*Proceedings of the 2009 Winter Simulation Conference*
*M. D. Rossetti, R. R. Hill, B. Johansson, A. Dunkin and R. G. Ingalls, eds.*

# COMBINATION OF JOB ORIENTED SIMULATION WITH ECOLOGICAL MATERIAL FLOW ANALYSIS AS INTEGRATED ANALYSIS TOOL FOR BUSINESS PRODUCTION PROCESSES

Philip Joschko
Dept. of Informatics
University of Hamburg
Hamburg, Germany

Bernd Page
Dept. of Informatics
University of Hamburg
Hamburg, Germany

Volker Wohlgemuth
HTW Berlin
University of Applied Sciences
Berlin, Germany

## ABSTRACT

This paper outlines the application of a special Environmental Management Information System (EMIS) as combination of discrete event simulation with ecological material flow analysis for a selected production process. The software tool serves as decision aid for economic as well as ecological business problems. A combined view of the material flow as well as job-oriented view on an enterprise allows for a unified and efficient model building process. This contribution summarizes the underlying concepts and the experiences with the development and utilization of a suitable software tool following this integrated view and describes the concrete problems and solutions at the example of modeling a complex semiconductor fabrication.

## 1 INTRODUCTION

Enterprise environmental protection is gaining a growing influence on the interests of decision makers in management for quite some time already. The reason for this is not only the increased environmental sensibility of the public, supporting a positive impact on the consumers by a "clean" company image. Beyond that, monetary aspects play a decisive role with fast growing material and energy prizes. Apart from the input flow, the output flow becomes also relevant, i.e. in context of the EU emission rights trading, costly emission certificates have to be included in company balances additionally. The identification of measures for reducing resource utilization as well as caused emissions gains next to its ecological implication more and more an economic dimension.

However, suitable computerized methods and procedures are required to support a systematic identification of improvement potentials. In order to handle complex company environmental protection activities in a cost effective way, several methods of Applied Informatics are available. An Environmental Management Information System (EMIS) is a software application used for the collection, documentation, and assessment of enterprise environmental protection information as well as for the generation, planning, and control of environmental protection measures in a company and therefore supports environmental management tasks. Many times, we deal here with balancing and decision support systems generating Input-Output-balances or visualizing material- and energy flows with related graphical representations. Material Flow Networks are common components of EMIS; they serve as accounting system for material and energy flows.

At the Informatics Department of the University of Hamburg, our group has been experimenting with modeling and simulation as other suitable methods for EMIS within a long year research project. The techniques of modeling and simulation have been well established as an important instrument for the analysis and planning of complex systems in many domains a long time ago already (Page and Kreutzer 2005).The impact to our investigations presented in this paper was the proposal to use simulation technique for supporting the application of Material Flow Network method (Wohlgemuth et al 2001; Wohlgemuth 2005). Following that proposal, simulation can be used to calculate unknown environmental quantities. For example, this allows to determine the necessary connected load of input flows realistically also from complex systems.

During our research project, prototype modeling- and simulation software named Material Flow Simulator Milan has been developed. On the one hand, its discrete event simulation components allow an accurate analysis of typically economic aspects:

- bottle necks in personal and machinery;
- the identification of effects of scheduled, as well as of random production interruptions;

- maintenance times on the production;
- the impact of machine empty operation times;
- the utilization of personal;
- the duration of jobs;
- the total throughput of products.

On the other hand, its material flow analysis components for the first time add an environmental view to the discrete event simulation model, i.e. a consideration of relevant material flows and transformations:

- consumption of commodities, resources and additives;
- energy demand;
- waste accumulation;
- emission generation.

Note, that material bookings linked to different indicators describing the material and energetic turnaround at the different machines, allow the precise assessment of the handled input- and output materials per product type, production step or machine. The Material Flow Simulator Milan therefore represents a special EMIS that applies discrete event simulation as methodology and data source for the analysis of company material flows.

The concept and the software of the Material Flow Simulator have been tested in practice by cooperating with a semi-conductor producer (Wohlgemuth 2005, Mäusbacher 2005, Vacek et al 2007). The complete fabrication of a company site in Germany has been represented in a computer model in a systematic manner, while in parallel the software tool has been further developed. The highly complex semi-conductor production process posed huge demands on our prototype during this development process. In this way a relatively complex, close to reality application scenario has been designed in order to identify strengths and weaknesses of the Material Flow Simulator and to advance with the software tool development. Departments of the site have been considered in own sub models and analyzed under different realistic scenarios. The results have been compared with reality and provided as decision aids to the management.

