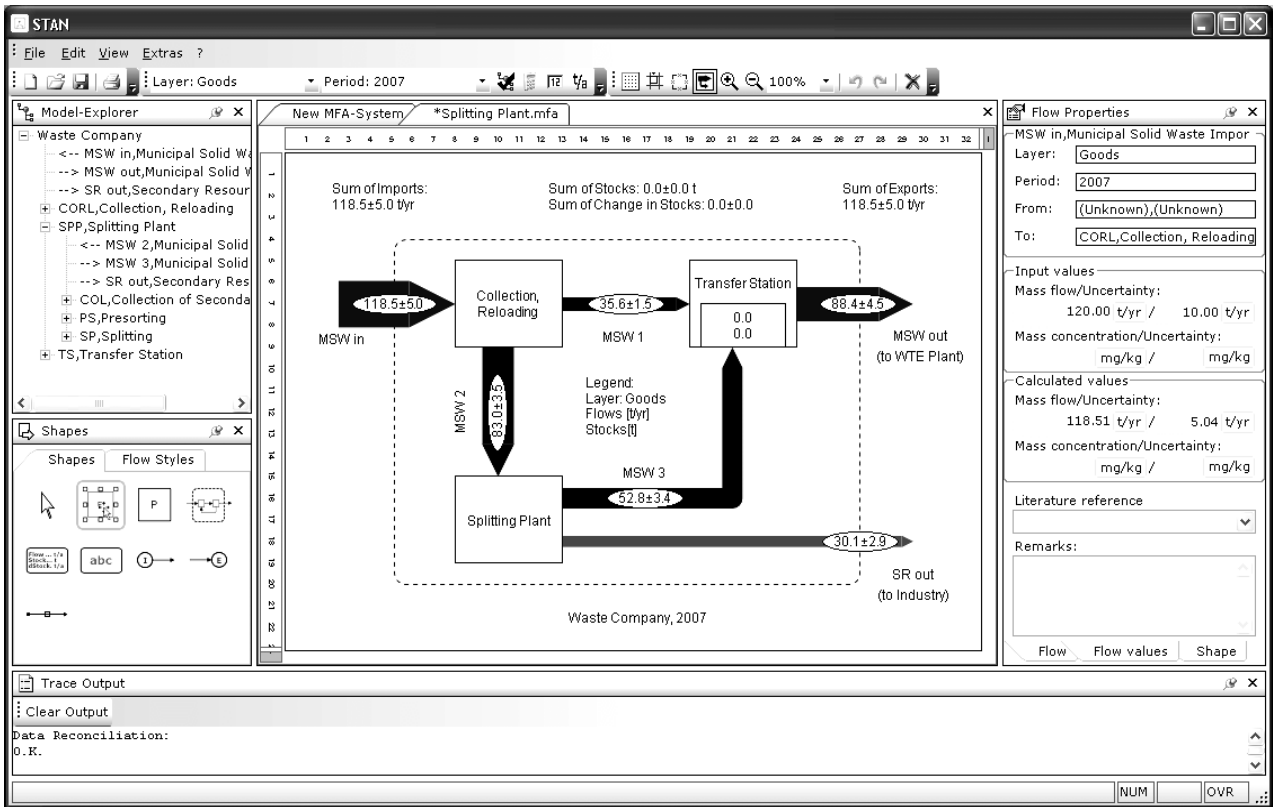


Fig. 1. Graphical user interface of STAN.

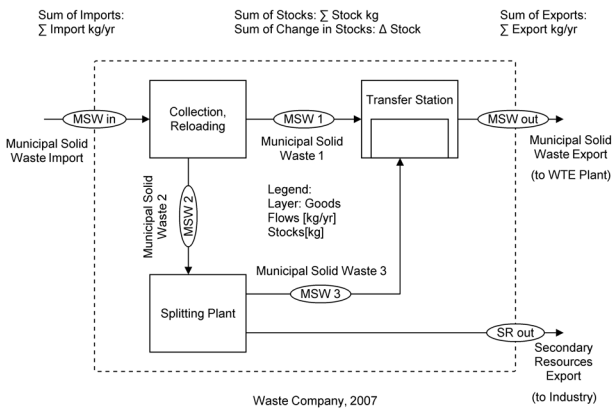


Fig. 2. Model of the system. The waste company uses a splitting plant to extract secondary resources (SR) from a part of the imported municipal solid waste (MSW) to sell them to the industry. The rest of the MSW and the residues from the splitting plant are collected at the transfer station from where they are exported to a waste to energy (WTE) plant.

to the most important commands (Fig. 1).

