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Advances in Environmental Informatics: Integration of Discrete Event Simulation Methodology with ecological Material Flow Analysis for Modelling eco-efficient Systems

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Abstract

In the first section we provide a short review of the rather young field of Environmental Informatics. We argue that Environmental Informatics methods and tools are powerful means in environmental information processing for supporting environmental protection and sustainable development. In the second part we introduce an integrated approach for modeling eco-efficient systems such as complex production systems under an economic as well as an ecological view. This modeling approach allows for the implementation of a combined model representing material and energy flows and bottle necks in machine capacities at the same time (instead of using two different models with different software tools). Finally present a case study from a real waver production site as a proof of concept for this substantial contribution to Environmental Informatics.

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1. Introduction

The protection of our environment continues to be one of the greatest challenges in our industrialized societies. This challenge is addressing politics, economy, citizens, as well as technology and research. It is clear that the various problems in environmental protection, environmental planning, research and engineering can be only solved on the ground of a comprehensive and reliable information basis. State and dynamics of the environment are described by biological, physical, chemical, geological, meteorological, or social-economic data. This data is time and space dependent and addresses past or current states. The processing of this data and the production of meaningful information on the environment, on its stress factors and mutual influence mechanisms are fundamental

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for any kind of environmental planning and preventive measures. Therefore environmental problem solving is mainly an information processing activity handling a wide range of environmental data. Solutions to our environmental problems are strongly dependent on the quality of accessible information sources. Certainly, qualified information is a very critical factor in carrying out decisive political actions and in changing people's attitudes on the environment. This information on environmental aspects is just as important for decisions on actions in environmental protection as for gaining knowledge in environmental research.

Meanwhile the application of information technology has become vital in the environmental domain in industry, in public administration as well as environmental research for providing the required environmental information on the appropriate level of detail, completeness, accuracy and speed. However, in this context straight forward data storage for environmental mass data is not at all sufficient. Rather the filtering of meaningful and up to date environmental information on the state of the environment from this data storage is required to support administrative and planning tasks in environmental protection. In this way one of the main goals of environmental information systems is addressed, namely to prepare the mass of collected environmental data in such a way that they can be used for routine operational environmental administration tasks as well as for political-strategic decision making.

Environmental information processing has recently focused on the following trends:

- environmental monitoring by means of remote sensing and the combination of data streams from all over the world,
- a policy for sharing and integrating environmental information across political, technical and organizational boundaries (e.g. on the level of EU) making wide use of internet technology,
- advanced model-based data analysis techniques, shifting the focus from data to dynamic system structures, industrial applications of environmental information processing, aiming at higher ecological efficiency of the economic system.

It is obvious that advanced computing technologies play an important role in these developments. Information processing in the environmental domain has been lacking a sound conceptual and scientific basis, since there has not been a significant research in this special domain for a long time. This is certainly not only a matter of Applied Informatics or Applied Computer Science, respectively, but an interdisciplinary task where many scientific disciplines should be involved (e.g. geo- and bio-sciences, natural sciences such as applied physics and chemistry, environmental engineering, management sciences, etc.). On the other hand, the growing field of environmental information processing is a great challenge to Informatics methodologies and their applications. From this process of mutual stimulation, some 20 years ago a new discipline has emerged in Central Europe, termed as Environmental Informatics.

2. Short Review of Environmental Informatics: Background and Main Issues

The rather young discipline of Environmental Informatics has been emerging in central Europe some 20 years ago with the claim of contributing to the development of a sound conceptual basis for environmental information processing on scientific grounds. However, Environmental Informatics does not see itself as a pure supportive discipline providing environmental sciences with computer tools. Much more it has to offer a wide range of powerful proven methods from Informatics or Computer Science, respectively, for complexity reduction and problem solving which can be also useful in the various environmental domains. We can define Environmental Informatics as follows:

Environmental Informatics is a special subdiscipline of Applied Informatics dealing with methods, techniques and tools of Computer Science for analyzing, supporting and setting up those information processing procedures which are contributing to the investigation, removal, avoidance and minimization of environmental burden and damages.(translated from Page and Hilty in [19]).