We organized this paper as follows: In section 2, we introduce our concepts of combining job-oriented simulation with Material Flow Analysis. We also describe how a model can be implemented with help of our software Milan. Section 3 concentrates on software-technical aspects. We describe the framework and underlying component architecture, which make the composition of own applications for the user possible. In section 4 we review the experiences we gained, when we implemented a model of complex semiconductor factory. Section 5 concludes the paper and provides an outlook on our further work.

## 2 PRODUCTION PROCESS SIMULATION AND MATERIAL FLOW ANALYSIS

The special challenge with combining discrete event simulation of production processes and ecological-oriented material flow analysis is to harmonize the different worldviews used by these approaches (Wohlgemuth 2005). Therefore, the job oriented perspective of discrete event simulation has to be connected with the global oriented perspective of material flow analysis.

### 2.1 Graph-based modeling of job-oriented perspective

Discrete event simulation is a powerful method to represent production processes closely to reality and to follow time intervals of different sizes from few hours up to several business years for investigating aspects depicted in the introduction. With the generation of pseudo-random numbers following given stochastic distributions natural variations such as varying intermediate arrival times of production jobs can be represented. There are several ways of implementing discrete event simulation models. Simulation libraries like DESMO-J (Page and Kreutzer 2005) offer a maximum on flexibility, but modeling of complex system requires much experience in programming in the according language and beyond that, it needs much time. Spatial modeling by means of 3d-editors and precast model components is more intuitive, but too complex for our intentions of implementing a prototype Material Flow Simulator, which can interact with other EMIS-components, because its requirements on actually non-relevant spatial data make implementation unnecessarily complicated. Accordingly, we had to choose another abstraction of production processes, which fits the demands of fast and well-arranged modeling also of complex systems, of expandability for domain specific application and of easily connecting material flow components.

Hence, we modeled job-oriented subsystem with help of a graph-based editor component. The advantages of using directed graphs are the intuitively understandable visualization, also the easy and fast editing of complex models. Moreover, the formal structure allows a computerized analysis. An expandable tool bar offers functional model components (e.g. machines) to the user. All model components can be manipulated with help of form windows. This allows to set up capacities of machines and to define features supported by machines individually. A feature is a machine's acticity, which is independent from other activites, but whose substeps are belonging together and must be executed consecutively. It is represented by a simple character string. A set of sub-steps is appointed for each feature a machine supports. To each feature sub-step a machining time is allocated and whether human skills are needed.

There are application specific machine types that can be added to the graph as nodes, whereas arrows placed between the nodes describe the path the product may follow during its manufacturing process. Specific nodes serve as system entry and exit points; their task is to generate and clock out production jobs. A production job contains a [set/number] of products out of a selected product line specified by a recipe. Recipes are defined with help of a tabular form editor, where rows represent recipe sub-steps. A recipe sub-step contains the string representation of a machine feature, but does not specify the machines to be used. Further nodes implement simple decision finding algorithms, which are responsible to route production jobs, if more than one accessible machine supports the feature requested by the actual recipe sub-step. Finally, there are nodes that represent sub-models, input- and output-ports to allow a hierarchical model composition. Figure 1 presents the GUI of Milan`s graph editor, which has loaded the graph-based machine model of a semiconductor production process.

