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Modelling of Energy Storage Devices and Converters for Energy Flow Simulation in Plant Simulation

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Abstract: Increasingly stringent fluctuating energy supply are forcing companies to adjust their energy consumption in production and production infrastructure. The future production infrastructure will play a key role here, as the targeted control of energy storage devices and converters will create precisely the energy flexibility required. Since production processes with regard to material flow are predominantly time-discrete processes, appropriate software systems are used for simulative investigations. In order to ensure a holistic view of the energy flow between the production process and the production infrastructure, it is necessary to simulate the energy flow of the production infrastructure in a time-discrete software environment, although the energy supply is a time-continuous process. The aim of this article is, therefore, to determine the information loss of the time-discrete simulation of energy flow systems in comparison to the time-continuous simulation.

1 Introduction

By 2030, the European Union aims to reduce greenhouse gas emissions by 40% and increase the share of volatile renewable energies and energy efficiency to 27% each (Europäische Kommission, 2016). A difficulty with the implementation lies in the volatile character of renewable energy sources since the energy supply needs to be adapted to the fluctuations in energy generation due to wind power and photovoltaic plants (Sauer and Weckmann, 2017). For this reason, industrial producers, both in discrete manufacturing and in the process industry, will have to adapt their plants to these purposes and become more energy flexible. The production infrastructure will play a key role since the targeted control of energy storage and converters provides a possibility to utilize the required energy flexibility. Since production processes with regard to material flow are predominantly a discrete event and time process, appropriate software systems are used for simulative investigations. Since the energy supply is a continuous process, it is necessary to simulate the energy flow between production infrastructure and production process in a time discrete software environment in order to ensure a holistic view.

Therefore, this article deals with the research question: Can energy flow of manufacturing systems be sufficiently estimated by time-discrete models in contrast to time-continuous models? For the simulative investigation of the energy flow, time-discrete simulation models are built in Plant Simulation and the results are compared with time-continuous MATLAB/Simulink models.

2 Related Work

Many simulation studies investigate energetic questions using the example of production processes, whereby the production infrastructure and thus the time-discrete simulation of the energy flow is rarely discussed.

In Beier et al. (2015), a method for the control of production and compressed air systems is discussed. The aim is to increase the energy flexibility while maintaining a dynamic system behaviour, whereby a hybrid simulation approach is chosen. Beier et al. (2016) describe the possibility of integrating renewable energy sources and energy storage devices into a production system by using a hybrid simulation approach consisting of a combination of discrete event and time-continuous simulation. A time-discrete model-based implementation for energetic considerations of production systems in relation to material flow simulation was presented by Stoldt et al. (2013).

The contribution by Fuss and Beißert (2014) investigates an approach to energy-integrated material simulation using the example of an aluminium foundry. In the process, components of an energy-oriented material flow simulation were developed and validated. The investigation focused on the evaluation of electrical energy consumption, whereby other energy sources such as compressed air supply were not taken into account.

Solding (2008) investigates a methodology for the efficient use of energy in production plants. The Discrete Event Simulation (DES) serves as an analysis tool for manufacturing systems and complements the use of energy models for industrial applications.

The simulation module *eniBRIC* maps the media/energy flows of production and production infrastructure systems on the basis of condition-dependent consumption (Schlegel et al., 2013). In the contribution of Stahl et al. (2013), a concept for a holistic time-discrete simulation of factory operation is presented. The focus is on energy and material simulation in order to map the production infrastructure and machines. Based on the previously described class library *eniBRIC*, it is extended by three simulation modules (Stoldt et al., 2017). The extension enables the simulation of energy storage devices and renewable energy producers using the liquid objects available in Plant Simulation.

3 Energy modelling in Plant Simulation

In energy modelling, computer-aided energy systems are created in order to analyse various assumptions about economic and technical conditions. The aim is to mathematically optimize models in order to reduce costs or energy consumption.

First, a definition for the energy in Plant Simulation needs to be defined. The suitability of material flow, fluids, and information flow objects for energy modelling is presented and evaluated according to various criteria. Based on the results of the definition of energy modelling in Plant Simulation, the energy flow of manufacturing systems is modelled, which is modified and has to be adapted to the respective purpose.

