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Material Flow Analysis for Eco-Efficiency with Material Flow Network Reference Models – Concepts and Case Study

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Abstract: Material Flow Analysis is a method for determination of material and energy flows in companies for ecobalances and process optimization. Ecobalancing provides a basis for efficient utilization of material resources and energies and for reduction of environmental harmful emissions and waste. Reference models in material flow analysis (e.g. with Material Flow Networks) serve as templates for the development of more refined models in the same domain. They facilitate material flow analyses by reducing effort in time and costs in the model building process by reutilization of predefined structures. In the context of a Thai-German cooperation project a reference model for the Thai agro-industrial branch of native starch production has been designed which reduces the entry level for material flow network modelling in Thai starch industry. Material flow analyses should help to reduce environmental impacts such as water pollution as well as to improve production processes on an economic level. Process improvements for eco-efficiency are targeted on a reduction of starch losses during starch production while a better yield of starch is allowed. The reference model has been developed with the software tool Umberto\textsuperscript{®} which is a graphical modeling tool for Material Flow Networks. The software supports a modular design of the reference model in order to make it easily adaptable to specific production processes in different starch factories. The general, well structured reference model approach for material flow analysis, developed to reduce environmental burdens and financial losses in Thai starch industry, is easily transferable to other industrial branches beyond Thai agro-industry as well as to other regions.

Keywords: Material Flow Analysis; Reference models; Eco-efficiency; Native starch production.

1. INTRODUCTION INTO MATERIAL FLOW ANALYSIS

Material Flow Analysis is an important constituent of Environmental Management Information Systems (EMIS). As modeling approach in material flow analyses so called Material Flow Networks are applied making use of special application software. Material Flow Networks are a method from Environmental Informatics and support computation of material and energy flows. Material Flow Networks, representing relevant energy and material flows and their transformations within a company, have been originally developed at the University of Hamburg as a powerful Material Flow Analysis method; see Moeller [1995] and Moeller [2000]. Material Flow Networks are a graphical modelling notation based on the popular Petri Net methodology for specifying concurrent systems in Computer Science and have been transferred into the Environmental Sciences. They provide both detailed information on environmental effects of a company or on ecological optimization of products as well as the influence of the associated material flows on the costs. In Material
Flow Networks the transitions, represented in diagrams by squares, stand for the location of material and energy transformations. Transitions play a vital role in Material Flow Networks, because material and energy transformations are the source of material and energy flows. Another defining characteristic of Material Flow Networks is their concept of places. Places separate different transitions. This allows a distinct analysis of every transition. Beyond that places can describe inventories for materials. Circles are used in diagrams to represent places. Arrows show the paths of material and energy flows between transitions and places. They constitute a combined flow and inventory analysis:

**Notation** used in Network Model of the starch production process:

- The central components of Material Flow Networks are the **Transitions**, which are marked as blue boxes in the network. They specify energy and material transformation processes in a production system. There are predefined rules for transformation of input into output materials which can be based on parameters, mathematical functions, standard transitions from libraries, or user defined transformation programs.
- **Circles** are so-called **Places**, i.e. inventory and connections without material transformation. They describe system boundaries (Input-/Output), take care of branching and fusing in the network or denote inventories. **Green circles** marked with a vertical line on the left are **Input Places** for materials and energy; **red circles** are **Output Places** for products and emissions. **Yellow circles** are connection places for material flow branching and storage.
- **Connections** shown as directed lines represent material and energy flows from Places to Transitions and from Transitions to Places. Several materials can flow in one arrow.
- Embedded blue boxes within another box denote **Submodels** which include another partial network in order to reduce model complexity.

**Figure 1: Graphical Notation used in Material Flow Networks** [Pimpisut et al., 2007]

Based on this early innovative Environmental Informatics idea a suitable software tool has been developed first as a prototype at the university institute and afterwards as a commercial software product under the name of Umberto® (s. www.umberto.com) in the nineties. Meanwhile Material Flow Networks and the related modelling software Umberto® are an established method and tool in the context of EMIS for building up accounting systems for relevant material and energy flows and transformations (including cost data) within a production process in a company in order to achieve Eco-Efficiency [Moeller et al., 2001]. Today the software is widely used in many industries on the national as well as on the international level.