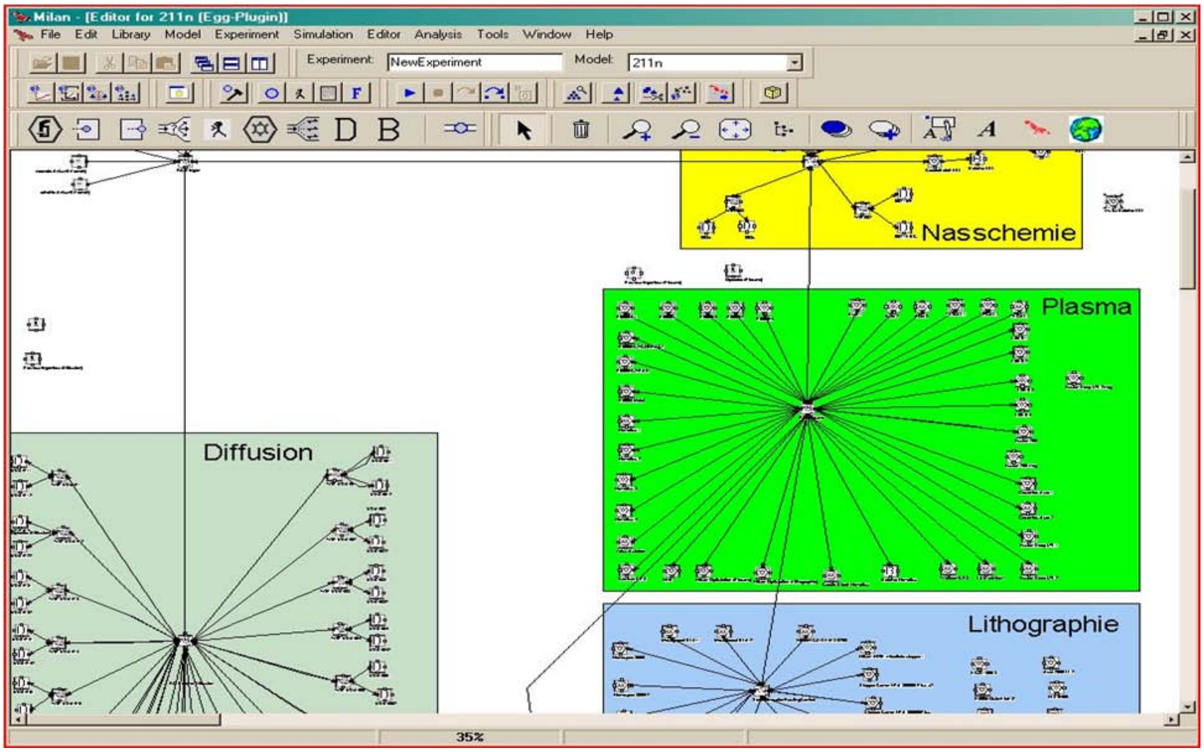


Figure 1: Material Flow Simulator Milan loaded a model of semiconductor production process

The formalized directed graph shown in the figure describes the static elements of a factory like machines, while the production jobs described by recipes and generated by entry points represent the dynamic elements of the system. Milan derives the structure of the business production process from these static and dynamic elements and creates an event-oriented simulation model. Event-oriented simulation is based on the processing of mutually scheduled events (Page and Kreutzer 2005). Events change the state of static elements and regularly insert the next events to be processed into an event calendar. The scheduling of an event is always linked to a static element, mostly to a selected machine, and to a dynamic element, i.e. to a production job. Because this is a kind of transaction-oriented modelling view of discrete event simulation methodology (Page and Kreutzer 2005), dynamic objects are also called transactions, and the static elements are also called blocks. With a starting event of a working process the machining time is determined using stochastic distributions, so that the next process step on the machine can be scheduled. If there are no steps left on the actual machine the dynamic element is routed to the next static block. This delivers the substantial economic statistics of machine park, human resources and production jobs mentioned at the beginning.

## 2.2 Material Flow Analysis

The next step is to integrate material flow associated aspects, so that our simulation model can act as environmental decision aid as proposed in the introduction. In a sense, material flow worldview is more global than discrete event view. Information is rarely linked to objects like products or process steps. Material Flow Networks, which were developed at the University of Hamburg (Möller 2000), are based on Petri-Net theory. Petri-Nets are directed graphs which can be formalized as 3-tuples $N = (T, P, F), F \subseteq (P \times T \cup T \times P)$, where T is a set of Transition nodes, S are inventory nodes, called Places, and each element of F describes a flow between two subsets of Places triggered by a transition of T. Initially places in Material Flow Networks hold a stock inventory at the beginning of some time interval. Then the relevant resource, material and energy flows during this period are computed. If sufficient transitions quantities are know, also the remaining unknown flows and the stock levels at the end of a period can be calculated. Sankey diagram technique allows comfortably illustrating the flows, while the wideness of an arrow indicates total throughput within one period in a selected place. Such diagrams are very useful for environmental information management of companies, because possibilities to save material and energy costs can only be recognized, if the material and energy flows are well-known. Although this global, period-related viewpoint is quite different from discrete event worldview, discrete event simulation can help to calculate unknown material flow quantities. Figure 2 illustrates how simulation can be used to calculate material flow networks. An activated transition generates parameters for executing a simulation experiment, in order to calculate unknown quantities, which will be returned to the material flow network. (Wohlgemuth et al. 2006)

