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Material Flow Analysis with Software STAN

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Abstract

STAN (short for subSTance flow ANalysis) is a free software that supports performing material flow analysis (MFA) according to the Austrian standard ÖNORM S 2096 (Material flow analysis - Application in waste management) under consideration of data uncertainties. The main idea behind STAN is the combination of all necessary features of a MFA in one software product: graphical modelling, data management, calculations and graphical presentation of the results. The benefits of the application of STAN are demonstrated on the example of a fictitious waste management company.

1. A short introduction to MFA

MFA is the systematic assessment of flows and stocks of materials within an arbitrarily complex system defined in space and time. The term material serves as an umbrella term for both goods and substances.

Goods are defined as economic entities of matter with a positive or negative value (e.g. drinking water, fuel oil, and solid waste, sewage, respectively). Some goods have no economic value, i.e. they are neutral in their values, e.g. air or precipitation. Goods contain substances. A substance is any (chemical) element or compound composed of uniform units. All substances are characterized by a unique and identical constitution and are thus homogenous (e.g. N, C, Cu, NH_4+, CO_2). Using this definition makes clear that “drinking water” is not a substance. It is composed of substances such as pure water, calcium, and many trace elements. Even “PVC” is not a substance, because it consists of polyvinyl chloride and some additives.

A model of a system consists of processes and flows. A process is a place where transformation, transport or storage activities of materials take place. Usually, processes are defined as black boxes, meaning that detailed information what is happening inside is not available or not taken into account. Only the inputs and outputs are of interest. Otherwise the process must be defined as a subsystem that contains two or more sub-processes. Flows connect processes. If they cross the system boundary they are called import or export flows. A flow is normally named after the good that is transported over it (e.g. raw materials).

The aim of material flow analysis is to describe and analyze a real system as simple as possible, but in enough detail to make the right decisions.

2. The story behind STAN

During the last 20 years 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 (Material Flow Analysis - Application in Waste Management). But there are still some shortcomings with regard to the application of MFA:

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1. Usually more than one software product is used during a 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.
3. There was no free software available that was special designed for MFA.

In order to overcome these deficiencies STAN was developed. STAN (short for subSTance flow ANalysis) 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.

3. The implemented calculation algorithm

Before starting a calculation to compute unknown quantities the graphical model created with STAN has to be automatically translated into a mathematical model using four basic types of equations:

balance equation: $\sum \text{inputs} = \sum \text{outputs} + \text{change in stock}$

transfer coefficient equation: $\text{output}_{x} = \text{transfer coefficient}_{\text{to output } x} \cdot \sum \text{inputs}$

stock equation: $\text{stock}_{\text{Period } i+1} = \text{stock}_{\text{Period } i} + \text{change in stock}_{\text{Period } i}$

concentration equation: $\text{mass}_{\text{substance}} = \text{mass}_{\text{good}} \cdot \text{concentration}_{\text{substance}}$

These equations could contain unknown, measured and exactly known (= constant) variables. Measured data always contain uncertainties! Because of that it is possible to encounter contradictions in data when only looking at the mean values. Imagine a process without a stock with one input and one output flow, both measured. Because of random measurement errors their mean values are likely to be not exactly the same, but should be. If those measured values are assumed to be normally distributed given by a mean value and a standard deviation the method of data reconciliation can be applied to adjust the data in order to resolve the contradiction. This is prerequisite for calculating the values of unknown variables and their corresponding uncertainties.

To find out which measurements have to be reconciled in huge systems elementary transformations of the linear set of equations (= equality constraints) have to be performed. If at least one equation can be found that contains no unknown and at least one measured variable data reconciliation can be applied to improve the accuracy of the measurements. It is also possible to check for contradictions in constant input data if the transformation leads to at least one equation that only contains exactly known variables.

