INFORMATION SYSTEMS FOR INDUSTRIAL ENVIRONMENTAL MANAGEMENT

L.M. HILTY
Department of Informatics, University of Hamburg
Vogt-Kölln-Str. 30
22527 Hamburg
Germany

ABSTRACT. Environmental management needs to be supported by computer-aided environmental information and management (CAEM) systems. Although comprehensive software systems for this purpose are not yet available, there are some programs that support environmental assessment, which is the basis for environmental management.

Industrial environmental management should also take into account the dynamics of production systems and product life cycles, which requires different methods of environmental assessment. Therefore, logistical strategies and their environmental impacts must be investigated, a task for which simulation techniques are employed.

1. Introduction

The need for environmental management systems in industrial production is a recent challenge to information technology. An environmental management system is the overall framework for the actions that an enterprise takes to manage its effects on the environment (Little 1993, FAW 1994). Regulations such as the Environmental Management Standard BS7750 (British Standard Institution 1992) and the EU "Eco-Management and Audit Scheme" (Commission of the EC 1993) are intended to standardize this framework. Information systems designed to support such actions or the overall framework are called *environmental management information systems* or *computer-aided environmental information and management (CAEM) systems.*

One approach to CAEM systems is to extend existing production planning and control (PPC) systems in such a way that they help to reduce emissions into air, water or soil. Such systems are called environmentally oriented PPC (EPPC) systems (Haasis 1994).

Other approaches emerge from the field of *ecobalances*. This term refers to studies or methods that are used to investigate the mass and energy flows in a given system, assess their ecological impacts, and valuate them. In many cases, the system under investigation is a product life cycle. Such an investigation is then called *life cycle analysis* or *life cycle assessment* (LCA). The goal is to assess the environmental impacts of a product "from cradle to grave", i.e., from the extraction of raw materials up to waste disposal.

Finally, in a field called "eco-logistics", methods of modeling and simulation are used to assess the resource efficiency and emission rates of logistical strategies (Hilty 1994b).

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2. Environmental Assessment

Environmental assessments of companies, products, or production processes are the starting point of environmental management. The result of an environmental assessment is a detailed documentation of the environmental effects of the system or activity under study. Environmental effects are changes to the environment caused by an activity; they can be divided into resource consumption (raw material and energy consumption), emissions or discharges (gaseous, airborne, liquid, dissolved or solid waste), and welfare effects on humans and possibly other organisms (including health effects).

Based on this information, a company can check legal compliance, identify the most significant environmental effects, and define an environmental policy. Further steps to environmental management are the initiation of more detailed environmental assessments of selected aspects, the arrangement of independant environmental audits, and finally the introduction of an environmental mangement system (Little 1993).