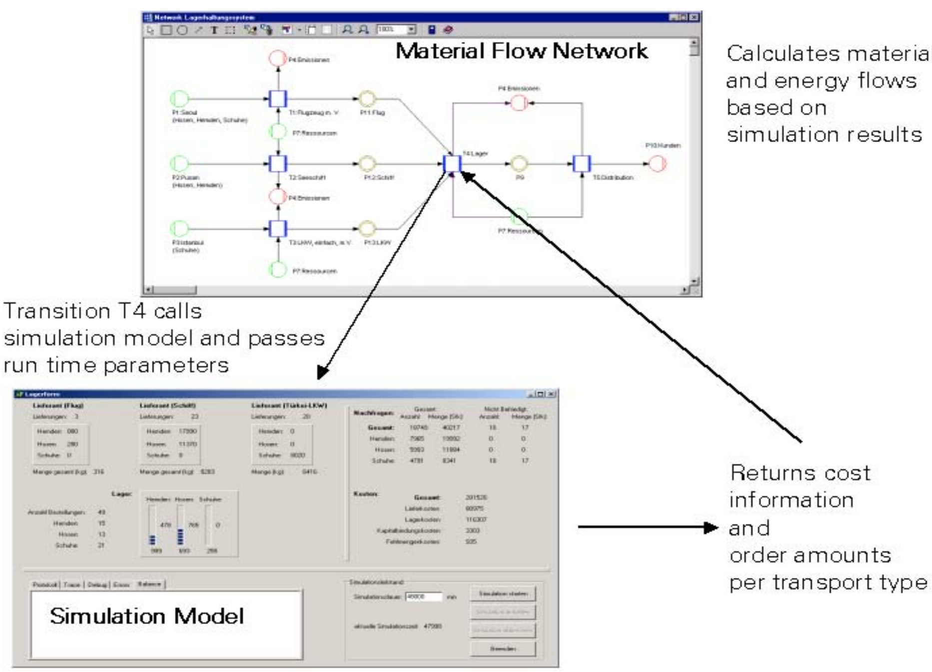


Figure 2: Linking discrete event simulation to Material Flow Networks (Wohlgemuth et al. 2006)

The period-oriented ecological material analysis also has an advantageous intersection with the job-oriented, discrete approach of simulation. Both attempts use the method of model building to map relevant system elements along the value chain to uncover weak spots under the called points of view. Quantity and characteristics of modelled machines, production jobs and recipes are identical in both models, which already put out a large part of these models all together. The combination of both approaches offers saving of costs and time in the model building process, secures model consistency and an enlarged scope for possible simulation scenarios.

To add the ecological, material flow oriented view to the job-oriented model, it has to be extended by different accounting indicators for material (Wohlgemuth 2005). We distinguish the following indicators:

- Basic load of a component. This indicator primarily signals consumption of electric standby energy; however it can also indicate any other kind of resource usage. The quantity of consumed resources depends on the length of time of the simulation run; it is irrelevant how long a machine works productively.

- Time depending activity of a component. This indicator triggers the accounting of a selected quantity of materials, depending on the machining time, when a machine is activated. Useable, these are additives and manufacturing resources that are depending on the time span in a linear way.
- Time independent activity of a component. This indicator is used to account a constant amount of resources, when a machine starts a manufacturing job. That is typical for the assembling of a product from single parts.

There are other indicators which provide nuances of the ones just explained, but they are beyond the scope of this paper (Wohlgemuth 2005). The indicators have to be defined individually for every model component. Indicators of type 2 or 3 have to be linked to machine features. In this way the events, which appear in an event-discrete simulation run, are attached to the accounting of material flow and energy flow in the same model. If a component is activated by an event, all activity depending indicators are triggered. Every notified indicator verifies whether it has to trigger a material or energy accounting. Depending on the kind of indicator the accountings refer to a machine, a machine feature, a product, the whole system or a combination from these. This allows a simple analysis of system limits and the generation of detailed eco-balances within the executed simulation experiments.

## 3 SOFTWARE-ARCHITECTURE

We implemented the Material Flow Simulator Milan as a component-based framework with several technical and domain specific plug-in-components. This is needed to achieve our requirements of a flexible cooperation between disjunctive functionality of classic simulation software and functionality of a material flow analyzer, as well as our demands to link our components with other EMIS-Software. As a result, user can compose and configure plug-ins individually for a selected application range depending on his demands.

Software components are functional, self-contained, and capable of delivery units of software, which need a software framework to be executed (Zwintzscher 2005). The framework offers different extension point, which the components can register to. This means that from the frameworks point of view, the component takes a contractual defined role, while the framework itself does not need to know, how the component was implemented or how it factually works. The only functionality the framework itself offers to the user, is the registration (i.e. registering and unregistering) of software components at runtime. Internally, it also offers communication channels to allow interaction between the loaded components.