Environmental Informatics is holding a mediation role. On one hand, it analyses real-world problems in a given environmental domain and defines requirements on information processing. On the other hand, it introduces the problem solving potential of Informatics methodology and tools into the environmental field (see Fig.1).

In environmental information processing we typically deal with many different, rather heterogeneous data structures and information sources such as text data on environmental laws or research projects, measurement data from monitoring networks, structural data on chemical substances, formatted engineering data on environmental

technology, just to name a few. In particular, environmental data is often geographically coded, i.e. information is attached to a particular point or region in space. The represented data objects are often multidimensional and have to be described by means of complex geometric objects (e.g. polygons or curves). In addition we usually have a temporal aspect in our environmental data sets. Also processing of empirical data with statistical methods as well as of vague, uncertain and incomplete information is a major concern in Environmental Informatics. A comfortable user access on heterogeneous and distributed environmental data bases and information systems via computer networks has to be supported. In this context meta data access and ontologies are crucial for user orientation. Environmental modeling is well established in the environmental field and requires appropriate software tools. And finally, environmental data must be presented and evaluated in a domain overlapping, multidisciplinary context. As a requirement, this information has to be often deduced from a number of domain specific primary data bases beforehand.

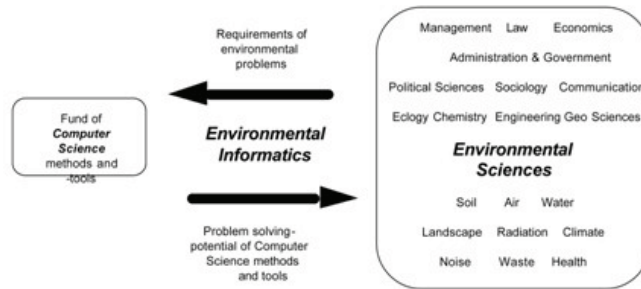


Fig. 1: Environmental Informatics bridges the gap between Informatics' methodology and the environmental application domain

On this background Environmental Informatics has to focus on a number of main issues. Thus, complexly structured heterogeneous data bases and distributed, Web-based information systems are investigated. Meta data or special meta information systems, respectively, as well as all kinds of user assistance are required for the very heterogeneous user groups in large scale environmental information systems. For spatial information processing aspects of geometric data structures and algorithms as well as of modern open and distributed Geographical Information Systems (GIS) have to be considered. Knowledge-based and qualitative concepts are of relevance in dealing with uncertain, vague and incomplete environmental knowledge and information. Complex environmental data has to be visualized by means of powerful scientific visualization approaches. Concepts and architectures for mathematical analysis and modeling software are required for computerized statistical analyses as well as for environmental modeling and simulation. Beyond that there is the key issue in Environmental Informatics of integration of data, information, models and knowledge from various distributed sources in the environmental sector.

During the last 20 years a scientific community has been formed in central Europe dealing with environmental information processing on a scientific level originally organized by the Special Interest Group "Computer Science in Environmental Protection" in the German Computer Society (Gesellschaft fuer Informatik - GI, see <http://www.iai.fzk.de/Fachgruppe/GI/welcome.eng.html>). Yearly conferences and workshops with a considerable number of participants and publications have been held ever since (in 2004 already the 18th yearly conference of the special interest group has taken place, see [29]). Quite some time ago the contributions to these conferences as well as the conference locations became more and more international (Strasbourg, France in 1997, Zurich in 2001, Vienna, Austria in 2002, Geneva, Switzerland in 2004, Bruno, Czech Republic 2005, Graz, Austria 2006, Warsaw, Poland 2007, Berlin, Germany 2009) and new thematically related international workshops have been introduced (e.g. International Symposium on Environmental Software Systems – ISSES, see [18] and [12] or ECO-INFORMA, see [25]). Meanwhile Environmental Informatics has emerged as a truly international and widely interdisciplinary research direction.