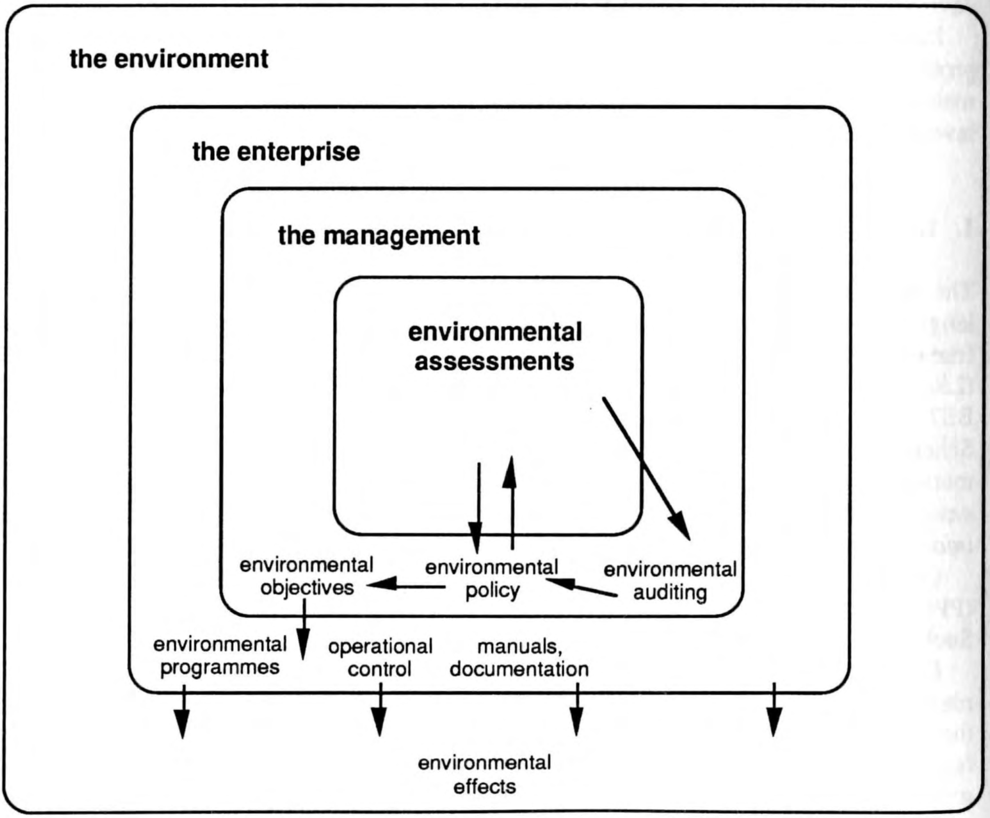

Fig. 1: Elements of an environmental management system (Little 1993)

Besides this *internal* use of the information gained by environmental assessments (see figure 1), there is also an increasing *external* demand for this kind of information (Wicke 1992):

- Customers and consumers increasingly consider ecological criteria when choosing a product or a service. This results in an increasing need for product and company related environmental information.
- Suppliers and buyers, in expectation of a long-term business-relationship, need environmental information of their partner. The buyer, if he wants to diminish the negative ecological impacts of his activities, is in special need of environmental information concerning pre-products and raw materials.
- Investors (shareholders and creditors) often consider ecological aspects. Banks, for instance, take potentially contaminated sites into consideration when granting a mortgage. Environmentally oriented investors choose the least ecologically damaging company if the capital return is otherwise equal.
- Insurances have to identify and evaluate the increasing liability risks resulting from environmental hazards.
- Companies are obliged to inform and answer inquiries from the authorities on environmental data, especially with respect to emission control.

2.1 ECOBALANCES: HISTORICAL BACKGROUND AND TERMINOLOGY

The result of an environmental assessment is very often called an ecobalance, and the same term is also used for specific methods of environmental assessment. There are at least two different ideas behind this naming:

1. The ecological effects of any system can be discribed on the physical level in terms of mass and energy flow through (and transformation caused by) the system. Therefore, the physical inputs and outputs of the system can be put on the two sides of a balance sheet. According to the first law of thermodynamics (mass and energy conservation), input and output must be balanced if measured in physical units.[1] The transformation caused by the system can be described as an increase of entropy, according to the second law of thermodynamics (entropy law).
2. Environmental assessment is regarded as an extension of traditional business accounting, assuming that environmental effects should be recorded and analysed with the same systematics and accuracy as monetary transactions are. This idea traces back to the Swiss engineer Müller-Wenk, who invented a system of ecological accounting based on a non-monetary (and non-physical) measuring unit for environmental effects.

Today, a broad range of methods for ecological assessment is subsumed under the notion of ecobalance.

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[1] However, the term ecobalance is rarely interpreted in this strict sense.

An important group is formed by ecobalances for products, better known as Life Cycle Assessments (LCA), which investigate all relevant ecological effects of a given product (from extracting raw materials to production, consumption, and waste disposal).

The German Federal Environmental Agency (Umweltbundesamt) has proposed a so-called standard model for such ecobalances, which is general enough to integrate various approaches and clarifies terminology also for other types of ecobalances (Umweltbundesamt 1992). It comprises four steps: goal definition, life cycle inventory, impact analysis/ assessment, and evaluation.