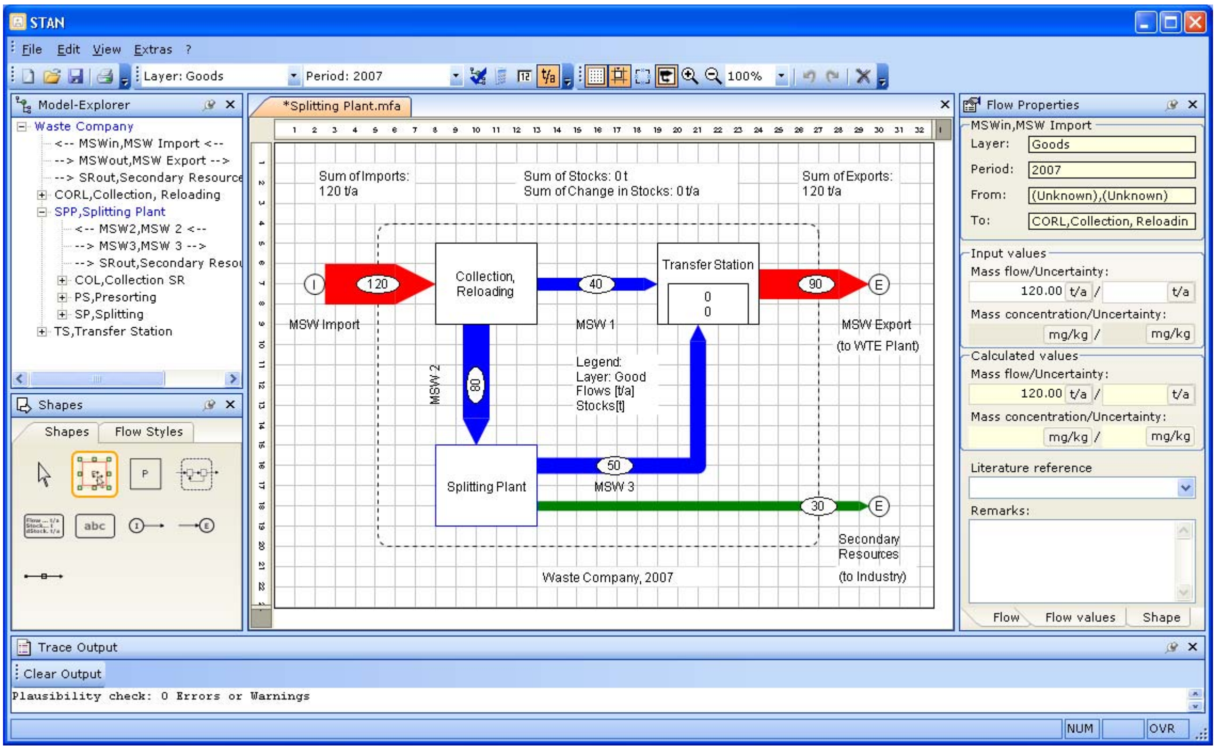
Because some of the used equations are nonlinear we have to deal with a nonlinear data reconciliation problem. If only equality constraints are involved it can be solved using iterative techniques based on successive linearization and analytical solution of a linear reconciliation problem [4]. In each of the iterations an approach based on the idea of Madron [5], he proposed a Gauss-Jordan elimination process of the original linear/linearized constraint matrix, is used to solve the problem. Subsequently, the improved values are used to calculate the unknown quantities. The corresponding uncertainties are determined with the method of error propagation.

A statistical test (measurement test) is used to check if the necessary corrections of the measured variables could be explained by random errors or if they might be due to gross errors [4].

Note that all defined layers and periods will be considered simultaneously during calculation.

4. Application example

This article is not focused on the human-computer-interaction that is necessary to operate STAN. If it is needed a short introduction to STAN 1.1.3 can be found in [6, 7]. For further information consult the context sensitive help that is implemented in STAN. It can be activated by pressing F1 on the keyboard. The language of the graphical user interface (Figure 1) as well as the help file can be switched between German and English.



Layer: Goods
Period: 2007

MSWin,MSW Import
Layer: Goods
Period: 2007
From: (Unknown),(Unknown)
To: CORL,Collection, Reloadin

Input values
Mass flow/Uncertainty: 120.00 t/a / t/a
Mass concentration/Uncertainty: mg/kg / mg/kg

Calculated values
Mass flow/Uncertainty: 120.00 t/a / t/a
Mass concentration/Uncertainty: mg/kg / mg/kg

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Plausibility check: 0 Errors or Warnings
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Fig. 3: Graphical user interface of STAN

We want to demonstrate the basic steps of a MFA and the benefits of the application of STAN on the example of a fictious waste management company (WMC).

4.1 Modelling the system

The WMC 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 outside of the system boundary (Figure 2).