In this paper we focus on a novel approach of integrating the traditional methodology of Discrete Event Simulation for modelling the dynamics of industrial production processes with the rather recent ecological Material Flow Analysis approach for describing material and energy flows, thus combining both economic as well as

environmental viewpoints in the same modelling framework. The remainder of our paper is organized as follows: In section 3 we briefly cover Discrete Event Simulation as a modelling and planning tool for industrial production and logistics processes under economic aspects (e.g. bottlenecks, machine utilization, maintenance, inventory, etc.) and contrast it with the more recent approach of Material Flow Networks to model material and energy flows in production chains, mainly under ecological aspects. In the central section 4 of this paper we demonstrate how we can combine Material Flow Analysis and Discrete Event Simulation within a single software environment by introducing a component-based framework called Milan. The framework assists users in performing material flow analyses by means of a Discrete Event Simulation model without any need to create an extra material flow model and for changing the software environment. A material input/output account, which is based on the same model used for compiling simulation results, can be created for the entire model. To test the design and applicability of the component-based combination of Discrete Event Simulation and analysing material flows, a case study has been performed at a semiconductor manufacturer (section 5). In the final section we give a summary and conclude that the software tool described in this paper creates customized Environmental Management Information Systems (EMIS) in which production processes and all kinds of energy and material flows can be analysed in terms of both economic measures and their environmental impact.

3. Methods and Tools of Environmental Informatics for Modelling eco-efficient Systems

3.1. Motivation

All business activities create flows of energy and materials, whose management forms an integral part of how a company interacts with its environment. Industrial Environmental Information Systems, also referred to as Environmental Management Information Systems (EMIS), are designed to detect, evaluate and prevent a wide range of environmental dangers and stresses. In more concrete terms EMIS consist of computer programs which support management by collecting, documenting and evaluating all relevant data about an enterprise's interaction with its environment and plan, initiate and control all activities related to environmental protection or management [1]. To serve the goal of preventing or reducing any negative environmental impacts, simple recording of relevant flows, e.g. in an environmental balance sheet (i.e. eco-balance), is rarely sufficient. Identifying critical ecological factors and judging the likely effectiveness of corrective measures often requires a model, which must reveal any relevant structures and flows.

Modelling is a powerful tool to investigate complex systems, such as those formed by an enterprise's network of material and energy streams. In the context of EMIS all aspects of relevance to the environment can be mapped into models whose behaviour can then be analysed in place of the real system of which they are representations. Applied Informatics has developed a number of software tools for making this process easier and in the domain of environmental protection we can now choose from a wide range of methods and software, which, when integrated in an EMIS, help users to model flows of energy and materials in a simple and effective fashion.

Since EMIS normally focus on ecological aspects of a production system, their capabilities of analyzing economic aspects as well are usually rather limited. By assigning costs or revenues to the flows of energy or material in a production chain in an EMIS based on Material Flow Networks as introduced in Section 3.2 a monetary cost accounting in addition to an environmental assessment could be introduced. Beyond that models covering both economic and ecological viewpoints would be most useful allowing the study of more complex economic-relevant problems, e.g. such as production programme planning or bottleneck detection in production facilities. For such questions, the application of Discrete Event Simulation models would be very suitable.

In this paper we focus on a novel approach of integrating the traditional methodology of Discrete Event Simulation for modelling the dynamics of industrial production processes with the rather recent ecological Material Flow Analysis approach for describing material and energy flows, thus combining both economic as well as environmental viewpoints in the same modelling framework. We argue that this approach developed in our working group at the University of Hamburg in the PhD-thesis of V. Wohlgemuth [1] can be rated as substantial contribution to Environmental Informatics because it has introduced a new modelling paradigm for eco-efficient systems.