A second group of ecobalances considers one company or one plant of a company. It can be viewed as a special case of the earlier concept of social balance (or social accounting), which aimed to account for social impacts of a company's activities in general. This approach may have failed because its comprehensive demand. However, putting the environmental impacts of a company onto a balance sheet seems to be the easier (because more specific) task, although it is complex enough and may not even be characterized as a well-defined problem.

The first approach, developed in the seventies, was Müller-Wenk's "ecological accounting" mentioned above. It is based on the concept of ecological scarcity, which allows for the quantification of all types of environmental impacts on one scale. This approach was later developed into the method of eco-balances recommended by the Swiss Federal Office of Environment, Forestry and Landscape (Bundesamt für Umwelt, Wald und Landschaft, BUWAL, 1990).

In the Federal Republic of Germany, there exist many approaches to use eco-balances within companies. Their smallest common denominator is the input/output balance of a plant. This balance documents the substances and forms of energy which enter the plant and leave it as products, waste or emissions. Here, the plant is regarded as a "black box". Because mass and energy are to be conserved for physical reasons, it can be required that input and output be completely balanced.

To detect environmentally crucial points and possible optimizations, it is usually necessary to take a more detailed view. In this case, subprocesses (process balance) or products (product balance) are examined. In this context, a product balance is to be understood as a subset of the input/output balance of the production plant; it requires to divide up the overall environmental impacts and to allocate them to the products and co-products of the plant. This type of product balance differs from the LCA-type balance mentioned above, because it covers only a short section of the product life cycle. However, as far as previous and subsequent steps are included (which means to extend the system boundary downstream or upstream the product life cycle), the initial product balance may expand smoothly into an LCA.

To account for permanent environmental use (e.g., land utilization), so-called substance balances are sometimes added to the balances based on mass and energy flow.

2.2 ECOBALANCES: SOFTWARE SUPPORT

To classify software systems for ecobalances, we differentiate between the following three steps of eco-balancing:

- *inventory assessment:* quantification of all (relevant) mass and energy flows caused by the system under study, including energy and raw material input and the related output in solid, liquid, or gaseous form; description and quantification of other forms of interaction with the environment (e.g. land utilization).
- *environmental impact assessment:* description and quantification of the environmental effects caused by the interactions determined in the invertory phase.
- *(e)valuation:* evaluation and presentation of the results of the preceeding phases to make them suitable for decision support. In this phase, priorities or weights are given to parameters of environmental effects, and different kinds of impacts are aggregated. Because this involves *values* concerning the relative importance of the parameters (e.g., health effects versus energy consumption), this phase is also called the valuation phase.

In some publications, another phase preceding the inventory assessment (goal definition, scoping/screening) is included (Fava 1993, Umweltbundesamt 1992). It comprises, among other issues, the definition of the system boundary, the choice of methods for the succeeding phases, and defining a strategy for data collection. At present, there seems to be no systematic approach to this first phase of environmental assessment nor, consequently, appropriate software support.[2]

The currently available software systems usually focus on one of the three steps listed above. They can therefore be classified into *inventory*, *impact* and *valuation* oriented systems. Most systems mentioned here are described in more detail either in the textbook "Product Life Cycle Assessment" (Pederson 1993) or in the proceedings of the conference "Informatics for Environmental Protection" (Hilty 1994a).

Inventory-oriented Systems. The most basic step of ecological assessment is collecting reliable data and integrating it into a model of mass and energy flow which is a consistent and valid representation of the system under study.

One of the first software systems developed was the LCA inventory tool (Chalmers Industrieteknik, Sweden), which supports modeling product life cycles with directed graphs. A database with the emission data of the most important materials, transport processes and energy carriers is provided.

The EcoNet system (Institute for Environmental Informatics, Hamburg/Institute for Energy and Environmental Research, Heidelberg, Germany) supports the modeling of mass and energy flow systems based on so-called material flow nets, an interpretation of Petri Nets. Ecobalances of companies, products, production and disposal processes on different system levels can be treated the same way. An expandable module library with

[2] This may change in future when the ISO 14000 series will be established.

predefined modules for the areas of energy, transport and waste disposal is available (EcoNet is discussed in more detail in section 2.3).