This helps the user to load only those components, which he needs in his working context. Presently he has the choice out of the following set of components, whereas he can configure every component individually (Wohlgemuth et al. 2006):

- A visual editor component for graph-based modeling of systems
- A component offering a event-discrete simulation engine (i.e. the Delphi version of DESMO-J, called DESMO-D, see <http://www.desmo-j.de>)
- A component offering stochastic distributions
- A material management component, e.g. offering indicators for material accounting
- An analysis component for statistic evaluation and graphical representation of simulation results
- A persistence component for archiving models and settings
- Diverse domain-specific expert components

In addition to general, technical components, at least one domain-specific component is required. Such an expert component contains a set of modules with specific behavior needed for selected application domains; e.g., there is an expert component containing semiconductor-specific machine types, like diffusion furnaces, measuring devices or simple workstations. Warehousing and transportation of goods can be investigated with help of another expert component. The modules, contained in an expert component, can be inserted into a model by means of a graph editor component as nodes, which have to be connected via arrows. The simulation component generates the associated discrete-event simulation model with help of transformation rules described within the expert component. To add ecological material flow analysis, the material management component has to be loaded. Figure 3 shows the component-based architecture of the Material Flow Simulator.

We implemented the framework and components in high level language Delphi. The component-based architecture was realised using COM-Technology. Every component brings out an own COM-Server according to principle of Inversion-Of-Control, which offers services to the framework. The framework decides whether and when these services are taken up and activates them if necessary as so-called In-Process-Server. An In-Process-Server is executed in the same process as the framework itself. The integration of COM-technology is carried out with so-called wrapper-classes, which encapsulate the functionality of components and deliver COM-compatibility. They also allow the re-implementation of component-architecture with another technology without making changes in functionality implementation of components, which eases reusing components in other EMIS-frameworks. A working group at HTW Berlin now re-implements the Material Flow Simulator with the newer, more advanced .NET-technology in the high level language C#. See outlook section for some details.

Advantages of component-based software implementation are the possibility to substitute an existing component by another one easily on the one hand; on the other hand the expandability and modifiability of components is simplified, because single components are not that complex than monolithic software is.

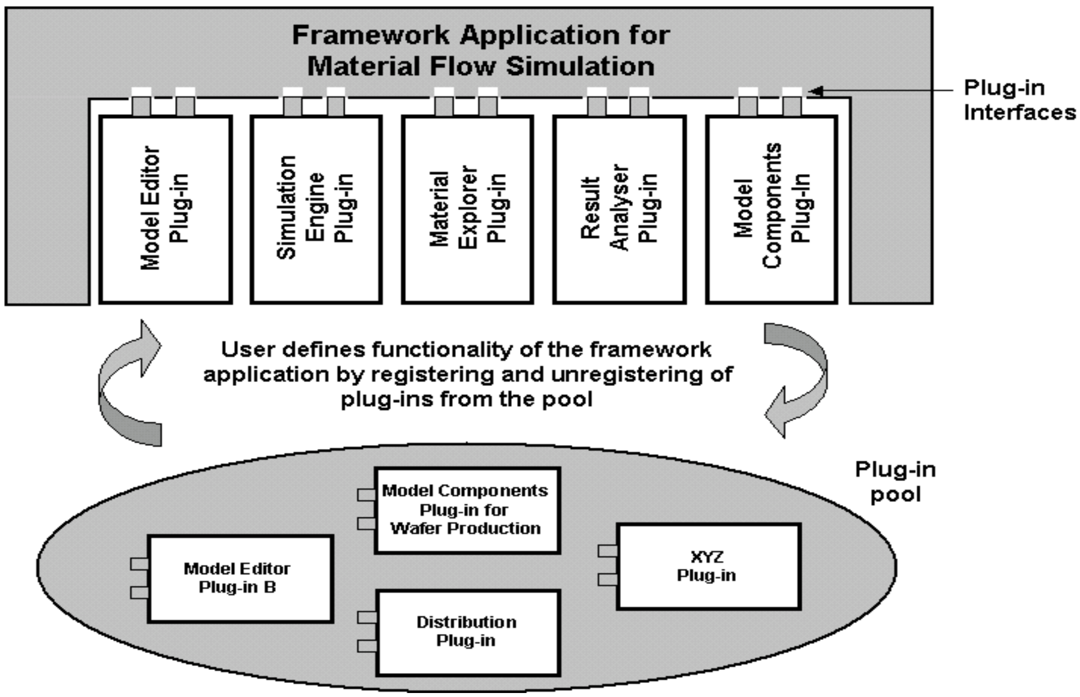


Figure 3: Plug-in-based software architecture (Wohlgemuth et al. 2006)

## 4 EMPLOYMENT WITH A SEMICONDUCTOR MANUFACTURER

We examined the practicability of our concepts in an empirical investigation within a semiconductor production site. In a co-operation project with a global player in semiconductor industry, the necessary data for a modeling of the factory has been provided. In this chapter, we describe, why the very complex manufacturing process of electrical construction units of silicon technology is an adequate testbed for our software Milan, we report on the model building process in semiconductor context and the quality of results we achieved when executing the simulation experiments.