In the case of material flow and fluid objects, analogies can be derived between the building blocks and energy flow of manufacturing systems provided in Plant Simulation. For the modelling using material flow objects, it is possible to describe the energy using moving units (MU), which are used in Plant Simulation to model parts that are produced and transported. The source that produces MUs serves as the energy source. Depending on the configuration, different types of energy sources can be modelled. For example, a photovoltaic or wind power plant can be realized with the help of a time series. Energy storage devices are represented by the storage device whose size, i.e. the number of storage locations, represents the capacity of the respective energy storage device. To map characteristic charging/discharging processes, methods need to be implemented in *SimTalk* which control the input/output of the energy. Energy converters are modelled by a *SingleProc*. For an energy conversion between two types of energy, an output control is required, which represents the efficiency. For this purpose, the incoming MUs are an offset against the efficiency and the converted quantity of MUs is the output. The advantages of energy modelling with material flow objects lie in the statistical evaluation and the more intuitive reproduction of other energy converters and storages. The time-consuming simulation period and complex implementation of physical properties in energy storage and conversion systems contradict the use of material flow objects. In addition, the scaling of the energy is critical.

Another possibility of energy modelling can be done with fluid objects. Similar to the material flow objects, analogies between the available fluid objects and energy flow of manufacturing systems can be detected. The energy is modelled by fluids, the fluid source serves as the energy source, the tank as energy storage and the mixer as an energy converter. Advantages of using the fluid objects are the visualization of the energy flow and the statistical evaluation. Furthermore, despite an event/time discrete simulation environment, it is a continuous process. Disadvantages of fluid objects are pre-implemented fluid mechanical properties and the complex programming of physical properties.

The third presented method of energy modelling uses information flow objects. The energy, storages and converters are modelled using methods, global variables, and tables. Calculations of charging/discharging times, the State of Charge (SoC) and recording of results are realized by means of methods. Technical parameters, charging/discharging times, the state of the energy storage or the SoC are stored in global variables, ensuring that different methods in the network can access them. A major advantage of information flow objects is the flexibility in modelling any production infrastructure component, regardless of the limitations of implemented properties in the material flow and liquid objects. Disadvantages are the susceptibility to errors and the limited possibility of visualizing the energy flow.

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***Table 1**: Possibilities for energy modelling in Plant Simulation*

Analogies	**Energy modelling**		
	Material flow	**Fluids**	**Information flow**
Energy	Movable objects	Fluid	-
Energy source	Source	Fluid source	-
Energy storage	Store	Tank	-
Energy converter	SingleProc	Mixer	-
Advantages	Statistical evaluation available, intuitive reproduction of other components	Statistical evaluation available, visualization of energy flow, continuous process	Flexibility, fast simulation
Disadvantages	No scaling of energy, long simulation time, complex implementation of physical properties	Consideration of fluid-mechanical properties, complex implementtation of physical properties	Error susceptibility, possibly no event creation

Fehler! Verweisquelle konnte nicht gefunden werden. shows various criteria for the qualitative and quantitative evaluation of the three presented possibilities of energy modelling and serves as a basis for the further course of the modelling. For this aim the

- simulation speed,
- flexibility in modelling, the extension of components and applicability to different applications,
- error susceptibility within the created networks and during simulation,
- complexity/clarity of the networks and traceability/expandability of the models,
- and accuracy of the simulation results

are investigated.

Table 2: *Evaluation of energy modelling in Plant Simulation*

Evaluation criteria	**Material flow**	**Fluids**	**Information flow**
Simulation speed	--	-	++
Flexibility	o	o	++
Error susceptibility	o	o	+
Clarity	++	++	-
Accuracy	-	+	++
Legend: - - = very low, …, ++ = very high			

In the following, the energy is represented by the information flow objects, as the accuracy of the simulation results, the simulation speed and the flexibility in modelling compared to the material flow and fluid objects best reflect desired system behaviour.

4 Modelling of energy storages and converters

The aim of this section is to introduce the modelling of production infrastructure components based on the results of the previous section. For the sake of clarity, the modelling procedure is shown using the example of an electrical capacitor. In the context of this contribution, the loss of information between the time-discrete and time-continuous simulation of energy flow in manufacturing systems is determined on the basis of a total of five energy storage devices, two energy converters, and three energy generators.

For this purpose, a component model is first defined, assumptions / constraint conditions are made, the implemented control and the mathematical-physical calculation methods (only for the electrical capacitor) are shown.

