Applying Life Cycle Assessment within Discrete Event Simulation: Practical Application of the Milan/EcoFactory Material Flow Simulator

Jürgen Reinhard¹, Rainer Zah², Volker Wohlgemuth³, Paul Jahr⁴

Abstract

This paper reveals the experiences of the application of a software tool that combines discrete event simulation (DES), material flow analysis (MFA) and life cycle assessment (LCA) in a single simulation model. This view focuses not only on economic optimization but also on material flow analysis opening the door to sustainable production in the future. Thus, the software unifies the economic and environmental perspective on a manufacturing system and therefore can be used for sustainable decision making. The paper will highlight important development phases, basic concept and important implementation issues as well as its practical application in the manufacturing industry.

1. Introduction

Manufacturing system simulation is an established approach for the planning and evaluation of the efficiency and effectiveness of manufacturing systems. DES is just one out of many available simulation paradigms but has proven its usefulness in the context of job-order related and time sensitive production flow planning. The reason for this is that for many dynamic processes such as manufacturing, transportation and inventory management, the change of system states can be well described by discrete points in time (i.e. events), rather than through continuous fluctuations.

One increasingly prominent application of DES is the simulation of material flows in manufacturing systems (Thiede 2012), i.e. its integration with MFA. MFA is a method for systematically accounting for the flows and stocks of materials or elements within a system defined in space and time (Rochat/Binder/Diaz/Jolliet 2013). MFA applied within a company’s manufacturing system usually focuses on the improvement of efficiency of the production processes, i.e. in such a way that materials and energy are used in the most efficient manner (Thiede 2012). The integrated application of DES and MFA in the context of manufacturing systems adds a dynamic, job-order related perspective to the usually static MFA. This allows the translation of the influence of time-dependent incidents in production (such as e.g. changes in machine states, machine breakdowns, supply disruptions, production of defective parts) on the associated change in the material and energy flows. We note that such material and energy flows provide an interesting starting point for the application of LCA.

1.1 Motivation

LCA is a technique for the comprehensive, quantitative assessment of the environmental impacts of products in a life-cycle perspective. It focuses on the compilation and environmental evaluation of all inputs and outputs associated with a product throughout its life cycle with the goal to pinpoint ecological weaknesses, compare possible alternatives, evaluate the main impact factors, design new products, measure the

¹ University of Zurich, Informatics and Sustainability Research, Binzmuehlestrasse 14, CH-8050 Zurich
² Quantis Switzerland/Germany, glaTec Technology Center, Ueberlandstrasse 129, CH-8600 Duebendorf
³ HTW-Berlin, University of Applied Sciences, Industrial Environmental Informatics Unit, D-10318 Berlin
⁴ The term „product“ includes both goods and services.
environmental relevance of a material or product and establish recommendations for actions (Finnveden et al. 2009). While it can be denoted as the most prominent methods for the environmental evaluation of products, its application in industry is still limited (Finnveden et al. 2009; Clark/Leeuw 1999). This is particular true for small and medium enterprises (SMEs). The most barriers reported are the perceived complexity of the method and the demand for high quality data (Frankl/Rubik 1998).

We note that the mapping of time-dynamic changes on material and energy flows can be easily translated into the realm of environmental impacts on the basis of LCA. Further, this translation is expected to reduce the barriers hindering the further pervasion of LCA in the manufacturing industry (Schtsky 2011). In this context, we present and discuss the main features of simulation tool that works as a one-stop-software-solution which allows the seamless integration of LCA with DES and MFA. In this regard, other authors have already presented possible approaches for selected energy flows (Thiede 2012) or selected system boundaries (Löfgren/Tillman 2011). However, we are not aware of other existing software solutions that allow the integration of LCA at this level of sophistication and within one single software model that combines the MFA, LCA and DES perspectives in a seamless way.

1.2 Goal & Scope

The goal of this paper is to support this claim by showing the concepts, implementation and features of the Milan/EcoFactory software tool. This paper will point out that it makes sense to use a single software to combine DES with MFA and LCA because both approaches had been used for a while in producing companies, though operating on different ends for different means and usually operated by different people but using a similar set of data. First experiences from practical applications of the software tool within the EcoFactory-Project will show the benefits of using the software for the simulation of ecological and economical aspects of manufacturing systems using an integrated approach.