### 4.1 Characteristics of Semiconductor Manufacturing

We selected semiconductor production as early adaptor, because both classical event-discrete simulation results (throughput, workload of machines, waiting periods etc.) and material flow aspects (emission of solvents, assigned quantities of acids and lacquers, supply of gases) play an important role in this complex production process (Wohlgemuth 2005).

In the factory of our co-operation partner, semiconductor components like transistors are manufactured. Thereby, one production unit is a set of silicon wafers that serve as medium for semiconductor components. The container for such a unit is called carrier, and contains up to 24 wafers of the same type. First, these very thin wafers are cut from a mono-crystal, pure silicon cylinder with a diameter of typical 5.9 or 7.9 inches. Then different procedures are used, in order to deposit up to 178 million semiconductor components per square inch onto the wafers. Finally, the individual components are cut out from the wafers and assembled into plastic packages. From now on, the components are called integrated circuits. Our model focuses the deposition process.

There are a high number of different product types, which do not only differ in number and arrangement of the existing semiconductor components, but frequently also in the process of deposition, i.e. there are a lot of different recipes and product types. Our model handles all of the more than 100 machines of the factory, but concerning the complexity, we had to abstract product range to about 20 main product groups.

There are carriers from different materials for various operational areas; for example there are carriers from Teflon for etching process or carriers from plastic for transportation. The factory personnel have to rearrange the wafers according to the tasks lined up. Hence, despite high automation, the production process is closely linked to human acting.

Note that the production cycle for finishing a set of wafers is with approximately one month quite long. In this period, the carrier goes through all departments of the manufacturing several times; it needs from two to three hundred production steps for completion. Frequently less than five production steps are accomplished off the reel in a department, before the department is changed.

Between two tasks a machine executes, only a relatively short time may elapse; otherwise maintenance costs rise, in order to make the machine ready for use again. Reason for this are impurities, which arise, if remaining gas in the machines has time to set off in the machines chambers. In order to avoid these maintenance times, production takes place 24 hours a day, seven days a week. For an adequate modeling, it is important to consider these maintenance times.

The yield at functional chips is an important characteristic for the quality of manufacturing. Whole production takes place in a cleanroom, since smallest dirt particle can make production useless. Positive pressure and recirculated air system provide for maximum cleanliness of air. Chemical impurities of used gases have to be avoided, too (Wohlgemuth 2007). Clean room circumstances are irrelevant for the modeling, however average loss through waste must be included into the model as well as time consumed by reviews, because faulty products are continuously segregated during the production process.

### 4.2 Modeling of production departments

At the beginning of co-operation, we implemented a semiconductor-specific component with special machine types (Mäusbacher 2005). This component has been refined in the course of the project according to additional requirements.

Departments of production were added gradually to a whole model. We analyzed each department in detail together with partners from the respective departments. Departments, which were not modeled yet, were represented thereby by dummy nodes. We cannot describe the differences between the departments wet chemistry, diffusion, photolithography or plasma in this paper in detail because of space restrictions.

Altogether 120 machines and 20 different product types with up to 270 recipe steps each were modeled. A simulation experiment consisted usually of 64 simulation runs, arranged into four scenarios to 16 runs each in order to achieve required accuracy of simulation results. Our scenarios differ in two experimental parameters: The arrival rate of production orders and the number of the available personnel. First scenario received arrival rate and staff assignment from the real data provided by the co-operation partner. A second scenario combines normal arrival rate with increased personnel employment, whereas a third scenario deals with an increased arrival rate at normal personnel employment. Finally, the fourth scenario contains an increased arrival rate and an increased number of available personnel. Each run simulates one business year, which took approx. 12-15 hours computing time dependent for a scenario on a 3GHz PC with 4GB RAM.

