Continuous Simulation in Material Flow Networks

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Abstract: Software systems supporting industrial ecology, corporate material flow analysis and life cycle assessment, are normally used as environmental accounting systems. Using these software systems it is easy to model material and energy flow networks with hundreds or even thousands of processes. Environmental accounting systems are not only utilised to analyse and control existing material and energy flow systems, they are also applied to assess future scenarios in steady-state models. But these systems do not support dynamic modelling. Even though dynamic behaviour is not the main focus of environmental accounting systems, sometimes simulation models are required to estimate material and energy flows depending on specific decision criteria (stock-keeping policies, water circulation design options in manufacturing processes, etc.). This article describes a way to integrate continuous simulation approaches into an environmental accounting system such as the material flow network approach.

The integration of continuous simulation concepts into material flow networks is only one example. It demonstrates how to integrate advanced concepts into an industrial environmental information system (EnvIS). For several other concepts such a way is possible (e.g. Coloured Petri-Nets to support discrete simulation). As a result the environmental information system acts as an infrastructure and consists of several modelling components. The accounting system of the EnvIS plays the role of a conceptual framework.

Keywords: Continuous Simulation, Dynamic Modelling, Environmental Information System, Material Flow Network, System Dynamics

1. FOUNDATIONS OF MATERIAL FLOW NETWORKS

The representation and interpretation of material and energy flows in a particular environmental or economic system has become one of the most important tasks of environmental management in organisations [Schaltegger, Burritt, 2000]. To provide accurate data for managerial uses it makes sense to base the material and energy flow analysis on business accounting methods [Wohlgemuth et al., 1997], which - similar to environmental management - also form the basis for rational decision making.

A well-established accounting method in the private sector is double-entry bookkeeping. The purpose of double-entry bookkeeping is to represent the financial flows and stocks of an organisation. This approach distinguishes between two types of accounts - asset accounts and nominal accounts. Asset accounts describe the capital and asset stocks of a company. Financial flows into the asset account increase the assets, outflows reduce them. By contrast, nominal accounts describe the profit and loss account. The accounting entries record the financial flows between source and destination accounts. This uniform method makes it possible to carry out two different evaluations - the profit and loss calculation and the inventory or asset calculation with the aim of achieving an inventory balance. Together they constitute the annual financial statement of the company.

This type of accounting system is essentially period oriented. It provides information on what financial flows have occurred in a period under review (fiscal year) and how the opening inventory has changed after this period.

The material flow network approach is such an accounting system. Here, material and energy flows are considered, instead of financial flows. This directly results in the necessity for including energy and material stocks in a company into the calculation. The objective of material flow networks is to trace the material and energy flows and stocks within a company or between different companies within a value chain [Möller, 2000, Schmidt et al., 1997].

Based on the concept of Petri Nets [Reisig, 1985] material flow networks consist of three different types of elements (see figure 1): The nodes in the network may be either transitions (visualised as squares) or places (represented by circles). Between these nodes there are arrows as linking elements. Transitions are those locations in a material flow network, where material and energy transformation processes occur. Each transition can, on the one hand, be connected to places from which it is supplied with materials and energy (input), and on the other hand be connected to places to which it delivers materials (output). Places represent storages in which time conversions take place [Wohlgemuth et al., 1997, Möller, 2000].

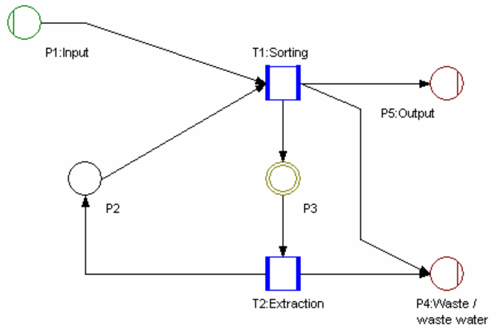

Figure 1. Simple material flow network (process water cycle)

Material and energy flow models are often very large and complex. With hierarchical networks the processes in the value chain can be displayed with regard to the different responsibilities and the necessary degree of detail. A transition can contain a whole subnet which is displayed by another network diagram so that any number of network levels can be modelled. Thus the degree of detail can be comfortably increased step by step at different levels of the network.