Further inventory-oriented systems are TEA (Tools for Ecological Analysis, Ecobilan, France), IDEA (International Database for Ecoprofile Analysis, Technical Centre of Finland) and GEMIS/TEMIS (Total Emission Model for Integrated Systems, Öko-Institut Darmstadt/Hessisches Ministerium für Wirtschaft und Technik, Germany).

Impact-oriented Systems. For an estimate of ecological impacts, data of chemical substances and their behaviour in the environment are needed.

The program SimaPro2 (Pré, The Netherlands) was conceived to support ecological product development. With the use of a database for materials and production processes, the direct and indirect environmental effects of a proposed product variant can be assessed.

Furthermore, there are several on-line substance databases offered worldwide, which document the environmental effects of chemical substances, e.g., the IRPTC (International Register of Potentially Toxic Chemicals, Health and Welfare, Canada).

Valuation-oriented Systems. The program EPS (Environmental Priority Strategies, Swedish Environmental Research Institute) supports the evaluation of resource consumption and emissions by quantifying the environmental burdens in monetary units. Other evaluation concepts (like ecological scarcity) can be considered as well.

The Institute for Research in Ecological Economics (Institut für ökologische Wirtschaftsforschung, IÖW, Berlin) developed a program together with PSI GmbH to visualize valuation results (qualitative judgements) in the form of a matrix for transparent decision support. The user works with a criteria catalogue based on the so-called ABC analysis.

EXCEPT (IBM Germany/Technical University Hamburg-Harburg) is a knowledge-based system which supports complex, rule-based ecological valuation methods. Here, most important is the documentation and explanation of valuation methods and the comparison of alternative assessments.

2.3 ECONET: A TOOL FOR ECO-BALANCE AND LIFE-CYCLE ASSESSMENT

Practical experience gained in large ecobalance projects lead to the development of a highly general and flexible software tool named "EcoNet" (Schmidt 1994). This tool is designed and implemented on the basis of Petri Net theory. Petri Nets have already proven to be useful in modeling systems of information flow; they are exploited here to support consistent modeling of energy and mass flow systems such as production systems or entire product life cycles. An additional advantage of this approach is that it is well-suited for the integration of ecobalance and simulation methodology, an issue that may gain importance in the near future.

Up to now, life-cycle assessments have been calculated by means of an extended matrix calculation, a fact that causes the method to appear less transparent and more difficult to handle than it should be, especially because calculations may require hours of CPU time on common workstations. These problems are now overcome by means of the EcoNet approach.

It is based on the theory of the so-called "Petri Nets" (for an introduction see Reisig 1989). This method is suited for modeling systems in which flows (of information, matter or energy) play a central role. Net theory was combined with concepts of ecological accounting by Möller (1994) and led to a new type (or interpretation) of the Petri Net formalism, called "material flow network" (MFN) or "Stoffstromnetze" in German. The pilot application of the MFN-based software tool is an international LCA project in which data from more than 60 European companies are collected, structured and integrated into an LCA tree, which is formally represented as a Petri Net.

The MFN approach has several advantages for LCA projects of this complexity. In the main,

- it helps to model systems of matter and energy flow in a mathematically consistent manner;
- it supports interactive graphical modeling in both top-down and bottom-up direction (stepwise refinement of models and modeling by combining basic building blocks, respectively);
- it allows the use of a spreading activation approach to network calculation, so that a partial numerical evaluation of a network model or any model fragment can take place at any time; inconsistencies detected due to data redundancy are fed back to the user immediately;
- it allows an algorithm of truth maintenance to be used, so that recalculation of inferred values – after the user has altered a value – is performed if and only if necessary.

As an example, Figure 1 shows a material flow analysis for a production plant. Describing systems in the Petri Net language necessitates a distinct separation of *processes* in which materials or energy are transformed, *storages* in which no transformation takes place, and material *flows*. Processes are formally represented as so-called *transitions* (shown as rectangles), stores as *places* (circles), and flows as *arrows*. Transitions and places, connected by arrows, alternate strictly in a Petri Net. Any number of materials or energy forms can flow in one arrow or be stored in one place respectively. Different transformation processes may take place in one transition. A transformation process can be represented by arbitrary mathematical functions. For LCA applications, however, it is often necessary to restrict the scope to mathematically invertable functions to enable backward calculations, i.e., calculating the inputs on the basis of a given service unit that is defined to be the main output of the system.