3.2. Modelling Background: Discrete Event Simulation versus Material Flow Analysis

Discrete Event Simulation is a classical and well established computer-based modelling method for analyzing industrial processes, e.g. in production systems. In many dynamic processes, particularly in industrial contexts like manufacturing, transportation and inventory management, system states change at discrete points in time, i.e. with occurring events, rather than through continuous fluctuations. For instance length of queues (i.e. number of items queuing for service as a system state variable) only changes when items arrive or depart, e.g. queues in front of a group of machines. Such queuing networks typically consist of discrete components, such as machines and work pieces, whose behaviours cause state changes at discrete events, which will typically be dispersed randomly along a model's timeline. In Discrete Event Simulation it is typical to treat many model components as individuals with their own properties and processing histories. During a simulation, models are "moved" along a simulated timeline, for which a model monitor with a simulation clock and an event list is needed. Event lists are used to record future events and to allow the model monitor to repetitively select and remove the next imminent event. The monitor then updates its clock to the relevant model time, which means that clock values jump in irregular intervals – from one model time point to the next. In this way all intermediate time values are skipped and all activities' durations are simply modelled through scheduling corresponding start and stop events. The model monitor also transfers control to a program that performs relevant changes to model states; e.g. the start of a processing activity. Such programs are called event routines and may schedule further events (e.g. the end of a processing activity) to occur at some time in the simulation's future. These are placed on the model's event list. Because of the stochastic character of many events in a simulation model (e.g. random arrival of production jobs) discrete event simulations can be seen as random experiments, which require a longer simulation period of the model with a significant number of repetitions. In [2] a concise introduction to Discrete Event Simulation's foundations is given.

In contrast Material Flow Networks model material and energy flows in production chains and are based on Petri-nets, a well established methodology in Computer Science. When adapted and modified for modelling the environmental aspects of an enterprise's operations, Petri-nets are also referred to as Material Flow Networks. They are a more recent innovation, originally introduced also at the University of Hamburg [3] to describe the flow of materials and energy caused by economic activities. Recording and analysing the environmental impact of such flows is one of the most crucial tasks of an effective environmental management information system (EMIS). Beyond Computer Science's Petri-net theory Material Flow Networks have been also inspired by concepts from Business Administration's double-entry bookkeeping (i.e. for material and energy flows instead of financial qualities) and cost accounting (i.e. for the assignment of financial values to material and energy flows).

Material Flow Networks are special Petri-nets, which consist of transitions, places and arrows. Transitions, represented in diagrams by a square, indicate the location of material or energy transformations. Because such transformations are sources of relevant flows, they play a vital role in a model. Places separate transitions, a feature which allows for more detailed analysis. Places can also serve as inventories, which are depleted and replenished by flows. In a diagram we use circles to represent them. Arrows show paths and directions of flows between transitions and places, such as energy and material. Figure 2 shows a Material Flow Network with several places and transitions.

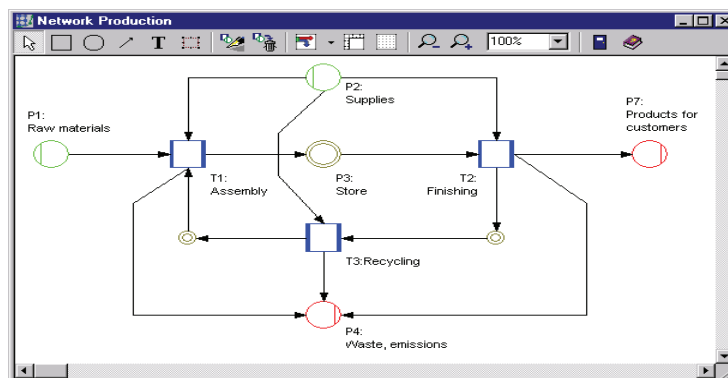


Fig. 2. A simple Material Flow Network

Material Flow Networks offer a wide range of representations for complex material flows and can be used to support a whole range of environmental management tasks. For example, they can be employed to gain deeper insights into production, consumption, transportation, waste treatment and other such processes. Transitions describe an activity or task, which is entered by any required materials and ejects new or modified materials as its output. In this way transitions serve to link material consumption and production. So-called transition specifications can summarize underlying processes in terms of mathematical expressions or algorithms, and programs are used for their computation. In addition to decomposing large systems and calculating a missing value, transition specifications also provide a seamless transformation from a descriptive to a predictive model. One powerful and user-friendly tool based on Material Flow Networks is the EMIS software Umberto® which has been introduced into the environmental software developed already by a university spin-off company in the nineties^b.