1.3 Structure

The article is structured as follows: first we will give an overview on the history and roots of the development of the Milan/EcoFactory software and the ideas behind it. Then we will describe the basic approach and concepts behind the software, covering system boundary issues and core components. After a short inside into software implementation aspects the paper describes shortly an application of the software in a Swiss manufacturing company. At the end a conclusion and an outlook of further developments is given.

2. History and Background

Discrete event simulations are a powerful method to represent production processes close to reality and to follow time intervals of different sizes from a few hours up to several business years for investigating aspects depicted in the introduction. The importance of the instruments for modeling and simulation was already well recognized for the usage in analysis and planning of complex systems in many domains (Page/Kreutzer 2005 for examples).

The adaptation for usage in light of our primary focus – to assist resource efficiency – was carried out around the year 2000, when the proposal was made to use simulation techniques for supporting the application of the Material Flow Network method (Wohlgemuth/Bruns/Page 2001; Wohlgemuth 2005). Material Flow Networks were developed at the University of Hamburg (Möller 2000) and are based on the Petri-Net theory. By these means, simulations can be used to calculate unknown environmental quantities, such as determination of the necessary load of connected input flows considering complex systems (Joschko/Page/Wohlgemuth 2009). Furthermore in Material Flow Networks information is rarely linked to
objects like products or process steps which follows the principle of hiding non-relevant data considering the simulation.

The original concept of merging DES with MFA was originally proposed by Wohlgemuth (Wohlgemuth, 2005) and later implemented as a software prototype, called Milan, written in Delphi. In the research project Emporer, Milan was ported to a newly developed application development framework called Empinia which has a strict focus on extensibility and modern software design concepts. The purpose of this reimplementation was the ability to compose the simulation software of many independently developed parts such as the simulation service, the simulation components, the persistence backend and the graphical user interface (Schnackenbeck/Mäusbacher/Panic/Wohlgemuth 2009). Using that kind of composition, it was possible to extend the existing simulation components with new functionality (like the accounting of materials during a simulation run) and to contribute completely new simulation components.

Milan was built on top of the Empinia framework (which is itself provides just infrastructure components to build complex desktop applications) by programming all the necessary components needed for modeling production systems and using the created models in DES. Additionally, to model the energy and material flows, components for modelling materials and units were created.

Thus, the software Milan resulted from a variety of research during the years 2000 up to today. While on one hand, its DES components allow an accurate analysis of typically economic aspects and industry related aspects, on the other hand, its material flow analysis components added an environmental perspective to the discrete event simulation model for the first time, i.e. a consideration of relevant material flows and transformations such as:

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

Various publications already hinted at the potential of the software. Although we presented the first application of the Material Flow Simulator Milan in 2006 (Wohlgemuth/Page/Kreutzer 2006), we then made several technological changes: reprogramming the software using newest technologies (Wohlgemuth/Schnackenbeck/Panic/Barling 2008).

The intensified work on different levels of the architecture and extensions of the simulation engine resulted in a powerful simulation tool that is currently working in different use cases in industry within the EcoFactory project, where life cycle assessment functionalities are added to the software. EcoFactory was a joint research project with the Swiss Federal Institute for Material Science and Technology (EMPA) and the BWI Center for Industrial Management, ETH Zurich, together with several Swiss companies. The goal of the project was to develop a procedure model including an associated software tool which supports industrial companies during their decision-making process to identify the highest potential for optimization and to improve the eco-efficiency of production processes. This includes:

- Formulation of a comprehensive process model to optimize the eco-efficiency of production processes.
- Development of an application-orientated software tool based on discrete event simulation and material flow analysis.
- Creation of an integrated indicator-system to measure the eco-efficiency of production processes.