Since material flow analyses can be very time consuming and costly it would be an advantage if a template for Material Flow Networks in a special industrial branch was at hand from the very beginning. Reference models offer such templates for the development of Material Flow Networks and allow a reduction of effort in material flow analyses.

One recent international application of Material Flow Networks has been a joint Thai-German project for establishing an EMIS in Thai native starch industry presented in this paper as well as in palm oil industry published elsewhere [Page et al., 2007].

The aim of this work is the development of a reference model for material flow analyses in order to facilitate them. In addition an indicator system is defined to evaluate material flows. The main motivation of this approach beyond the facilitation of material flow analyses is an environmental and economic improvement of production processes.

This paper is organized as follows: After this short introduction into Material Flow Networks as a modelling approach in material flow analysis and to the Thai-German...
cooperation project we discuss the general ideas of reference modelling in material flow analysis. In Chapter 3 we introduce a case study in Thai starch industry where a production reference model as subtask of a joint Thai-German development project for an EMIS has been deployed. The background of the EMIS project is disclosed and the system components briefly described. The different steps of the design process of the starch production reference model, the model structure, the Key Performance Indicators and computational results are explained. Finally some concluding remarks with a short summary of the findings in the project as well as with some hints on the generality of the approach beyond the special application domain round up this paper.

2. REFERENCE MODELS IN MATERIAL FLOW ANALYSIS

Since we cannot rely on a generally accepted definition for Reference Models in literature we understand Reference Models as information models for supporting the construction of other models in a given domain or industrial branch. They represent an idealized mapping of systems onto models in a special domain and serve as template for model building in this area. Therefore the main asset of reference models is its benefit in generating more specific models with less effort. In Material Flow Analysis the effort in modeling as well as data collection can be significantly reduced by predefined model structures and data sets. Also an adaptation of given model structures is straightforward for achieving a good match with the real world production system.

In order to achieve the aim of providing a model template with reference models they have to meet a number of requirements. First we gear towards generality, which means that a reference model has to be suitable for the deduction of a range of specific models. Adaptability of reference models to special needs as well model extensibility are required. Usability means that a reference model should be specified to the extent that it can be already applied without modifications. In the context of material flow analyses reference models should support all modeling steps completely. With the delivery of characteristic structures and generalized data in a reference model the requirement of completeness is fulfilled. Beyond that, modifications of reference model components should be supported by user instructions and hints. The greatest assets of reference models lay in the model building phases of model design, data collection and model implementation. In model aggregation a specific model is assembled from different model modules. Therefore a modularization of reference models is useful where sections of a production process or plant are defined and compiled as partial reference models or sub models, respectively. The user might concentrate on a few production sections with separate partial reference models which have to be relatively independent from each other.

In order to carry out a material flow analysis efficiently a comprehensive model documentation is required which describes model application step by step and explains each part of the reference model in an understandable manner. Since the modeling process is carried out in a software environment data and model structures are reusable. Finally transparency of all modeled structures, collected data and of computational model results is required in the reference model building process.

3. CASE STUDY: REFERENCE MODEL FOR NATIVE STARCH PRODUCTION IN THAILAND

The Department of Industrial Works (DIW) in Bangkok in cooperation with the German Society for Technical Cooperation (GTZ) has carried out a development project “Management Information Systems for Industrial Pollution Prevention and Control” from 2005 until 2007, where the authors have been acting as project consultants. The main result of this project has been the development and implementation of a special Environmental Management Information System for Eco-Efficiency in different agro-industrial sub-sectors including native starch in Thailand. An integral part of this EMIS has been a material flow reference model for native starch production based on Material Flow Network methodology. Native starch is used in food, textile and paper industry. Starch production is one of the largest and most important agro-industrial branches in Thailand. However, the
production of native starch from Tapioka plants has negative impacts on the Thai environment. In particular this is obvious in water pollution caused by high organic exposure of sewage from the production process. Beyond that starch losses accumulate during the different steps of the production process. In order to investigate and improve ecologically relevant processes material and energy flows at the production of native starch are analyzed by means of material flow analysis. For example by balancing these flows it can be estimated how much and where exposed sewage at the production process of starch per ton is accumulated. Based on the results measures for improvement can be taken with positive effects on the environment. In Thailand around 85 native starch factories exist running similar production technologies. A reference model can provide a standardized Material Flow Network for these factories in order to reduce their effort in material flow analysis.