On the Drawing Area predefined objects (processes, flows, system boundaries and text fields) from the Shapes window can be used to assemble a model of a system. In the Model Explorer window the built model can be explored in tree view. Each element of the model has properties that can be changed in the

Properties window. This is also the place where data are supposed to be entered manually. The Trace Output window displays calculation related messages.

## 2. Modelling a System

Models are designed from predefined elements such as processes, flows, system boundaries, and text fields in a graphical way (Fig. 2).

By default, inserted processes contain no stocks. Afterwards, if desired, they can be converted into processes with stocks or subsystems. Subsystems offer the possibility to model the inner structure of a process in more detail by decomposing the process (Fig. 3). Along the perimeter of a process anchor points for flows can be found. The number of available anchor points can be altered by changing the process size. Internal flows connect two processes while import or export flows are used to link a process to the area outside of the system boundary. The course and appearance of flows can be changed optionally. A system boundary surrounds all processes of a model and is crossed by import and export flows. For labelling reasons text fields can be used. Besides free text, placeholders for system variables can be inserted that will be automatically replaced with the appropriate data (e.g. flow units in legend).

## 3. Entering Data

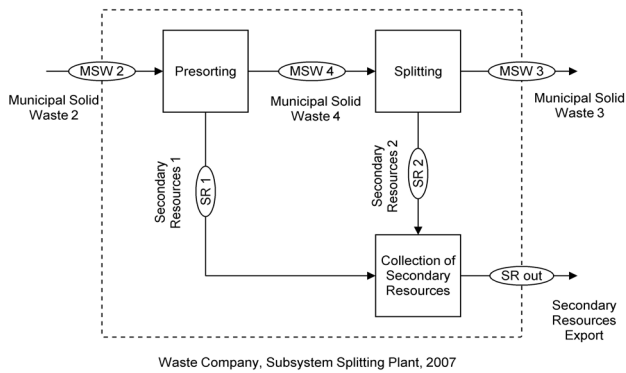


Fig. 3. Subsystem splitting plant. In the splitting plant the MSW is pre-sorted to extract the easily removable SR before being put into the splitting machine to get the rest of them. The outputs of the splitting plant are the residues of the MSW and the collected SR.

Data (mass flows, stocks, concentrations and transfer coefficients) can be entered manually with units and data uncertainties for different data layers (1 × goods, n × substances and 1 × energy) and time periods. For that purpose given units can be applied or own defined. If other units than those displayed are needed, the keyboard can be used to enter them directly after the values. The display unit is always offered by default. For the model graph mass flows and stocks will be automatically converted to display units (Fig. 4). Uncertain data are assumed to be normally distributed given by mean value and standard deviation.

In order to simplify the data entry a data table for all input data is available (Fig. 5). With the help of this table it is possible to group data and import or export it from or to Microsoft Excel. The design of STAN followed the “philosophy” that everything that is better accomplished in Excel (graphical interpretation of data, spreadsheet calculation, Monte Carlo simulation, etc.) should be done there.

#### 4. Calculations

If redundant information is given it will be used automatically during calculations to improve uncertain data (data reconciliation). Thereby all existing data layers and periods will be considered simultaneously. Possible gross errors will be recognized automatically by statistical tests. The reconciled values are used to calculate observable unknown quantities. The corresponding uncertainties are computed by the method of error propagation.