The EcoFactory approach led to the linkage of the software tool Milan to the well-known Life Cycle Inventory (LCI) Database Ecoinvent® which is the world’s largest database for LCI data, containing over 4000 processes categorized by geographic regions. By offering such an interface to the Ecoinvent LCI da-

---

5 www.ecofactory.ethz.ch
6 www.ecoinvent.ch
the efforts for data collection and performing a LCA for companies is reduced significantly (Sproedt/Plehn/Schneider/Schönsleben 2011). Furthermore, industry specific generic reference models were created to improve the applicability of the software tool in industry.

3. Concept
This chapter describes the basic concepts behind the Milan/EcoFactory software. However due to limited space there is only a rough overview given.

3.1 System boundaries
The system boundaries of our simulation approach can be separated into a foreground and a background system (Figure 1).

![Figure 1](image)

**Figure 1**
Scope of Milan/EcoFactory
Source: own depiction

The foreground system is the collection of processes on which measures may be taken concerning their mode of operation as a result of decisions based on the study (Tillman 2000). The background system consists of all other modelled processes influenced by measures taken in the foreground system (Tillman 2000). In our perspective, the foreground system is the manufacturing system of interest (1). The background system consists of all processes triggered by the consumption/transformation induced by the manufacturing systems, i.e. all interventions associated with the fulfilment of the need generated by the foreground system (2). This also includes the recycling and treatment of wastes associated with the manufacturing system. The downstream usage of the product leaving the factory gate (e.g. the use phase) is not considered (3). That is, the system boundaries follow a cradle-to-gate approach.

3.2 Core Components
Figure 2 shows the overall core components of Milan/EcoFactory and their interaction.
The manufacturing system simulation (foreground system) consists of the DES model (1) that activates and controls the Material flow (MF) model (2). The DES model expresses the probabilities of events (e.g. E1, product arrives) associated with the entities (e.g. products) that travels through the system. Typically, it consists of discrete components such as machines and work pieces, whose behaviours cause state changes through discrete (Wohlgemuth/Page/Kreutzer 2006). Each event occurs at a particular instant in time and marks a change of state in the system. The MF model allows the modelling of the materials and energy transformations associated with these events and the duration between events, i.e. the energy, materials and natural resources required and waste (materials) and emissions caused by the production of intermediate and final products.

In general, to assess the environmental impacts of these flows one has to consider (i) the direct use of natural resources (e.g. water from river used for cooling, etc.) and the direct emissions caused during production (e.g. phenol, pentane, etc.) as well as (ii) all interventions associated with the provision of the material and energy that are required and transformed. This information is retrieved in the form of aggregated life cycle impact assessment (LCIA) data from the life cycle inventory (LCI) database Ecoinvent (4). Ecoinvent is the world’s largest database for LCI data; on the basis of >1500 elementary flows (natural resources and emissions) more than 4000 unit process inventories are offered. In addition, the database provides the aggregated LCIA results of more than 30 LCIA methods for all unit processes and for all relevant elementary flows.

The interface between the aggregated LCIA results provided by Ecoinvent and the Milan/EcoFactory software is realised via a material browser. The material browser allows the matching and transformation of all energy, material and resource flows used in the material flow model (2) into the unit processes and elementary flows provided by Ecoinvent (3). In addition, it provides the means to model entire new unit
processes on the basis of the aggregated LCIA results. This feature is not very important for elementary flows but very meaningful for the generation of specific unit processes. Even though >4000 unit process is a lot, it is by no means an accurate match for the highly specific materials and energy mixes required by the manufacturing industry. For example, a company might be interested in the potential reduction in global warming potential (i.e. CO₂ equiv. emission per year) that is related to the shift of 40% of their conventional electricity consumption to certified sources (e.g. hydropower, etc.). This can be modelled by matching one kWh of electricity (used in the MF model) with 0.6 kWh from conventional sources and with 0.4 kWh from certified sources (both from the Ecoinvent database).

4. Implementation Issues

The software architecture of the Milan/EcoFactory tool can be viewed as a set of layers of application building blocks. A simplified version of this architecture is depicted in Figure 3.