4.1 Component models and assumptions

A central assumption in modelling is that the energy flow follows the material flow. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the simplifications made to the models, which are defined for consumption values, energy generators, storage units, and converters.

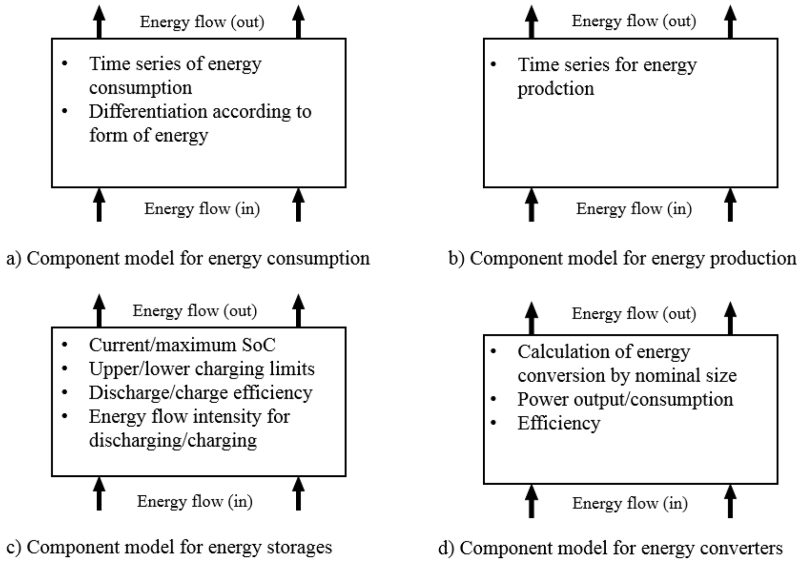

***Figure 1**: Component models for the energy flow of manufacturing systems, referring to Stoldt et al. (2017)*

The interface between the production process and the production infrastructure is formed by tables with time series for power. This means that the process is completely decoupled from the infrastructure, whereby the performance values (consumption) of the production process need to be known (**Fehler! Verweisquelle konnte nicht gefunden werden.**a)). Similar to the consumption, the power of the volatile energy sources is also stored as time series (**Fehler! Verweisquelle konnte nicht gefunden werden.**b)). In the energy storage models, the current/maximum SoC, upper and lower charging limits, efficiencies and energy flow intensity are critical for implementation (**Fehler! Verweisquelle konnte nicht gefunden werden.**c)). Energy converters are implemented as stationary models, e.g. the energy flow is characterized only by the nominal values of the respective energy converter. The power output/consumption and efficiency were considered critical (**Fehler! Verweisquelle konnte nicht gefunden werden.**d)).

4.2 Energy storage control

The energy storage devices are implemented as bang-bang servos which assume the state's discharge and charge (Lutz and Wendt, 2014). **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the implemented control flow diagram of an energy storage device. After starting the simulation, an initial method is called, which determines, depending on the memory configuration and the specified current filling level, whether the energy storage device is in the discharge or charge state. If the energy storage device is in the discharge or charge state, the corresponding subprogram is executed. After the respective energy store has been discharged or charged, the system checks whether the simulation time has been reached. If the simulation duration defined before the simulation start is reached, the EndSim method is executed, which prepares the results. The simulation is then ended. If the simulation time is not reached, the discharging and charging processes repeat themselves, whereby each time the loop is run, the state of the energy storage device is checked, which was previously defined in the subprograms discharging and charging.

The control flow diagrams of the subprograms for discharging and charging the energy storage devices are shown in Figure 3 and Figure 4.