4. The Material Flow Simulator: Integrating Discrete Event Simulation with Material Flow Analysis

The idea of a Material Flow Simulator that integrates economic and ecological perspectives is based on a combination of Discrete Event Simulation with Material Flow Analysis as already mentioned. Material Flow Analysis and Discrete Event Simulation are combined into an integrated modelling software environment, which, for example, in the case of our application domain of semiconductor manufacturing (see Section 5) allows us to ask questions like:

- Can we save energy if we buy a new machine without changing throughput?
- Can we increase the utilization of a machine by changing the production process without increasing waste accumulation or energy demand ?
- Can we produce more wafers without buying more lacquer and in compliance with legal limits on solvent emissions ?

To offer an integrated view based on the same model of both simulation performance (e.g. through measures like throughput, utilization, adherence to delivery dates etc.) and Material Flow Analyses, we have developed a concept in which so-called material indicators play an important role. These indicators combine the event-oriented worldview of the simulation engine [2] with strategies for keeping track of materials. More specifically, a material indicator defines which materials are needed as inputs or emitted as outputs from model components. Referring to the example of a semiconductor manufacturer outlined in the next section one can define a material indicator for a coater which reserves a certain amount of lacquer as required input at the start of a task. At the end of the task any remaining lacquer is recycled and some solvent is registered as an output flow.

During a simulation experiment the Material Flow Simulator records all material or energy usage each time a resource consumption or material emission event occurs. This is accomplished by material indicators mentioned above, which store material and energy consumption for each event or activity; i.e. pairs of start and finish events. Figure 2 shows how simulation events and material booking indicators are related.

In this example of a transportation process there are 8 events, which participate in 4 activities and 2 processes. The two processes describe lifecycles for e.g. two vehicles, each of which is involved in a transportation activity. Driving activities are part of and nested inside transportation activities. They cover a distance and occur in between corresponding start and stop driving events. Vehicle characteristics and driving distance, for example between an inventory depot and a supplier, determine an activity's environmental burden in terms of CO₂ emissions. These are recorded by the relevant material booking indicators.