![Figure 3](image)

**Figure 3**
Milan software architecture
Source: own depiction.

The foundation of applications built on top of the Empinia framework is an infrastructure layer, which provides basic software functionality needed for desktop applications, such as:

- a graphical user interface, providing the application window, menus, toolbars, common dialogs and a layout mechanism for arbitrary sets of views that can be filled with user controls by higher application layers (e.g. property editors for the entities of the domain layer, visual editors, navigation),
• a persistence backend, which is used to store user created content in databases or files,
• and a highly configurable extension mechanism, which can be used to extend the application in almost every aspect.

The contents of this layer do not provide any domain specific components and are only used to support the components of the layers above it. An advantage of this architecture is its high level of reusability of infrastructure components. Every new component in this layer extends the possibilities of all applications based in the framework (Jahr/Schiemann/Wohlgemuth 2010).

Using many of the functionality provided by the infrastructure layer the domain layer provides elements that are needed to create a specific application domain (such as simulation, waste management, metering). Each domain provides entities related to it as well as User Interface (UI) components to manage them. Milan/EcoFactory uses a subset of the available domain packages – most importantly the simulation domain which was created for it. The domains for event-discrete simulations and the core production system component domains use Empinia’s extension mechanism to extend the simulation domain. In addition to the simulation related domains, Milan/EcoFactory uses the material and unit domains to model the material and cost flows. These domains are shared with other applications that are actually built on top of the same software stack.

Applications that solely use the infrastructure and domain layers can only be used to manage (create view, edit and delete) entities of the selected domains. This is where the application layer comes into play. Components of this layer use the available domain entities to create complex functionality. Milan/EcoFactory uses a visual editor to compose production system models and configure any aspect of the selected production system components. Entities of the material domain can be connected to form complex material trees, including the materials that were imported using an access to the Ecoinvent database. It provides editors for the accounting of materials and costs to specific DES events during a simulation. Additionally, a user interface for the control of running experiments is provided, which allows the export of the simulation result to Microsoft Excel.

Some of the application layer functionally was created or revised during the EcoFactory project, especially the creation of new production system components. On the production system side, Milan/EcoFactory currently supports modelling of products, system boundaries (entry and exit points to the system), workstations (with different kind of behaviour, like parallel processing, homogeneous and inhomogeneous product batches and many more), storages, as well as assembly and disassembly stations.

5. **Practical Application**

5.1 **Basics**

One of the companies which would like to optimize its production processes is HUBER+SUHNER AG. Clearly, a “green” factory it is no easy undertaking to keep an eye on the MFA dimension (e.g. energy efficiency, material efficiency, etc.) and its corresponding environmental impact on midpoint (e.g. global warming potential, photochemical oxidation, etc.) and endpoint level (Swiss method of ecological scarcity, Eco Indicator 99, etc.) in addition to all the necessary economic factors. This is exactly what is analysed with the Milan/EcoFactory software based on one single model. The economic model is linked directly to the methods and data used for life-cycle evaluation, allowing production experts to determine which machines run for how long during a process, and what materials are required for a particular manufacturing step. The ecological dimension extends far beyond mere energy saving, with pollution emissions, resource usage and wastage also being factored into environmental impacts on mid- and endpoint level. In fact, all common Life Cycle Impact Assessment (LCIA) methods available from the Ecoinvent database can be applied.
5.2 Modelling

The execution of material flow simulation requires the creation of a model that represents the analyzed system. Up to now this has required two models, one for the material flow analysis and another one for the simulation-related aspects. The material flow simulator Milan/EcoFactory, however, is able to integrate both specific views into one model. It retains the common model structures and adds the different sets of parameters. These parameters, such as sets for material accounting or probability distribution streams, can be added subsequently to the model structure.

The modeling is done using a graphical network consisting of nodes and edges and hence reflecting the origin, i.e. the Petri-Net Theory. The nodes describe important model elements where products are handled or stay for processing for a certain period of time. Edges work as logical connections between these elements and are also intended to show the process flow direction.