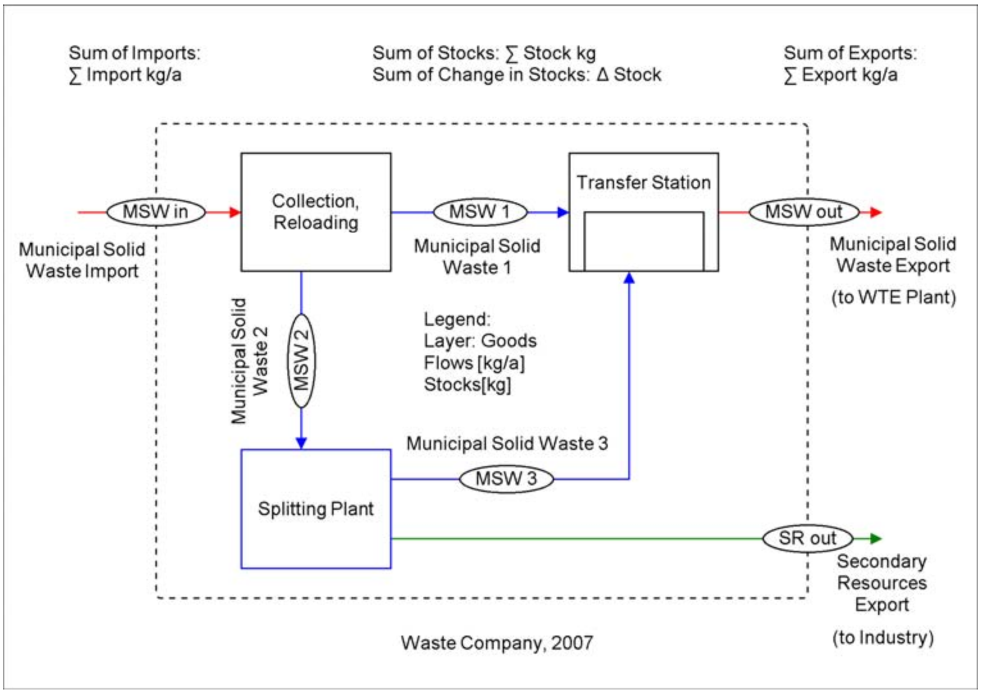

Fig. 2: Model of the system.

The WMC has to deliver a graph of their system for the year 2007 to local authorities. Because of trade secrets it does not want to show what is going on inside of the splitting plant. So it decides to model this process as a subsystem.

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 (Figure 3).

4.2 Entering data

On the layer of goods all available data including their corresponding units and uncertainties are entered or imported (MSWin = 120 ± 10 t/a, MSWout = 88 ± 5 t/a, SRout = 30 ± 3 t/a). It is assumed that at the beginning of 2007 the transfer station was empty and that during the period no change in stock occurred (Figure 4).

The rates of how much of the imported MSW is going to the splitting plant and how much of it is extracted as SR during pre-sorting are known. These information is modelled with transfer coefficients in the process collection - reloading (TC1 to MSW2 = 0.7) and in the sub process pre-sorting (TC2 to SR1 = 0.1).

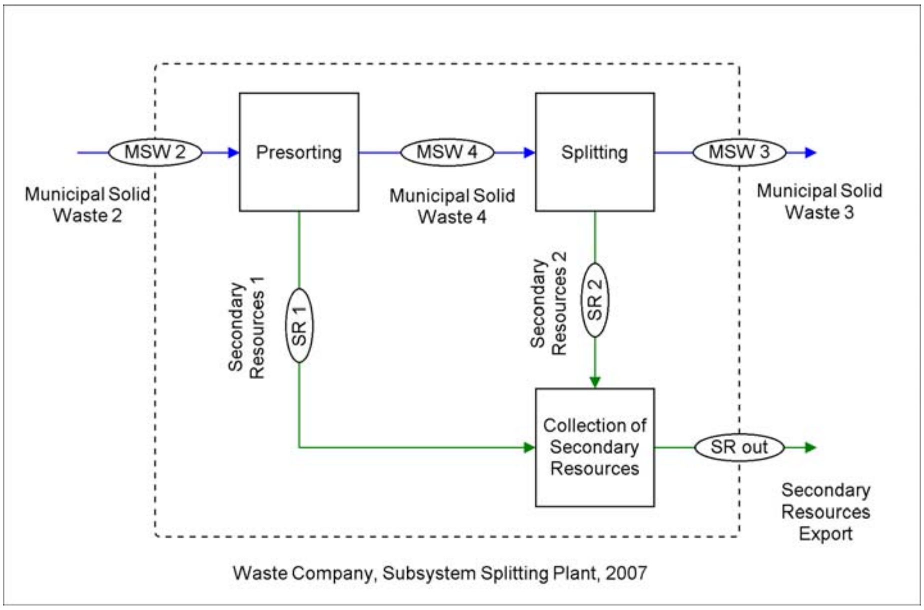

Fig. 3: Subsystem splitting plant.