^asee www.umberto.com

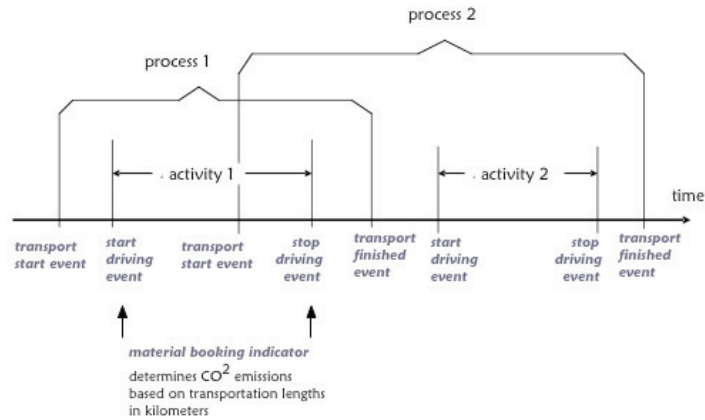


Fig. 3. Processes, Activities, Events and Material Booking Indicators

Reusability and flexibility have been guiding principles in the software design of the Material Flow Simulator which has been developed under the name of Milan within a 3-year cooperation project in the field of Environmental Informatics ([4], Special Issue Environmental Informatics) between the University of Hamburg and chip industry using simulation technology to improve eco-efficiency in waver production. This is achieved through a component-based architecture, where application specific components are inserted into a modular modelling software framework. Framework implementation was based on Delphi, an integrated software development platform that includes Object Pascal and a number of class libraries. Component development also has made use of Microsoft's COM architecture (the further development has been based on .NET more recently). By reusing existing components, component-based software aims at increasing flexibility and reducing software development time and development costs. The material flow simulator serves these goals by offering core functionalities that can be augmented through plug-in components for various modeling phases; e.g. model construction, experimentation, data analysis and display. It supports both production job-based and material-based modeling viewpoints. By using different plug-in components we can, for example, display simulation results in terms of either input-output material balances or standard statistical measures such averages or variances [1].

The Material-Flow Simulator's component-based plug-in architecture permits easy reusability and extension. Since plug-ins are customized components, the Material Flow Simulator will load them dynamically; i.e. "on demand". This means that the simulator itself becomes simply a framework for managing different processing functions, each of which is provided by a separate plug-in component.

A number of plug-ins in two different groups have been developed for use in Milan. The first group's plug-ins provide functionality for Discrete Event Simulations and include:

- a plug-in for creating random variables from a specified probability distribution; e.g. exponential, normal, uniform etc.
- a plug-in for basic time and event list management; i.e. a so-called simulation engine, containing a scheduler, a clock, an event list handler etc [2].
- a plug-in that allows model creation in a graphical manner; i.e. a so-called model editor.
- plug-ins for specific application domains, which contain specialized model components for this area of application; e.g. model components for production systems like buffers, work stations, fork lifts, resources etc..
- a plug-in for analyzing and visualizing simulation results; e.g. pie charts and x/y-plots for single model components or entire models.

The second group of plug-ins deals with aspects of Material Flow Analysis. This includes:

- a plug-in for the administration of all materials used in the model which has been obtained from the Umberto® material flow analysis software. This plug-in contains commands for exporting simulation results and model structures to Umberto® for further analysis.
- a plug-in with material indicators for the integration of Discrete Event Simulations and Material Flow Analyses, as mentioned above.

All these plug-ins can be integrated into the software framework and can theoretically be replaced with alternative plug-ins; as long as their developers adhere to a few predefined interfaces.

In this way the Material Flow Simulator integrates economic and ecological system descriptions into a single modelling framework, while its component-based nature significantly reduces model development time and increases adaptability at the same time.

5. An Application of the Material Flow Simulator from Semiconductor Industry

As a proof of concept for the component-based combination of Discrete Event Simulation and material flow analysis, an empirical study has been performed at a semiconductor manufacturer. Since manufacturing semiconductor components is a complex process during which many planning and control problems need to be solved, this domain is well suited for an empirical test of the Material Flow Simulator's implementation. In semiconductor production many costly and environmentally critical materials (e.g. developer chemicals, paints, solvents, acids), which emissions into the ecosystem could cause substantial damage and which safe decommissioning is an expensive process, are frequently used. Testing our framework with a model of semiconductor production including both economic (e.g. bottlenecks detection, maintenance planning, machine acquisition etc.) and environmental aspects (e.g. emissions, raw material and energy consumption etc.) proved therefore very useful for the framework's further development. Due to the complexity of the complete simulation model incorporating all production sub-systems, which has been the final aim of the simulation study, only the sub-section of lithography has been selected for presentation in this paper to communicate the general idea. More details on the complete model can be found in [5] and [6].

The production processes in the lithography stage play an important role in structuring wafer surfaces, since they determine a semiconductor's geometry. Lithography uses light-sensitive photo paints, which are deposited on a wafer and then exposed and developed through lithography masks. Since this happens at multiple layers, wafers must be routed through the lithography stage multiple times. How many passes are needed will depend on the semiconductor's type. Although neither simulation nor Material Flow Analyses have ever been used in this part of the company, applying them in combination proved advantageous for pinpointing bottlenecks and for observing all legal requirements on solvent emissions in parallel.