Different parts of the network can subsequently be combined to form a new transition. This makes it possible to build up hierarchical network structures. Moreover, it is possible to extract an input/output balance for the environmentally relevant parameters (e.g. material and energy flows or stocks) at any point of the network.

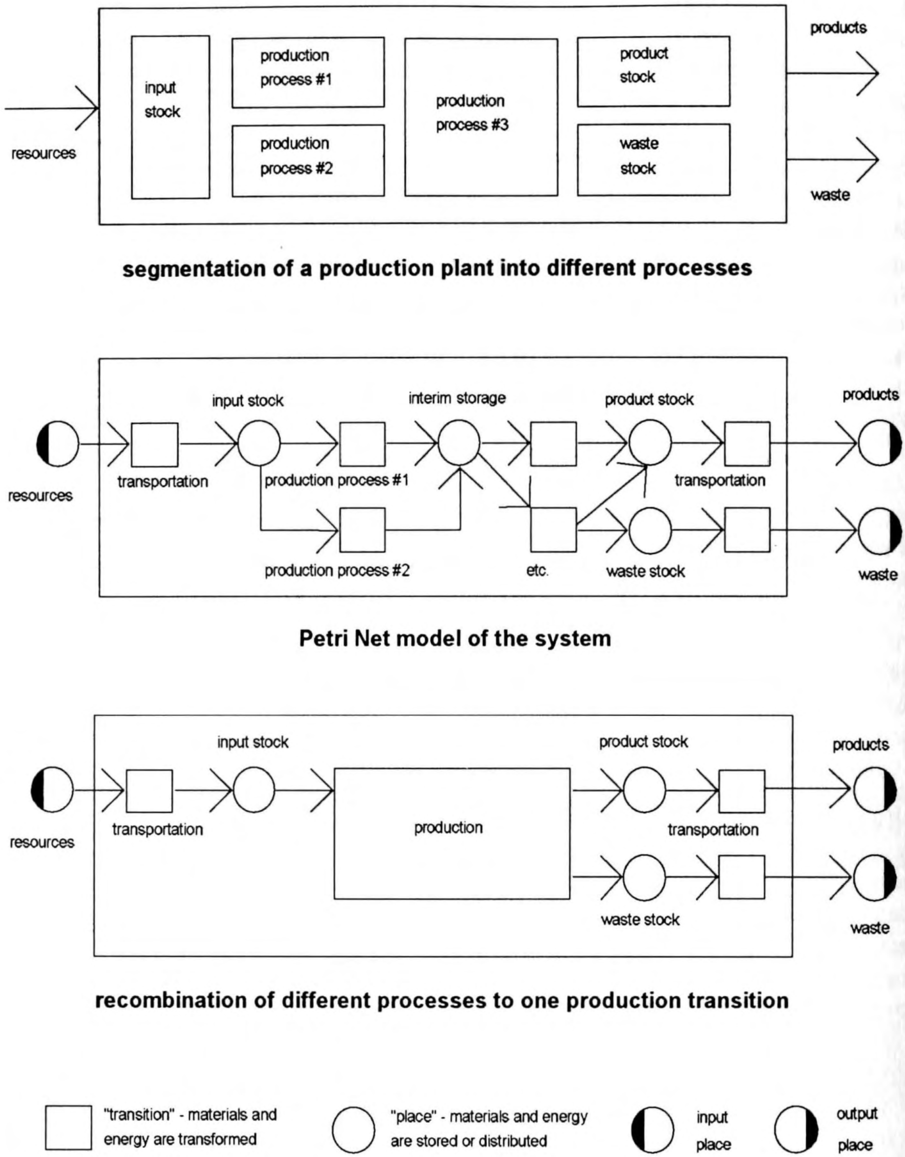

Fig. 2: Material flow analysis of a production plant based on an extended Petri Net formalism. Places representing the system environment are designated as input or output places.