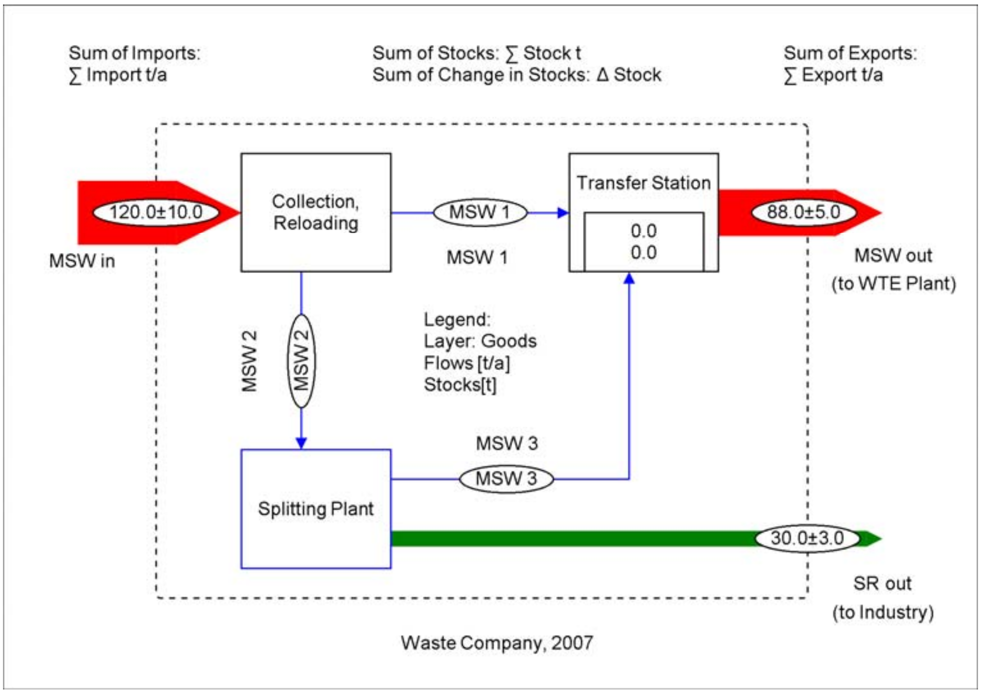

Fig. 4: Model with entered data

Additionally a layer for a substance of interest was defined. On this layer the substance concentrations (c) of a few flows were given (c of SRout = 100 mg/kg, c of MSW1 = 20 mg/kg and c of MSW2 = 50 mg/kg).

4.3 Calculations

Because no change in stock occurs within the system the sum of imports should equal to the sum of exports. Looking only at the mean values of the entered data on the layer of goods one realizes that this is not the case: the sum of imports (= 120 t/a) does not match the sum of exports (118 t/a). Normally with contradictions of this kind it is not possible to calculate any unknown quantities. The problem can only be solved if at least one of the variables involved is measured (i.e. it has a measurement uncertainty). In our case all import (MSWin) and export flows (MSWout and SRout) are measured. Because of that it is possible to apply the method of data reconciliation. 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 (Figure 5). The statistical tests performed points out that all necessary corrections of the measured data can be explains by random errors.

The information given on the substance layer was also sufficient to calculate all substance mass flows of the main system (Figure 6).

4.4 Displaying results

The results of the calculations are presented clearly in form of a Sankey diagram. Thereby the width of an arrow is displayed proportional to its mass flow value (Figure 5 and Figure 6). The scaling factor can be adjusted manually. If necessary the displayed data can be made anonymous by referring it to an arbitrary value (e.g. sum of imports, sum of exports).