#### 5. Displaying Results

The results of the calculations are presented clearly in form of a Sankey diagram on the drawing

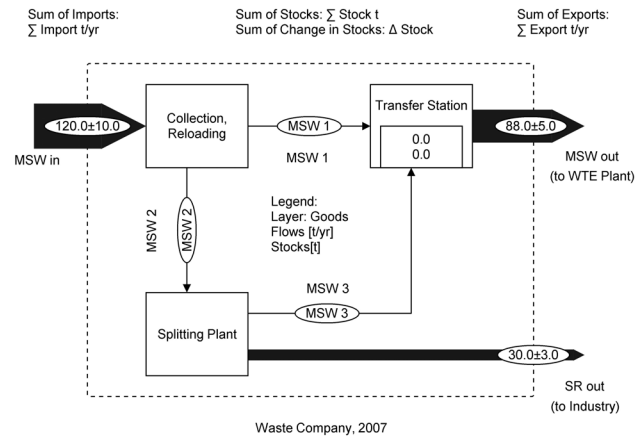


Fig. 4. Model with entered data ( $MSW_{in} = 120 \pm 10 \text{ t y}^{-1}$ ,  $MSW_{out} = 88 \pm 5 \text{ t y}^{-1}$ ,  $SR_{out} = 30 \pm 3 \text{ t y}^{-1}$ ). It is assumed that at the beginning of 2007 the transfer station was empty and that during the period no change in stock occurred. Additionally transfer coefficients in process Collection, Reloading ( $TC_1$  to  $MSW_2 = 0.7$ ) and within subprocess Presorting ( $TC_2$  to  $SR_1 = 0.1$ ) were given.

Flow	Flow val.	+/- Flow v.	Concentrati...	+/- Concentrat...	Remarks
Period: 2007					
Layer: Goods					
MSW 1.Munici...					
MSW 2.Munici...					
MSW 3.Munici...					
MSW 4.Munici...					
MSW in.Munici...	120 t/a	10 t/a			
MSW out.Muni...	88 t/a	5 t/a			
SR 1.Secondar...					
SR 2.Secondar...					
SR out,Second...	30 t/a	3 t/a			
Layer: Sub Substance					
MSW 1.Munici...			20 mg/kg		
MSW 2.Munici...			50 mg/kg		
MSW 3.Munici...					
MSW 4.Munici...					
MSW in.Munici...					
MSW out,Muni...					
SR 1.Secondar...					
SR 2.Secondar...					
SR out,Second...			100 mg/kg		

Fig. 5. Data table with grouped input data.

area. Thereby the width of an arrow is displayed proportional to its mass flow value (Figs. 6 and 7). The scaling factor can be adjusted manually.

The calculated values of single objects are also visible in the Properties window. If multiple periods have been defined it is possible to display the values of a single flow as a time series.

The model graph can be exported in different graphic formats (bmp, emf, exif, gif, icon, jpeg, pmg, tiff, wmf) in arbitrary resolutions. If necessary the displayed data can be made anonymous by referring it

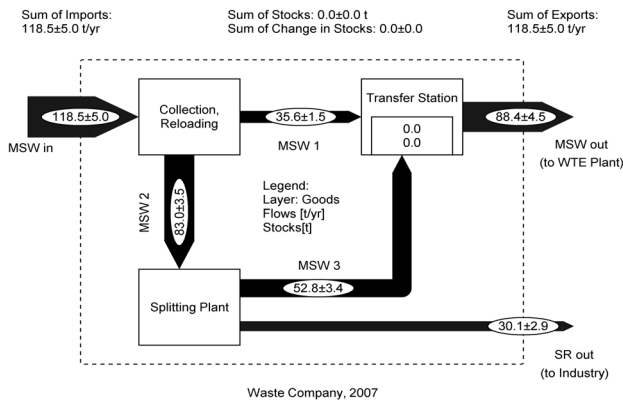


Fig. 6. Model graph with calculated data. Because no change in stock is allowed the sum of imports should equal to the sum of exports. This redundant information can be used to reconcile the uncertain input values of  $MSW_{in}$ ,  $MSW_{out}$  and  $SR_{out}$  that do not match. During this procedure values with higher uncertainty are altered more than those with lower uncertainty. Additionally their uncertainties are reduced. Values without uncertainty are not changed at all. All unknown flows could be calculated. Their uncertainties were computed with the method of error propagation.