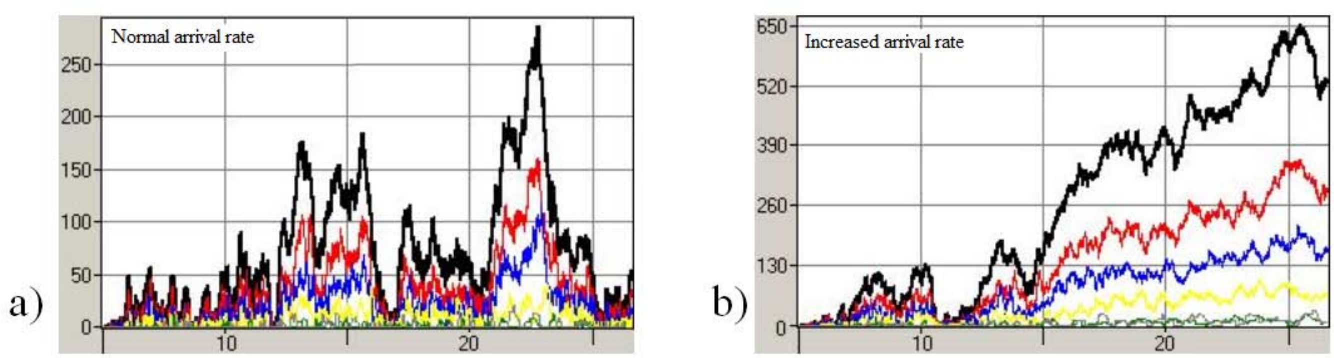


Figure 4: Queue in front of a workstation in different scenarios

Figure 4 shows an example output of the analysis component. Both diagrams illustrate the number of carriers (y-axis) in the FIFO-queue in front of the same machine in the same period (x-axis). Different colors indicate different product types. Diagram a) is taken from the results of a simulation run using a normal arrival rate; note that the machine reduces the queue completely on a regular basis. Diagram b) is taken from a run using an increased arrival rate; the machine cannot reduce the queue promptly.

### 4.3 Modeling of Material Flow Bookkeeping

After we implemented a model of a department, we integrated relevant material bookings. In particular power and gas consumption of individual machines were collected.

Table 1 shows power consumption of a certain type of machine. The data are subdivided in consumption without process (no-load operation) and consumption during a certain task. The consumption was collected specially for this project, because it was not available on the required level of detail before.

Bookings can be assigned both to machines and products. Table 2 shows the consumption of three different gases related to the phases of a recipe step. Since machining time is crucial for gas consumption, this is indicated in the table (Step Term). The recipe step consists of three phases, which are to be regained as columns of the table. For each phase, consumption of individual gases and average machining time are indicated.

Most of the necessary data on material bookings of individual machines could be selected from different tables. When sufficient measuring data was unavailable, employees of the enterprise had to make suitable estimations.

In the course of model implementation necessity for some additional, special indicators became clear (see section 2.2). Since these were implemented into the software, the ecological aspect could be integrated successfully into the overall model.

Table 1: Power input of machines

| Facility | Supply voltage of facility | Power input stand-by mode | Power input processing phase 1 of task x |
|---|---|---|---|
| Machine X | 208 V | 8,3 A / 1.726 W | 14,2 A / 2.954 W |
| Machine Y | 208 V | 6,4 A / 1.331 W | 9,4 A / 1.995 W |
| Machine Z | 208 V | 6,1 A / 1.269 W | 6,1 A / 1.269 W |
| Over-all power input: | | 4.326 W | 6.218 W |

Table 2: Gas consumption in the phases of a recipe step

| Recipe Y | | | |
|---|---|---|---|
| Phase | 1 | 2 | 3 |
| GAS 1 sccm | 2000 | 2000 | 2000 |
| GAS 2 sccm | 0 | 0 | 100 |
| GAS 3 sccm | 500 | 250 | 0 |
| Pressure mTorr | 1200 | 1200 | 1200 |
| Step Term | 01:25 | 00:30 | 00:30 |

## 5 EXPERIENCE AND OUTLOOK

It turns out that close-to-reality simulation of high-complex production with integrated material flow analysis is in principle feasible. From the departments of the co-operation partner there was expressed large interest in the software tool. However, the possibility of capacity planning of the production has been of main interest (i.e. economic side), also system behavior with increased order arrival rate. Concerning environmental analysis, the possibility of predicting quantity and throughput of required gasses and lacquers in future scenario analysis interested most.

However, the effort for the implementation of such an integrated model is quite high. It was the data collection phase, which proved more difficult than expected. Although, we worked with an enterprise of high-tech industry, where all process steps are well defined and logged. Nevertheless, it was often not possible to access certain information from the in-house database for different reasons. For example, the database contained no suitable queries, or data was obviously not correct. For instance, such wrong data records occur, if an employee works on further carriers before booking the last one, in order to book them later all together. Thus, information about control times at machines had to be inquired by the factory personnel or determined by observation. Some data had to be roughly estimated with support of the in-house specialists, e.g. the distributions for failure probabilities and maintenance times, since no data records were made available.

The data situation makes it difficult to keep the model up to date, since constantly new product types are introduced and processes are changed in semiconductor production. A component that queries the data automatically from existing operational IT-infrastructure would be desirably for support of the job order planning. The software tool would have to be at least able to recognize obviously wrong data records. For the reasons just mentioned, it cannot be expected that automated data base tools make manual inputs dispensable.