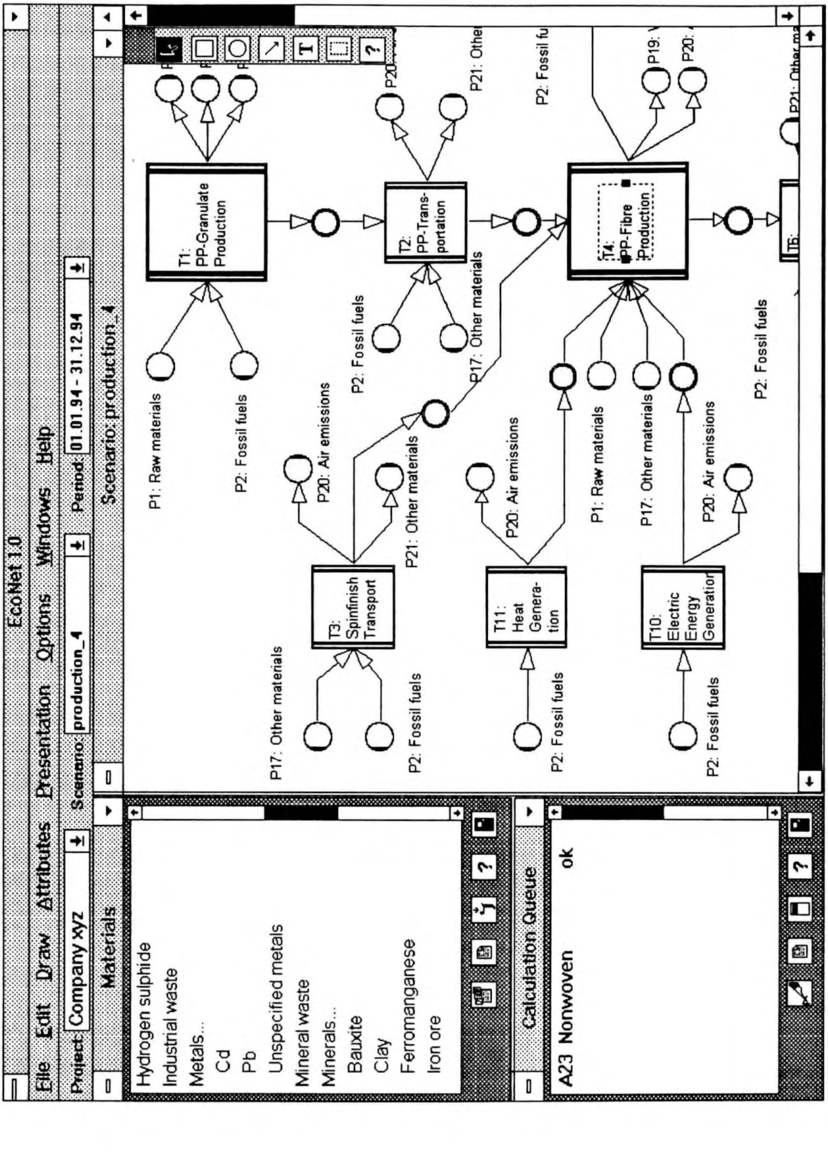

Fig. 3: The EcoNet user interface. The large window shows a part of an LCA-tree represented as Material Flow Network (MFN).

Figure 2 shows the EcoNet user interface. The user creates the network structure by means of a direct manipulation graphics editor (large window, right part of the screen). By mouse-clicking the objects (places, transitions, arrows), the user can open more specific windows that give access to detailed information, such as the mathematical definition or partial ecobalance of a transition, or material flows in an arrow. The left part of the screen shows a material tree (window "Materials"), which specifies the conceptual hierarchy of materials which is used in the project the user is currently working on. Below, the window "Calculation Queue" monitors the calculation status of the network.