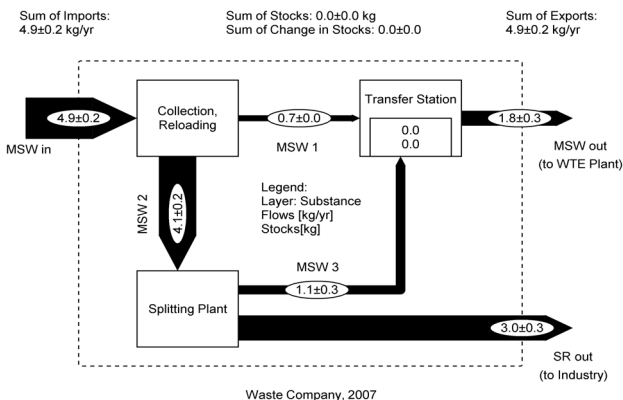


Fig. 7. Additionally a substance layer was defined. On this layer the substance concentrations ( $c$ ) of a few flows were given ( $c$  of  $SR_{out} = 100 \text{ mg kg}^{-1}$ ,  $c$  of  $MSW_1 = 20 \text{ mg kg}^{-1}$  and  $c$  of  $MSW_2 = 50 \text{ mg kg}^{-1}$ ). With this information all substance mass flows of the main system could be calculated.

to an arbitrary value (e.g. sum of imports, sum of exports).

### 6. Help File

In STAN a context sensitive help is implemented which can be activated by pressing F1 on the keyboard. Besides general information about the active window, links to certain topics of the manual can be found. The language of the user interface including

the help file can be switched between English and German.

### CALCULATION ALGORITHM

During calculation a graphical model created with STAN is automatically translated into a mathematical model using four types of equations (Eqs. 1-4):

Balance equation:

$$\sum \text{inputs} = \sum \text{outputs} + \text{change in stock} \quad (1)$$

Transfer coefficient equation:

$$\text{output}_x = \frac{\text{transfer coefficient}_{to} \cdot \text{output}_x}{\sum \text{inputs}} \quad (2)$$

Stock equation:

$$\text{stock}_{\text{Period } i+1} = \text{stock}_{\text{Period } i} + \text{change in stock}_{\text{Period } i} \quad (3)$$

Concentration equation:

$$\text{mass}_{\text{Substance}} = \text{mass}_{\text{good}} \cdot \text{concentration}_{\text{substance}} \quad (4)$$

These equations could contain unknown, measured and exactly known (constant) variables. If through elementary transformation of the created set of equations (equality constraints) at least one equation can be found that contains no unknown and at least one measured variable data reconciliation can be performed to improve the accuracy of the measurements. To reach this goal Madron [4] proposed a Gauss-Jordan elimination process of the original linear constraint matrix. Since some of the used equality constraints are sometimes nonlinear the method of successive linear data reconciliation is chosen to solve the nonlinear data reconciliation problem iteratively. In each of the iteration the equality constraints are linearized and the arising linear reconciliation problem is solved analytically. Statistical tests are used to check if the necessary corrections of the measurements could be explained by random errors or if they might be due to gross errors. Subsequently, the improved values are used to calculate the unknown quantities. The corresponding uncertainties are determined with the method of error propagation [5].

### DISCUSSION

STAN is often used simply for displaying mass flows of goods and substances as Sankey arrows. This approach offers the advantage that the largest flows of materials can be recognized immediately. But due to measurement uncertainties contradictions in input data are inevitable. Often it is not clear how to handle these inconsistent data. STAN offers the possibility to reconcile these values in order to find the best fitting

ones without guessing. Gross errors in input data are detected by statistical tests. In this way possible contradictions in given data are resolved which is prerequisite for calculating the values of unknown variables and their corresponding uncertainties.

STAN is also suitable for performing dynamic MFA by using the period feature. Instead of directly applying continuous mathematical input functions STAN offers the possibility of assigning single values of discretized functions or time series to the corresponding time steps (periods).

## CONCLUSIONS

A wide spread use of STAN offers the opportunity to describe and analyze arbitrary systems with a standardized method. It can be instrumental as a base for modelling material flows for the assessment of the economic, resource and environmental value of materials.

A free copy of STAN is available for download under [www.iwa.tuwien.ac.at](http://www.iwa.tuwien.ac.at). For detailed information contact Oliver Cencic (+43-1-58801-22657, [o.cencic@iwa.tuwien.ac.at](mailto:o.cencic@iwa.tuwien.ac.at)).

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Discussions of this paper may appear in the discussion section of a future issue. All discussions should be submitted to the Editor-in-Chief within six months of publication.

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