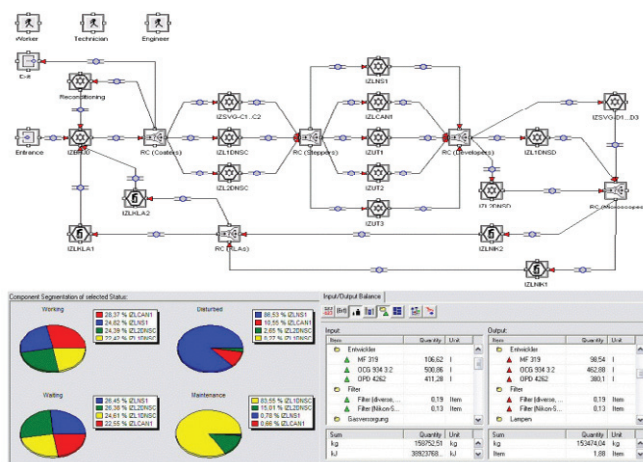


Fig. 4. Model of the Lithography Process and the Results of its Simulation (lower left) and its Material Flow Analysis (lower right).

We used our Material Flow Simulator to model the lithography process and constructed a plug-in for this domain. This focused attention on semiconductor-specific model components, which helped us to map typical lithographic and other processes to a simulation model (see Fig. 4). During this process a number of different model components have been created. Coater, Stepper, Developer and Repacker were represented by workstation components, two measuring devices were mapped to a MeasuringDevice component and entry and exit point

components were used to define system boundaries. RoutingControl specified wafers' paths through the model, and a Connection component has been binding all other components together. Developing these components and integrating them into our application framework was achieved in a relatively quick and timely fashion. Other existing components, such as the model editor, the discrete event simulation engine and various material management functions could be directly reused. To display residence times and other semiconductor-specific characteristics, some extensions to the existing analysis plug-in were made. Using the Material Flow Simulator framework significantly reduced the effort of combining simulation and material flow analyses of the system under investigation. In the past such investigations could not have been made from within a single software and would have required the use of separate software tools with corresponding increases in development, maintenance and analysis effort.

After analysing the production of 6 inch wafers, a second model for investigating 8 inch wafer production has been built for the semiconductor manufacturer, which planned to extend production with this larger wafer size. The model allowed the analysis of various aspects of such a diversification; e.g. changes in throughput and bottleneck shifts and changes to the consumption of energy and raw materials. All these had ecological consequences as well as effects on the costs of wafer production. This investigation also highlighted an additional advantage of combining simulation with material and energy flow analyses. Since both techniques use a common model, we can explore both environmental and economic impacts of changes in production techniques and material flows.

6. Summary and Conclusions

Discrete Event Simulation and Material Flow Analysis are complex techniques, which are most useful for Environmental Informatics' applications; however their mastery is requiring sound technical knowledge. Both methodologies are well served by specialized software. Although they have different roots, they share a common point of view and make use of computer models of production and distribution processes. Traditionally two separate models were required to feed information to each of these methods, and different software tools were employed for their capture. As a result, two models needed to be maintained, which often showed high levels of redundancy. Thus assuring model consistency has been a crucial task.

This paper has suggested a novel approach for integrating Discrete Event Simulation and Material Flow Networks methodology into a common framework, based on a single model. This approach has the potential to significantly ease both a model's development and its maintenance. The component-based software described in this paper creates customized Environmental Management Information Systems (EMIS) in which production processes and all kinds of energy and material flows can be analysed in terms of both economic measures (e.g. throughputs, utilizations, bottlenecks etc.) and their environmental impact. The component-based architecture of the relevant software permits effective reuse of existing components, which functionality can then be accessed through a few well documented interfaces. An example for cooperation between the commercial Umberto® EMIS software with some discrete event simulation components in the application domain of wafer production has been applied to show the effectiveness of this concept.

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