Transitions can either be defined by the user, in which case he specifys simple mathematical relationships between the input and output flows. Or they can be taken from a predefined transition library, in which the most important processes such as energy generation processes, transportation processes or production of basic materials are compiled. This library is being continuously expanded by the ifeu-Institute. However, a transition can also remain undefined if all flows connected with the transition are known. In this case the numerical ratio of the input and output flows is linearly scaled (or can be automatically transformed to a linear equations transition definition). This way of modeling is useful if the real process must be treated as a "black box" in the absence of other information than input and output flow data.

The Petri Net approach in the new software tool "EcoNet" leads to a powerful general modeling tool with a strong mathematical background. Thanks to this approach, the tool can easily be extended to allow decentralized data collection, access to large databases and even system simulation. The latter aspect could be useful in future to integrate simulation methods into methods of ecobalancing.

3. Eco-logistics

Logistical systems have various impacts on the natural environment. Logistics is a crucial issue in overcrowded areas, where traffic is a main cause of environmental and health problems. Megacities will need, among other changes, a redesign of their logistical systems to approach sustainbility (Hilty 1994c).

The term *logistical system* is used here for socio-technical systems of coordinated material, energy, and information flow.

An ecological assessment of logistical systems can start from data representing the relevant physical inputs and outputs of the system, including energy and package material on the input side, solid waste and emissions on the output side. Starting from this perspective, a method for the simulation of logistical systems and their environmental impacts was developed. Case studies with this method lead to the design of a flexible tool for this application field, built on top of the general purpose discrete-time simulation package DESMO (Discrete Event Simulation in Modula-2; Page 1992).

Increasing material flows are an essential issue in environmental pollution and waste of natural resources. For this reason, it is important to study the relationship between the strategies of the actors within a logistical system and the logistical processes taking place. A general stochastic model of logistical systems in natural environment was designed that allows for the representation of the actors' strategies and of the physical processes that are controlled by these strategies (Hilty 1994b). This general model, called JAM, can be specialized to instances that meet the requirements of particular problems, for example the environmental assessment of "just in time" strategies in a given real system. The model can be applied by a user to a particular problem by specifying

- the infrastruture (topology, distances, restrictions...),
- the system's own contribution to transportation load by the so-called task process,
- the overall load by other logistical systems using the same infrastructure,
- the vehicle fleet employed.

For a given specific model, different *scenarios* can be specified. For each scenario, the most important ecological and economical variables can be derived by stochastic discrete event simulation. Central ecological variables are fuel consumption, air pollutant emissions, and dynamical land use. The latter specifies how much area is occupied by an activity for how long. Its measuring unit is "square-meter hour" (m^2h).

The robustness and ecological sustainability of different location structures and logistical strategies at a short-, medium- or long-term time horizon can be analyzed by systematic model experiments (i.e. variation of assumptions, sensitivity analysis).

The model parameters include complex formal objects such as attributed graphs, functions, probability distributions, and processes. Some of the parameters are discussed in more detail to give an impression of the wide application range of the model:

- *Transportation network:* An attributed graph describing the network topology and the relevant distances and capacities. In addition the edges can be attributed with utilization restrictions (e. g. speed limits, weight limits, time limitations such as night traffic bans) and specific variable costs like road tolls.
- *Task process:* This process generates the tasks for the logistical system where a single task incorporates the quantitative and qualitative requirements on a transportation event. This includes delivery lot size and time margins for delivery or receipt (punctuality requirements). The task process itself is specified by a set of probability distributions (i. e. distribution functions and relating distribution parameters) for the job attributes.
- *Emission factors:* These are functions describing the relationship between vehicle type and driving modes on one hand and pollutant emissions (NO_x, C_nH_m, CO, CO_2, particles) on the other hand. Emission factors for freight vehicles are known from several research projects, e. g. studies by the German Federal Environmental Office (Umweltbundesamt 1983), or the CORINAIR (1991) studies. Emission factors are usually based on standardized operation cycles. These cycles are matched with the simulated velocity-time curves from the model. In this way the fact can be taken into account that some kinds of vehicle emissions greatly increase in traffic jam situations whereas they are relatively low when driving at a constant speed (except for the upper part of the velocity range).

