Combining Discrete Event Simulation and Material Flow Analysis - A Modelling Tool for Eco-efficiency in Waver Production

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Abstract: Simulation is a common planning technique in production industry, especially in the economic evaluation of different design alternatives for production processes. This is in particular important in the field of waver production because of the huge investments in the highly sophisticated production processes. Another important issue of waver production is its impact on the environment. Along the production chain of a waver mainly different lacquers, acids, pure water and nitrogen are consumed leading to special waste handling procedures. Thus, waver production is a good example for a production process where both economic and environmental aspects have to be taken into account when planning process changes. Apart from material and energy flow information relevant economic performance indicators like throughput, average waiting times or mean service times can be derived from simulation studies. This paper focuses on a novel approach integrating (economic) Discrete Event Simulation techniques with (ecological) Material Flow Analysis with a component-based software tool, the Material Flow Simulator Milan. In cooperation with a waver producer the concept of the developed modelling framework has been verified within a practical case study. The total production process has been mapped into a combined simulation model in a stepwise procedure incorporating the different production sub-systems (e.g. Lithography). In this sense using discrete simulation techniques in combination with Material Flow Analysis could be one promising holistic approach to estimate production efficiency measures with respect to their impacts on environment and costs before they come into operation.

Keywords: Modelling, Discrete Event Simulation, Material Flow Analysis, Environmental Management Information System, Semiconductor Production, Software Tool, Eco-Efficiency

1. MOTIVATION AND OVERVIEW

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 (see [10], p. 144). To serve the goal of preventing or reducing any negative environment-mental 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 behavior can then be analyzed in place of the real system of which they are representations. Applied Computer Science has developed a number of software tools for easing this process 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 materials in a production chain in an EMIS based on Material Flow Net-works as introduced in Section 2 a monetary cost accounting in addition to an environmental assessment could be introduced. Beyond that models covering both economic and ecological view points would be most useful allowing the study of more complex economic-relevant problems, e.g. such as production program 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 to describe material and energy flows, thus combining both economic as well as environmental viewpoints in the same modelling framework. Our paper is organized as follows: In section 2 we briefly cover Discrete Event Simulation as a modelling and planning tool for industrial production and logistics processes under economic aspects (e.g. bottlenecks, ma-
chine 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 3 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 frame-work 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 analyzing material flows, a case study has been performed at a semiconductor manufacturer (section 4). 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 analyzed in terms of both economic measures and their environmental impact.

2. 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 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 behaviors 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 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 agenda. 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. Chapter 2 in [7] gives a concise introduction to Discrete Event Simulation’s foundations.

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 at the University of Hamburg (see Moeller (2000)) to describe the flow of materials and energy caused by economic activities. Recording and analyzing 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 and cost accounting.

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 trans-formations. 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 1 shows a Material Flow Network with several places and transitions (see Appendix).

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.

3. THE MATERIAL FLOW SIMULATOR - BASIC CONCEPTS AND IMPLEMENTATION

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. Within this context it aims to help answer all ecological and economic questions that are relevant for

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1 See www.umberto.com
both tactical and strategic management decision making (see [10], p. 177)). Material Flow Analysis and Discrete Event Simulation are combined into an integrated software environment, which, for example, in the case of our application domain of semiconductor manufacturing (see Section 4) 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 (see Chapter 10 [7]) 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 who 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 in the appendix 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 indicator. 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 (see EMS 2006, Special Issue Environmental Informatics) between the University of Hamburg and chip industry using simulation technology to improve eco-efficiency in wafer production. This is achieved through a component-based architecture, where application specific components are inserted into a modular 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 made use of Microsoft’s COM architecture. 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 (see ([10], p. 180)).

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 variates 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 (see Chapter 6 of [7]).
- 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 processing.
- 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 Milan 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.

4. A CASE STUDY FROM SEMICONDUCTOR INDUSTRY

To test the design and applicability of the component-based combination of Discrete Event Simulation and analyzing material flows, an empirical study has been performed at a semiconductor manufacturer. Since the manufacture of semiconductor components is a complex process during which many planning and control problems need to be solved, this domain is well suited to an empirical test of the Material Flow Simulator’s implementation. In semiconductor production many expensive materials (e.g. developer chemicals, paints, solvents, acids), whose emission into the ecosystem could cause substantial damage and whose 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 is the final aim of the simulation study, only the sub-domain of lithography is presented in this paper.

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, using them in combination proved advantageous for pinpointing bottlenecks and for observing all legal requirements on solvent emissions at the same time.

We used our Material Flow Simulator to model the lithography process and constructed a plug-in for this domain. This focussed attention on semiconductor-specific model components, which helped us to map typical lithographic and other processes to a simulation model (see Fig. 3 in Appendix). 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 binds 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 programs 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.

5. SUMMARY AND CONCLUSIONS

Discrete Event Simulation and Material Flow Analysis are complex techniques, whose mastery requires 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. Assuring model consistency was a crucial task.

This paper has suggested a novel approach for integrating Discrete Event Simulation and Material Flow Networks into a common framework, based on a single model. This 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 analyzed 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, whose functionality can then be accessed through a few well documented interfaces. An example for cooperation between the Umberto® EMIS and some simulation components patterned after Microsoft’s COM architecture in the application domain of wafer production was used to show the effectiveness of this concept. To develop good plug-in components, we must identify suitable linguistic abstractions for relevant application domains since such “application languages” suggest interfaces and signatures for components. A more detailed example for this approach can be found in [10].
REFERENCES


APPENDIX: FIGURES

![Network Production](https://example.com/network.png)

**Figure 1:** A simple Material Flow Network
Figure 2: Processes, Activities, Events and Material Booking Indicators for CO₂

Figure 3: Model of the Lithography Process and the Results of its Simulation (lower left) and its Material Flow Analysis (lower right).