As a result a period-oriented material and energy flow model is obtained. The evaluation of such models result in different reports – that is, providing data for inventories, ecobalances, life cycle assessments, Sankey diagrams, and eco-efficiency indicators.

2. CALCULATIONS IN MATERIAL FLOW NETWORKS

A basic task of software systems based on material flow networks is to calculate the stocks at the end of the period and to aggregate the material and energy flows in order to show them in balance sheets. Therefore the algorithm utilises the initial inventory and the material and energy flow data.

A major challenge of software systems based on material flow networks is data collection. How can we estimate all the material and energy flow in our network? One solution is to connect the software system to enterprise resource planning systems (ERP systems) and to utilise the business accounting components. Unfortunately, these components contain only a small part of the data needed. Normally they don't include environmental data like carbon dioxide emissions or water consumption.

To draw the complete picture of the material and energy flows in the network, it is necessary to calculate unknown flows using models of sub-systems in the network. In material flow networks transitions are used to integrate models of sub-systems.

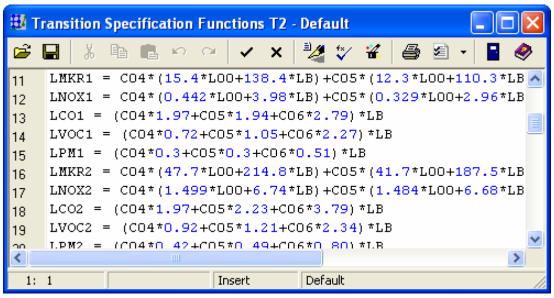

Figure 2. Typical transition specification (transport process)

The aim of these models is to estimate material and energy flows based on known flows. In a simple case the model consists of coefficients. These coefficients specify the linear relationship between different material and energy inputs and outputs. One advantage of the period oriented material flow networks is the possibility to integrate more complex models using non-linear functions (see figure 2).

The main purpose of calculation algorithms in software systems based on material flow networks is to support data collection and estimation. As an accounting system the material flow network approach is not focussed on dynamic behaviour of systems.

3. DYNAMIC MODELLING

Even though material flow networks are widely used in industry to control and to forecast material and energy flows in organisations, it is often difficult to specify the input data of the models. Sometimes it is easier to describe the dynamic behaviour of the system in a simulation model. In this case the simulation model "imitates" a real system during a given time period.

If the number of state changes in the simulation model is finite, we call these models discrete event simulation models. Discrete event simulation models are used to analyse for example warehouses, production chains or call centres [Page, 1991]. In some systems the states change continuously. To deal with these dynamic systems continuous simulation models are more appropriate.

One approach to integrate simulation models into material flow networks is to interpret simulation models as single transitions. In that case the result of the simulation should be a collection of input and output flow data of the transition. Further information regarding discrete simulation models as transition specifications in material flow networks is available in Wohlgemuth et al. [2000] and Möller et al. [2001].

4. SYSTEM DYNAMICS

A more ambitious approach to integrate simulation models into material flow networks is to utilise the structure of the network. To support discrete event simulations we can apply high-level Petri Nets like Coloured Petri Nets [Jensen, 1992].

Another well-known modelling technique is System Dynamics [Forrester, 1961, Hannon, Ruth, 1994]. System Dynamics supports continuous simulation. Therefore System Dynamics models contain a number of stocks (shown in System Dynamics diagrams as rectangles, see figure 3) and flows (shown in System Dynamics diagrams as double-lined arrows).

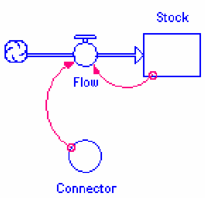

Figure 3. Elements of System Dynamics diagrams

Any flow directed to the stock increases its level, and the flow going out of the stock decreases its level. The amount of flow in and out is regulated by rates (visualised as "water valves"). Connectors (visualised as circles) are used as helper elements to specify user-defined functions and parameters. They are linked to other nodes in the diagram ("information flows").

As in material flow networks, System Dynamics diagrams contain nodes that represent storages. The water valves can be interpreted as special transitions. However, a visualisation of the information flows for calculation purposes is not provided in material flow networks (compare figure 4 and figure 5).