Besides the size of the model and the simulated time of one business year brought the assigned 32-Bit-PC to a capacity limit, since the maximum RAM size of 4GB was completely used. This is on the one hand due to the immensely large number of products and associated material bookings during one financial year, which keep in memory for a later analysis. Another reason is the unsatisfactory Garbage Collector of the COM technology, which is not able to dissolve cyclic references sufficiently. For larger models or longer periods, the Material Flow Simulator has to run on 64-Bit-PCs.

In summary the material flow simulator Milan represents a successful prototype. It shows that material flow analysis and job-oriented discrete event simulation can be linked with one another. Joint economic and ecological analyses claimed in the introduction of this paper are feasible; e.g., concrete bottlenecks at certain machines could be identified, and subsequently dissolved by the co-operation partner. Concrete material requirements of individual machines or product types could be determined.

At present, methods tested with the Material Flow Simulator Milan are revised in a new project at the University of Applied Sciences Berlin (see <http://www.empinia.de>). Experiences gained from the Milan project, were directly integrated into the conception of the new framework. Here more modern .NET technology is used instead of the outdated COM-technology, in order to facilitate component-based development . An open-source, component-based framework is under development here, from which new, individually cut EMIS can be built up or extended (Schnackenbeck, Wohlgemuth, and Panic 2008). This is to improve the general development of EMIS, as well as the future employment of simulation technology as method within EMIS.

## REFERENCES


Mäusbacher, M. 2005. *Entwurf und Implementation von Halbleiter-spezifischen Komponenten zur Produktionssimulation und Materialflussanalyse als anwendungsspezifische PlugIns für den Stoffstromsimulator Milan*. University of Hamburg: Thesis.

Möller, A. 2000. *Grundlagen stoffstrombasierter Betrieblicher Umweltinformationssysteme.* Bochum: Projekt.

Page, B. and W. Kreutzer. 2005. *The Java Simulation Handbook – Simulate Discrete Events in UML und Java*. Aachen: Shaker.

Schnackenbeck, T., V. Wohlgemuth, and D. Panic. 2008. Entwicklung eines Open-Source-Rahmenwerkes als Grundlage zur Implementierung von betrieblichen Umweltinformationssystemen. In *Konzepte, Anwendungen, Realisierungen und Entwicklungstendenzen betrieblicher Umweltinformationssysteme (BUIS)*, e.d. V. Wohlgemuth. Aachen: Shaker.

Vacek, J., V. Wohlgemuth, P. Joschko, M. Mäusbacher, and B. Page. 2007. Einsatz eines Werkzeuges zur Stoffstromsimulation bei einem Halbleiterhersteller. In *Simulation in Umwelt- und Geowissenschaften*, e.d. J. Wittmann, V. Wohlgemuth . Aachen: Shaker.

Wohlgemuth, V. 2007. Möglichkeiten und Probleme des Einsatzes von Methoden der Modellbildung und Simulation im Kontext des betrieblichen Umweltschutzes. In *Simulation in Umwelt- und Geowissenschaften*, e.d. J. Wittmann, V. Wohlgemuth. Aachen: Shaker.

Wohlgemuth, V., Page, B., Kreutzer, W., 2006. Combining discrete event simulation and material flow analysis in a component-based approach to industrial environmental protection. *Environmental Modelling & Software*: 1607-1617.

Wohlgemuth, V. 2005. *Komponentenbasierte Unterstützung von Methoden der Modellbildung und Simulation im Einsatzkontext des betrieblichen Umweltschutzes*. University of Hamburg: Thesis (PhD). Aachen: Shaker.

Zwintzscher, O. 2005. *Software-Komponenten im Überblick.* Bochum: W3l.


## AUTHOR BIOGRAPHIES

**PHILIP JOSCHKO** studied Computer Science and Psychology at the University of Hamburg. Since he holds a diploma (MSc) degree in Computer Science he works as a research assistant and PhD candidate within the Center of Architecture and Design of IT-Systems at the workgroup of Prof. Dr. Page. Research interests are discrete event simulation, cooperative model building processes and the EU emission trading system. His email is <joschko@informatik.uni-hamburg.de>.

**BERND PAGE** holds degrees in Applied Computer Science from the Technical University of Berlin, Germany, and from Stanford University, USA. As professor for Applied Computer Science at the University of Hamburg he researches and teaches in the field of Computer Simulation as well as in Environmental Informatics. His email is <page@informatik.uni-hamburg.de>.

**VOLKER WOHLGEMUTH** studied Computer Science at the Universities of Hamburg and Canterbury, Christchurch, New Zealand. Since 2005 he is working as a professor for Industrial Environmental Informatics at the HTW Berlin, University of Applied Sciences. His research fields are material flow management, modeling and simulation business systems and Environmental Management Information Systems (EMIS). His email is <volker.wohlgemuth@htw-berlin.de>.