Manipulating model parameters for the simulation and material flow perspective is done by means of property editors enabling a simple and consistent way of setting values for all types of properties. Standard editors are implemented for the production system domain. These allow changes to component-specific parameters, such as setting distributions, accounting rules, queue lengths or capacities etc. In figure 4 on the left hand side a part of the material flow model for the Swiss company HUBER+SUHNER AG is shown. The building block of class entry point is selected so that all properties of this building block that are relevant for the production process can easily be accessed. These properties are part of the job-oriented perspective whereas on the right hand side of figure 4 cost flows and material flows that are related to the production process can be defined. Material flows are very important for modelling MFA/LCA relevant aspects of the company.

![Figure 4](image)

**Figure 4**

Material flow simulation model editor and Flow properties

Source: own depiction.

The graphical manipulation of building blocks leads to a faster development of a model. The graph editor can be used to manipulate and create models. The editor itself can work in different domains. Domain specific functionality and the graphical representation have to be defined by plugin developers enabling the editor to handle new domains and their components which also use plugin definitions.
5.3 Results

No analysis can be done without results. These are shown in reports which can be designed with the help of the reporting system. The data for the reports is aggregated during simulation runs by a system of observers that listen to changes in the material accounting and simulation entities. The material flow simulation software Milan/EcoFactory offers plenty of reports with regard to both the job-oriented (DES) perspective (like throughputs, arrivals, mean service times etc.) and the MFA/LCA perspective (energy consumption per machine or product, amount of waste per product, emissions etc.). However, it is also possible to export all data to MS Excel for user-specific evaluations.

Because the Milan/EcoFactory software integrates DES aspects with the MFA/LCA perspective in an integrated, seamless way it is possible to present the ecological and economical perspective of sustainability in one diagram as shown in figure 5. Here the production costs per unit are displayed in relation to the environmental impact for some products of the company. This diagram is solely based on the results compiled from the simulation runs of the Milan/EcoFactory software. It allows the immediate identification of the most relevant products. The same diagram format can be used to identify the importance of manufacturing processes and machine stages (idle, processing, failure, etc.).

![Exemplary results combining ecological and economical aspects](image)

Figure 5
Exemplary results combining ecological and economical aspects
Source: (Plehn/Sproedt 2013).

6. Conclusion and Outlook

Based on the experiences of the usage of the Milan/EcoFactory software in Swiss companies the application of the software offers a huge potential. It seems that the Milan/EcoFactory material flow simulator helps manufacturing companies to understand the interdependencies of the environmental and economic performance of their production system. Combining both the economical perspective of DES with the more ecological view of MFA/LCA leads to more transparency in the complex interactions within a pro-
duction system of a company. Furthermore, this approach adds a dynamic perspective to a LCA analysis by systematically considering the influence of time-dependent incidents in production (such as e.g. machine breakdowns, supply disruptions, production of defective parts). Though this new perspective, the discrete event material flow simulation model increases the precision of the environmental analysis significantly to better support the decision making process and leads to a reduced effort for the user, since the MFA is now based on a dynamic simulation model. So changes to the model also become effective to the LCA without having to run the analysis again.

However, the benefits of the program do not unfold under all circumstances. It is most helpful to those companies which are already actively engaged in reducing their environmental impact and who wish, as a next step, to ecologically optimize their production processes over the full life cycle. Vice versa, manufacturing companies which have just started with the continuous improvement process associated with environmental management systems will find it difficult to unleash the full potential of Milan/Ecofactory. Often, as a first step, it is sufficient to study a company’s electric power consumption data and monitor the efficiency of its production machinery. This allows the specialist to suggest basic changes which, without any detailed analysis, will result in considerable improvement. The Milan/EcoFactory software can then be used to give the ecological focus of the business the ultimate fine tuning.

Thus, using the Milan/EcoFactory material flow simulation software helps a company to analyze the ecological and economical pillars of sustainability of its business. Furthermore, we are actually working on the integration of the social dimension of sustainability into the software and on mobile data acquisition tool using tablets and smart phones.

ACKNOWLEDGMENTS

The research project Emporer was funded by the German Federal Ministry of Education and Research (BMBF). The authors thank it for its support.

The research project EcoFactory has been conducted with the EMPA and the BWI/ETH Zürich (P. Schönsleben, M. Baertschi, J. Plehn and A. Sproedt). The authors would like to thank them for the fruitful collaboration.

Bibliography