3.1 Components of Environmental Management Information System

The EMIS aims at the enlargement of the information basis for the management in the native starch factories and therefore at an improvement of the management decision process under environmental as well as economic criteria.

The MIS Software for Eco-Efficiency consists of different components including the data base application, the material flow reference production models as well as the Assistant programs. An essential component of the EMIS for eco-efficiency is a production data base application for the Native Starch sector. The main focus of the data base applications is short term data (daily to monthly and beyond) and monitoring of the production process on a timely basis. They provide (economic as well as ecological) Key Performance Indicators (KPIs) on a short term scale as well as short term reports supporting factories in day-to-day business. The data base applications have been introduced only recently in a number of native starch factories in different regions of Thailand as a data collection and data storage facility in a stepwise procedure. The users in the companies will also be able to produce some standard reports and outputs from the standard relational data base management system.

In contrast material flow analysis reference Models (MFA-models) based on Material Flow Networks have a long term focus on flexible time periods such as quarters, six months, or yearly periods and beyond. Thus another central component of the MIS for Eco-Efficiency is a suitable EMIS software product such as Umberto® supporting the development of material flow analysis models. This software component reads in company measurement data from the data base by defined interfaces and runs Material Flow Reference Models for the selected industrial sub sector of Native Starch production (as well as other sectors like Palm Oil). The reference model represents the principal processing steps of the production process of native starch. Since MFA modelling is very much a data-driven approach, the data base application of the EMIS plays an important role as central data source. In addition process knowledge by specialists in the project team has been incorporated into the modelling process.

Due to the typical similarities in the production processes in most companies of an industrial sub-sector the MFA model represents a branch-specific Reference Model used by all companies. Quantitative differences between the productions in the single companies are covered by varying parameter values derived from the respective company data base. Structural differences in the production processes, however, require model adaptations on submodel level, i.e. there might be different submodel versions in operation in single factories taking care of differences in technical production processes. The MFA model delivers long term KPI’s, material and energy balances for the whole production process or of sections of the process, can highlight critical flows and provides what-if-analyses comparing different options for improvements and cost reductions. Typical analysis results are for instance comparisons of company eco-efficiency with benchmark values defined for the industry under investigation.

IT-users in the companies such as production managers will be working with the runtime version of the EMIS model (“Umberto®-Runtime”) and will be supported by so-called Assistants in order to facilitate the EMIS application. The user is prompted for certain data
items which can be typed in manually or accessed from the database in a guided dialog. The Assistants will transfer the input data and parameters to the EMIS model for processing. Beyond data input the selection of available reports and analysis is also supported by the guided dialog. The Assistant program is an essential prerequisite for bringing MFA-models to non-technical users in Small and Medium Enterprises typical for agro-industrial sectors in Thailand. The EMIS architecture and the Assistant programs are discussed in more detail in Pimpisut et al. [2007].

3.2 Reference Model for Native Starch Production

The development of the reference model followed the typical steps of the model building cycle, see e.g. Page [2005]; the most relevant ones are addressed in this section. The modelling software Umberto® has been applied in the project in order to provide material flow models and transition modules in reusable form. Due to the use of Umberto® with its interactive graphical modelling approach the steps model design and model implementation are closely linked.

At the beginning of the modelling process the general description of the production process of Tapioka Starch has been defined as main goal of model development. Next to generalized empirical data from the production database information from technical documentation and literature has been incorporated. Inconsistencies in the data had to be identified and cleared. Significant differences in the technical processes resulted in alternative material flow networks on the submodel level.

At the beginning of the modelling process all material and energy types in the reference model have been identified and installed in the material administration of the Umberto® software tool. Materials and energy forms (uniformly named materials in Umberto®) are structured into hierarchical material groups in order to allow a clearly arranged material management. Beyond that this structure can be found in the eco-balances later. Ecological, economic and technical characteristics can be defined as special material properties. For example starch content has been designated as technical material property for the material Fresh Tapioca Root. Ecologically relevant characteristics are sewage types coming up during the different stages of starch production. These are described by COD (chemical oxygen demand)- and BOD (biochemical oxygen demand)-values.

The modelling itself is started with the decomposition of starch production into different production sections, i.e. Material Preparation, Extraction and Drying Process, Utility, and Treatment System (see Fig. 3 below). The reference model has been designed on two aggregation levels. On the higher aggregation level the four main sections of starch production are modelled in a rough form. System boarders of the investigated production system are specified by Input and by Output-places. For the linkage of the four sections or the transitions Connection-places (○) are used. Connection places serve as a well defined transfer from the output of one transaction to the input of the following transaction, if these processes are directly linked. Material and energy flows are displayed by directed edges.