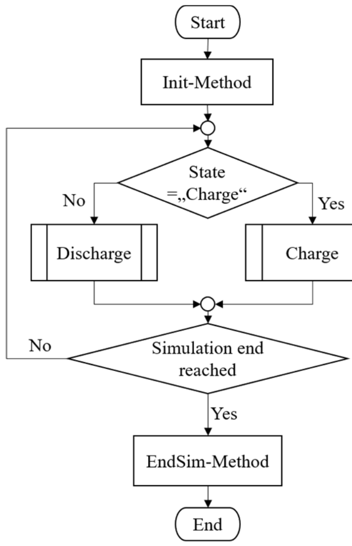

***Figure 2**: Control flow diagram of an energy storage device*

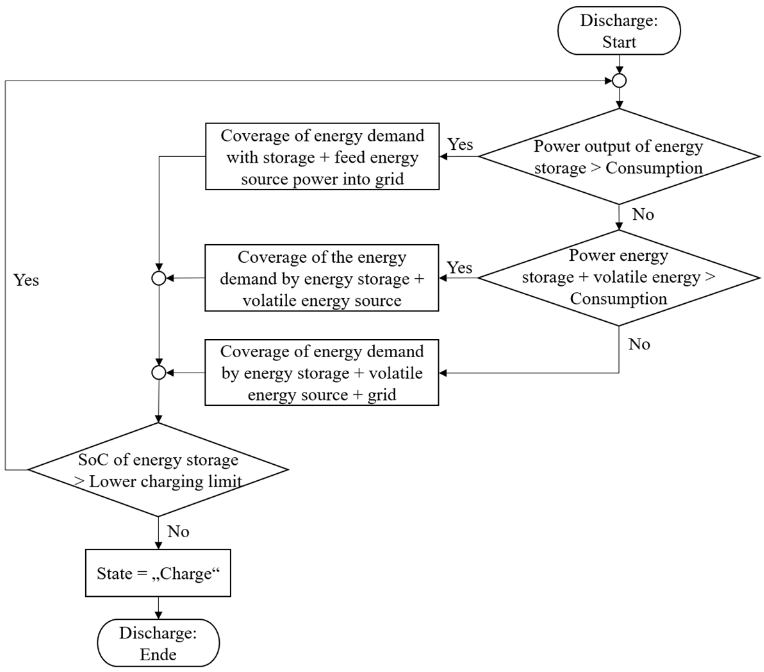

***Figure 3**: Control flow diagram for the discharging subprogram*

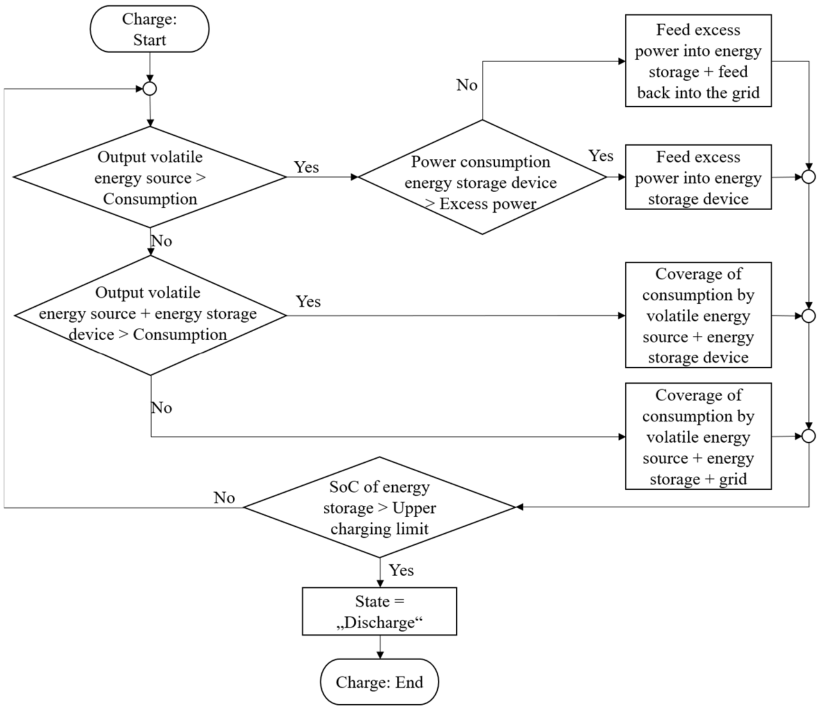

***Figure 4**: Control flow diagram for the charging subprogram*

4.3 Exemplary model of an electrical capacitor

The electrical capacitor is simplified and modelled as an RC circuit, which is used for time-discrete and time-continuous models(Steffen and Bausch, 2007). The formulas implemented in Plant Simulation for calculating the SoC and the discharging or charging are represented in formulas (1) and (2).