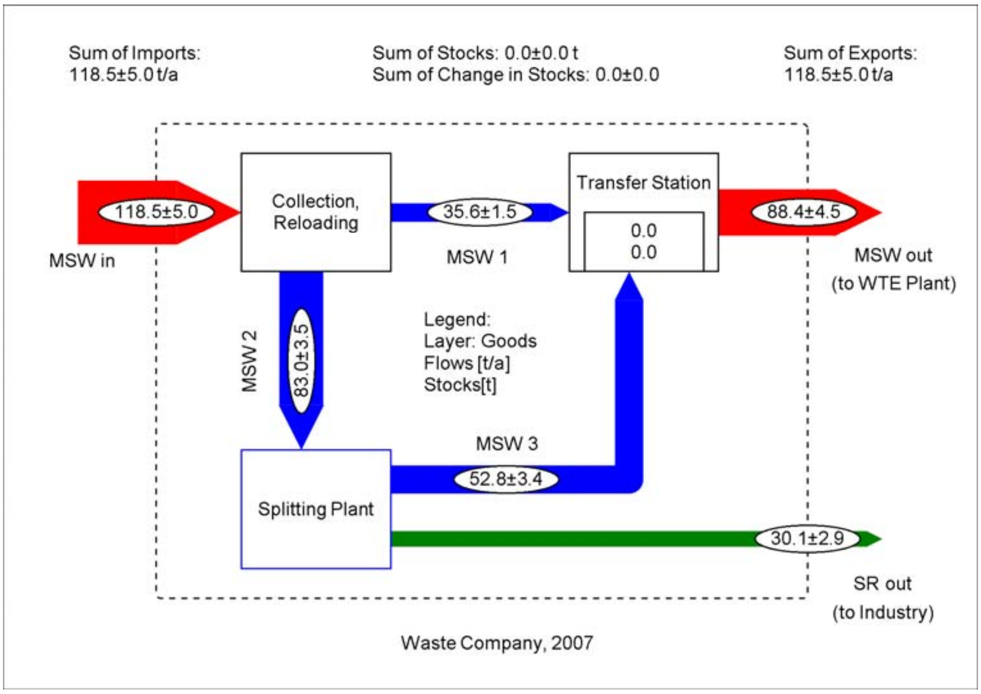

Fig. 5: Model graph of the main system with calculated data on the layer of goods

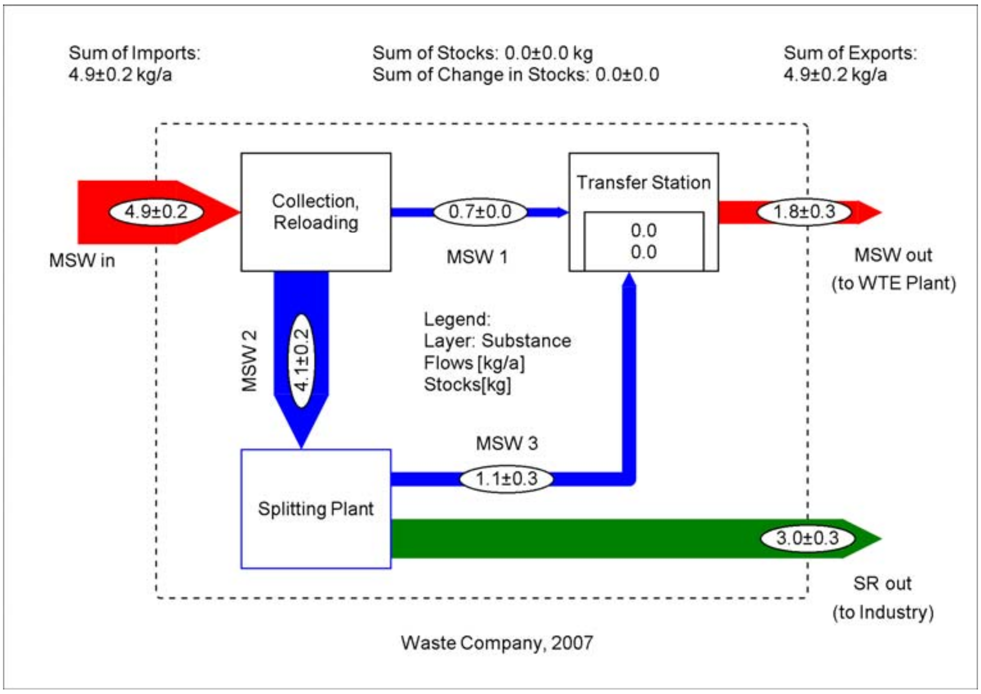

Fig. 6: Model graph of the main system with calculated data on the layer of the considered substance

5. Discussion

STAN is often used simply for displaying mass flows of goods and substances as Sankey arrows. This offers the advantage that the largest flows of materials can be recognized immediately.

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 measured 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.

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.

Since the release of STAN in October 2006 more than 1,800 users (June 2008) from all over the world (25 countries) have registered on our website und downloaded STAN. Because of a lot of positive feedback we have decided to continue developing STAN. The new version is planned to be released in January 2009.

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

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