The average velocity decreases with increasing transportation network load, i. e. the average *time costs* for the users rise. Further a higher load leads to a reduced predictability of transportation performance resulting in higher average delay costs. Time and delay costs are added in every single case to the other transportation cost in the model. Higher time and delay costs result in a reduced transportation demand. In the opposite direction capacity extensions or transportation optimization can stimulate demand. This central mechanism is represented in the model by demand elasticities (distinguished according to different participant groups).

It is important to note that *three* types of flow variables are used in this model, which makes it different from the matter/energy flow models used in the methods discussed in section 2:

- *Material flow.* Material flow between actors is modeled by the movement of discrete, individual vehicles that can be loaded or unloaded at nodes of the traffic network. A vehicle "knows" its goal in space and time and has an individual strategy to achieve this goal. In other words, the vehicle behaves like a truck that decides dynamically in which direction to go at road intersections. This microscopic representation of the traffic between the actors is combined with a macroscopic representation of all the remaining traffic, i. e. passenger traffic and goods traffic between entities explicitly not represented in the model. This combination of micro- and macroscopic modeling was especially designed to get a distinguisted picture of fuel consumption, pollutant emissions and other ecologically relevant aspects of the vehicle movement patterns.

- *Energy flow.* Energy flow is not modeled in detail, but the total energy used for transportation is calculated by accumulating the energy used by the microscopic vehicle movements. In the same way, uncontrolled material flows, mainly the material emissions of internal combustion engines, are calculated.

- *Information flow.* Information flow between actors is in facts the flow of orders from buyers to their suppliers. Generally, an order contains an interval of time, delimited by an earliest and a latest tolerated time of delivery. It is important to note that being early can cause problems in logistical systems. One example is a waiting queue in front of an unloading platform, where the vehicles waste space, time, and energy.

A comprehensive description of the model would contain a list of all provided classes of model entities with their respective attributes. This would be beyond the scope of this article. However, there is one kind of attribute that is crucial to our model: the strategies of the active model entities. The *ordering policy* of a buyer is an example of such an attribute. For some readers it may be unfamiliar to regard a potentially complex algorithm such as an ordering strategy as an *attribute* of a model entity. However, it is not unusual to treat procedures as data; on the level of the computer program, these procedural attributes are implemented using procedure types and variables.

Simulation studies with problem-specific instances of our general model could help in answering a number of interesting questions in the context of logistical strategies and natural environment. To what economical and ecological cost can a given logistical strategy be kept up in the long run? Is the system under study ecologically sustainable? Which qualitative requirements (speed, punctuality, flexibilty, etc.) cause how much cost? Which substitutional relationships exist between these requirements?

Answers to these and similar questions can be derived from the complex interaction of the various random processes involved and the assumptions on the medium- and long-range development of the frame conditions. They are different in each scenario. Here the benefits of computer simulation are obvious, because the complex interactions could not be represented by purely analytical models.

4. Conclusion and Outlook

There is a variety of approaches to support environmental assessments by sophisticated software systems. However, environmental assessment is only a part of an environmental management system. For the future, it will be important to find integral solutions, i.e. computer-aided environmental information and management (CAEM) systems which provide software support for a comprehensive environmental managment.

One approach to CAEM systems is to develop production planning and control systems into systems for integral environmental protection (Haasis 1994). Clearly, the challenge of integrating information systems for production and recycling will be of great importance (Rautenstrauch 1994).

Systems for environmental assessment, as discussed in section 2 of this article, will have to be integrated into (or extended to) such more comprehensive systems. It will also be necessary to consider the dynamic interactions of production, consumption and recycling processes in environmental assessments, which means to introduce the dimensions of space and time into environmental management. This issue leads to the approach of eco-logistics and to the integration of simulation methods into software tools for environmental management, as discussed in section 3 of this article.

The overall framework for integral CAEM systems will be set by standards such as the ISO 14000 standars family, which is expected to play a similar role for environmental managment as the ISO 9000-series did for quality management.

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