On the second aggregation level the four main sections are modelled as partial reference models with a higher degree of detail. The models are created as subnets of embedded transitions on the first layer (represented as sub models with double lined squares).

These subnets are stored as modules in a library and are retrievable anytime. A horizontal adaptability is reached by this modular architecture of the reference model. In this way different subnets are created for varying production steps in starch production. For example the use of a biogas system is optional in the treatment system. Therefore two alternative subnets are specified for this section.

In the partial reference model Material Preparation the process steps from acquisition to grinding and milling of Fresh Tapioca Root are modelled. The partial reference model Extraction and Drying Process comprise the production steps from Fruit Water Separation over Starch Refining until Cooling and Bagging. Here the separation of fruit water in starch production is optional. Therefore two different Material Flow Networks have been specified including Extraction with as well without fruit water decanter.
The partial reference model Treatment System is also modelled and specified in two different variants as mentioned above (i.e. Treatment with biogas plant and without biogas plant), because the Biogas system is only optional in Thai starch industry. Finally transitions for Water Treatment, Hot Air and Electricity Generation are specified in the partial reference model Utility (s. Fig. 2).

**Figure 2: Structure of Reference Model „Starch Production Process“ [Raspe, 2007]**

The computation of the Material Flow Network for native starch production, based on data for transition parameters, input-output values and material properties, results in an input-output eco-balance. In the balance sheet input/output materials are sorted by material hierarchies defined in material management. The sums of input and output materials are indicated in their basic units of kg and kJ. The computational direction can be influenced by the specification of material flow quantities either as input or as output parameters. For example with the quantity definition of Fresh Fruit Root as input value the model is computing in a forward direction; i.e. starting from the input side all material and energy flows are computed depending on input values. Whereas with the option of backward computing of the network the output value of end product Native Starch is specified and the network is computed step by step towards the input side. Both computational directions have been implemented in the reference model by appropriate transition specifications.

Another form of output with Material Flow Network models are so-called Sankey diagrams showing mass-proportional flows through the networks. In this context Sankey diagrams are applied to visualize starch losses along the production process steps of significance interest to the starch factories. In this way identification of significant losses at critical process steps can be highlighted (s. Fig. 3).

An indicator system (called Key Performance Indicators- KPIs) for eco-efficiency has been developed by the Thai project partner DIW in order to monitor and benchmark starch production in the participating Thai factories under economic as well as environmental aspects. The implementation in the reference model has been carried using the Umberto® Validation System. The Key Performance Indicators have been specified by defining equations with mathematical expressions and applied to the eco-balance data produced by the reference model. These indicators can be grouped by production section.

In Fig. 4 shown in the next section we can see the set of KPIs used in the reference model for starch production, however indicating only fictitious values. Please note that these values are only of exemplary character, because real factory data have not been made available for publication.

### 4. CONCLUSIONS

The aim of this work has been the structured development of reference models for material flow analyses. An exemplary reference model has been assembled for Thai starch industry as part of an Environmental Management Information System project. The motivation is the simplification of material flow analyses by means of reference model building. Reference models facilitate model building in a special domain because they serve as templates.
Figure 3: Material Flow Network of Reference Model „Starch Production“

The reference model has been constructed in a systematic fashion following the model building cycle from computer simulation as a guideline. The implementation has been carried out with the material flow analysis modelling tool Umberto® which allows graphical model construction. Based on the information provided in the project a reference model has been developed for Thai starch as well as palm oil industries. It represents the structures, the data and the Key Performance Indicators in a production domain in a general form which can be easily adapted to special production processes in different factories. The modelling approach of using individual subnets allows a further specification of the reference model (“horizontal adaptability”). With the possibility of storing different production variants as modules in a library (as offered by the software tool) a reference model is obtaining completeness for varying production facilities in an industrial branch such as starch production in the course of practical application step by step.

However, the approach of reference model building is of general interest, it does not restrict itself to agro-industrial domains such as starch or palm oil production. The approach of reference models in material flow analysis can be used for many other industrial branches and in other countries as well as long as the production processes are fairly standardized.
REFERENCES