System Dynamics software tools use classical integration procedures like Euler-Cauchy or Runge-Kutta to perform the simulation [Cellier, 1991]. Particularly, Euler-Cauchy algorithms work similar to period-oriented calculations in material flow networks. Schmidt [1995] has imitated the Euler-Cauchy algorithm within material flow networks using a sequence of very short periods and "multi-period" calculations. In multi-period calculations the periods are linked so that the stocks are transferred between the periods. That's exactly how the Euler-Cauchy algorithm works.

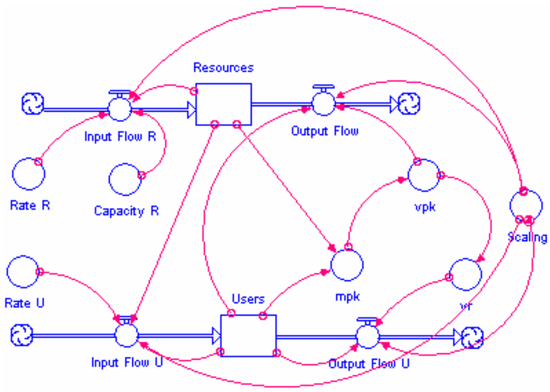

Figure 4. Tragedy of the commons (System Dynamics diagram)

From here it is a small step to integrate numerical integration procedures seamlessly into material flow networks: The time periods of the network become the simulation period of the System Dynamics model, and the periods of the multi-period calculations are substituted by the time steps of the numerical integration procedure.

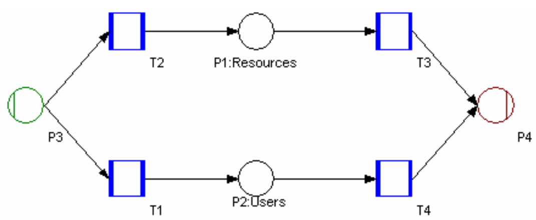

Figure 5. Tragedy of the commons (material flow network)

Figure 4 shows a simple example (tragedy of commons) in the System Dynamics version; figure 5 the equivalent material flow network model. The tragedy of commons model is a typical System

Dynamics reference model. Several other reference models are available [Bossel 1994, Hannon, Ruth, 1994].

The absence of information flows is obvious in figure 5. From the System Dynamics perspective this is a disadvantage. On the other hand the material flow networks are targeted on the visualisation of material and energy flows. The usage of the same diagram elements avoids breaks in the user interface (see figure 8) and makes it possible to apply the same graphical presentations, particularly Sankey diagrams.

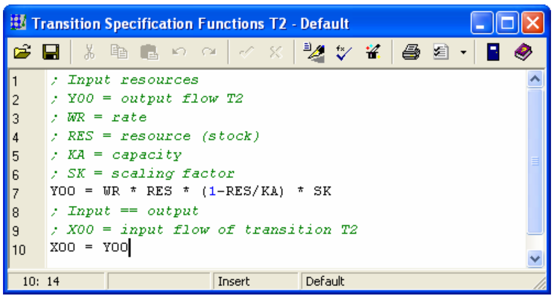

Figure 6. Transition specification functions of T2 (logistic growth)

Whereas in the System Dynamics models the water valves control exactly one flow, in transition specifications several input and output flows can be incorporated and mappings between inputs and outputs can be specified. So the water valve can be considered as a special case of transition specification (see figure 6, line 10). Regarding material and energy flow analysis this is a practical enhancement of the System Dynamics approach.

5. THE LINK BETWEEN SYSTEM DYNAMICS MODELS AND MATERIAL FLOW NETWORKS

As described above the simulation models basically serve as a data source for the environmental accounting system. The question arises how to transform data from the simulation models into a period oriented accounting system. In fact, the transfer of stocks is quite simple, because the simulation periods comply with the periods in the accounting system. The stocks in the simulation models at the end of the simulation period correspond to the stocks at the end of the accordant period in the accounting system. Regarding the flow data it is necessary to calculate the average value for each period (see figure 7). This requires minor extensions of the numerical integration procedures. The aggregated values are transferred into the accounting system.

On the one hand this results in a substantial extension of the material flow network approach: The extensions facilitate System Dynamics on the level of material and energy flows and stocks. On the other hand apart from calculation time conventional material flow networks yield the same results as before. Indeed, the integration of numerical integration methods into the calculation algorithm of material flow networks constitutes a substantial extension of this modelling approach.

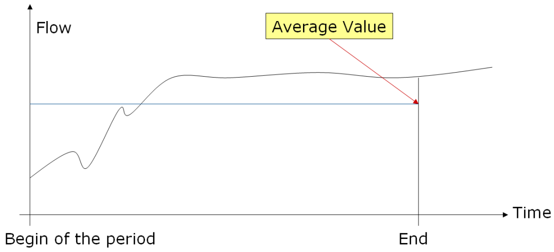

Figure 7. Calculation of period oriented flow data based on a simulation model

Normally it isn't necessary that a simulation model covers the whole network. In hierarchical material flow networks the simulation can be restricted to a subnet so that the simulation model comprises only those system elements which are essential for the simulation model (see figure 8). As material flow network models normally contain hundreds or even thousands of transitions and places [e.g. Skrzypek, Wohlgemuth, 2000], embedding simulation models into material flow networks in such a manner allows combining huge material flow network models and complex simulation models.

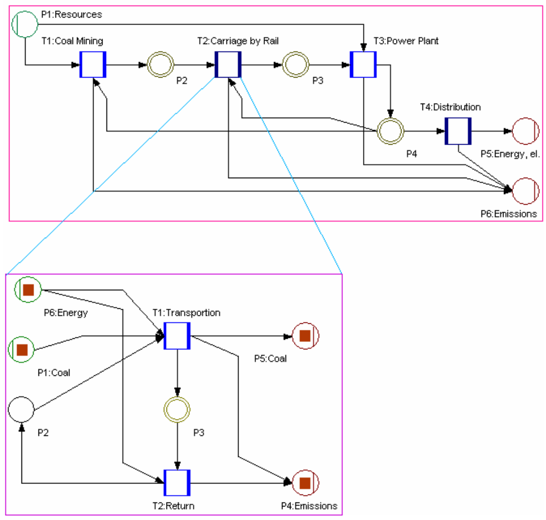

Figure 8. Simulation model as a subnet of transition T2

Subnets of hierarchical material flow networks can be exported and imported and saved separately so simulation models can be incorporated in a so-called process library. Process libraries contain a large number of process specifications that can be used in material flow models and life cycle assessment respectively [e.g. Frischknecht, 2001]. Process libraries supporting material flow networks not only contain linear specifications, it is possible to store non-linear specifications as well as encapsulated subnet models in such databases [Mampel, 1997]. Systems Dynamics reference models like tradegy of commons (see figure 4 and 5) constitute the basis of a new type of models in the process library [Bossel, 1994]. Indeed some of the available System Dynamics reference models do not comply with the requirements of representing material and energy flows and stocks in companies and value chains. It will be necessary to develop more reference models that cover the requirements.

Making such process libraries accessible to a number of users also allows to separate work tasks and to assign them to different users according to their role and level of know-how:

Modelling experts can design and validate generic simulation models (reference models), while other users download and customise these generic models.

6. ENVIRONMENTAL INFORMATION SYSTEMS

The integration of System Dynamics is only one example of integrating modelling techniques into an environmental accounting system such as the material flow network approach. The accounting system becomes an overall concept or rather a conceptual framework of the environmental information system [Rautenstrauch, 1999, Page, Rautenstrauch, 2001]. Modelling techniques used by System Dynamics, high level Petri Nets or discrete event simulation can be integrated in the framework as components.

This approach allows using component-oriented programming [Möller, Rolf, 2003]. The framework has to provide several interfaces to support of

- registering and un-registering components to integrate calculation algorithms as well as specification components,
- accessing the database of the information system,
- using the other components of the system on a standardised way,
- making the components accessible by script languages of the system.

New software technologies like CORBA, .NET, J2EE, XML or Web Services facilitate component-oriented software development. The programming languages of the application developers can be referred to as a “glue language” [Hammond, Robinson, 2000]. They are utilised to glue the components together.

7. CONCLUSIONS

As shown above, material flow networks can be characterised as an environmental accounting system. Appropriate calculation algorithms provide assistance for data collection, in particular by evaluating transition specifications.

Compared to other material flow analysis approaches, material flow networks consist of two different types of nodes. Although places are irrelevant in life cycle assessment and material flow based cost accounting, they become more important in simulation models. In contrast to life cycle assessment dynamic modelling is focussed primarily on stocks and their changes over time. Because of the places continuous simulation techniques like System Dynamics can be integrated seamlessly into the overall concept.

Environmental information systems require an overall concept and an environmental accounting system respectively. This concept has to provide interfaces to different modelling approaches so that component-oriented programming can be applied. In fact, the integration of continuous simulation approaches into material flow networks can be interpreted as an experiment to survey the coverage of the material flow network approach in this respect.

8. REFERENCES

Bossel, H., Modellbildung und Simulation, 2. Edition, Braunschweig, Wiesbaden, 1994

Cellier, F. E., Continuous System Modeling, New York, Berlin, Heidelberg, 1991

Forrester, J. W., Industrial Dynamics, Cambridge, MA, 1961

Frischknecht, R., Life cycle inventory modelling in the Swiss national database ECOINVENT 2000, in: Hilty, L.M., Gilgen, P.W. (Eds.), Sustainability in the Information Society, Marburg, 2001

Hammond, M., Robinson, A., Python Programming on Win32, Beijing et al., 2000

Hannon, B., Ruth, M., Dynamic Modeling, Berlin, Heidelberg, New York, 1994

Jensen, K., Coloured Petri Nets – Basic Concepts, Analysis Methods and Practical Use, Volume 1, Berlin, Heidelberg, New York, 1992

Mampel, U., Die Prozeßbibliothek in Umberto, in: Schmidt, M., Häuslein, A., Ökobilanzierung mit Computerunterstützung, Berlin, Heidelberg, New York, 1997

Möller, A., Grundlagen stoffstrombasierter Betrieblicher Umweltinformationssysteme, Bochum, 2000

Möller, A., Page, B., Rolf, A., Wohlgemuth, V., Foundations and Applications of Computer based Material Flow Networks for Environmental Management, in: Rautenstrauch, C., Patig, S. (Eds.), Environmental Information Systems in Industry and Public Administration, Hershey, London, 2001

Möller, A., Rolf, A., Informationsversorgung eines erweiterten Umweltcontrollings, *uwf UmweltWirtschaftsForum*, 11. Jg, H. 2, 2003

Page, B., Diskrete Simulation, Berlin, Heidelberg, New York, 1991

Page, B., Rautenstrauch, C., Environmental Informatics – Methods, Tools and Applications in Environmental Information Processing, in: Rautenstrauch, C., Patig, S. (Eds.), Environmental Information Systems in Industry and Public Administration, Hershey, London, 2001

Rautenstrauch, C., Betriebliche Umweltinformationssysteme, Berlin, Heidelberg, New York, 1999

Reisig, W., Petri nets: an introduction, Berlin, Heidelberg, New York

Schaltegger, S., Burritt, R., Contemporary Environmental Accounting, Sheffield, UK, 2000

Schmidt, M., Modellierung von Stoffrekursionen in Ökobilanzen, in: Schmidt, M., Schorb, A. (Eds.), Stoffstromanalysen in Ökobilanzen und Öko-Audits, Berlin, Heidelberg, New York, 1995

Schmidt, M. et al., Environmental Material Flow Analysis by Network Approach, in: Geiger, W. et al. (Eds.), Umweltinformatik'97, Marburg, 1997

Skrzypek, V., Wohlgemuth, V., Anwendung und Integration von Umberto® in die betriebliche IT-Struktur am Beispiel der Bertelsmann Großdruckerei MOHN Media Mohndruck GmbH, in: Bullinger, H.-J., Beucker, S. (Eds.), Stoffstrommanagement – Erfolsfaktor für den betrieblichen Umweltschutz, Stuttgart, 2000

Wohlgemuth, V. et al., Computer based support for LCAs and company ecobalances using material flow networks, in: Alef, K. et al. (Eds.), Information and Communication in Environmental and Health Issues, Eco-Informa-97, Vol. 12, 1997

Wohlgemuth, V., Page, B., Einbettung von Transportmodellen und diskreten Simulationsmodellen in Stoffstromnetze, in: Cremers, A. B., Greve, K. (Eds.), Umweltinformatik `00, Marburg, 2000