$$U_C(t) = |U_0| \cdot \left(1 - e^{-\frac{t}{RC}}\right) \tag{1}$$

$$U_C(t) = |U_0| \cdot e^{-\frac{t}{RC}} \tag{2}$$

with: $U_C(t) \triangleq$ voltage at capacitor at time t

$U_0 \triangleq$ nominal voltage

$R \triangleq$ electrical resistance

$C \triangleq$ capacity

$t \triangleq$ time

The energy stored in an electrical capacitor is calculated using the following formula:

$$E_{el} = \frac{1}{2} \cdot C \cdot {U_C}^2 = \frac{1}{2} \cdot Q \cdot U_C \tag{3}$$

with: $E_{el} \triangleq$ electrical energy

$Q \triangleq$ electrical charge

$U_C \triangleq$ capacitor voltage

The following equation is used to simulate the time-continuous models:

$$\mathrm{u_e(t)} = \frac{1}{\mathrm{RC}} \int \mathrm{u_e(t) - u_c(t)dt} \tag{4}$$

with: $\mathrm{u_e(t)} \triangleq$ capacitor voltage

$\mathrm{u_c(t)} \triangleq$ voltage of the power source

5 Results

This chapter presents the results of time-discrete and time-continuous simulation. First, the production system that will be used to test the given production infrastructure is defined. Finally, the loss of information is determined and visualized.

5.1 Considered production infrastructure

The models are tested using a modified version of the learning factory of the Institute for Machine Tools and Production Technology, TU Braunschweig. The assumed learning factory consists of seven production stations, of which the consumption of each individual station is known. In addition, there are feed-in capacity values for a photovoltaic and wind power plant (Schulze et al. 2019). Within this case study, the production infrastructure consists of a battery storage system, an electrical capacitor, flywheel storage, and compressed air supply (Figure 5). The production stations assembling A and B are supplied with electrical energy by the flywheel storage, the stations transport, furnace and CNC by the battery and the stations assembling and press by the electrical capacitor. In addition, all stations - with the exception of the station furnace - are supplied with compressed air. In more detail, the battery is connected to the photovoltaic system and the compressed air supply to the wind turbine. The power supply for the capacitor and the flywheel storage are provided by the grid.

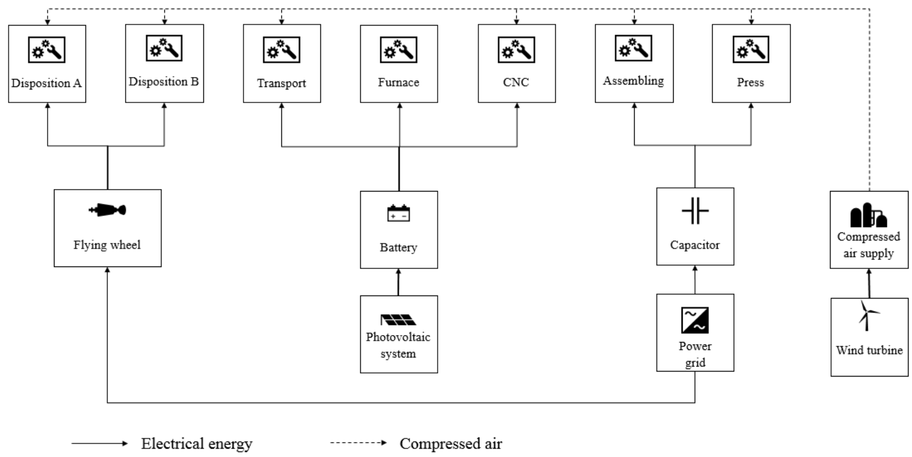

Figure 5*: Exemplary simulated production infrastructure*

The consumption of the production stations and the feed-in power of the energy sources are time series with time step Δt of 1 second. Accordingly, the SoC of the energy storage devices are also given with Δt of 1 second.

In order to obtain meaningful results, the simulation is carried out twice. The two simulation runs differ in the feed-in profiles of the volatile energy sources, the energy consumption and the configuration of the individual energy storage devices.

5.2 Determination of error measurement

This article uses two methods to determine the error measure: the mean absolute error (MAE) and the root of the mean square deviation (RMSD) (Andres and Spiwoks, 2000; Krausz, 2017). The mean absolute error indicates the average distance between the observed values of the time-discrete and time-continuous simulation of the production infrastructure and is calculated as follows:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|\hat{x}_i - x_i| \tag{5}$$

with: n ≙ number of measurements

$\hat{x}_i$ ≙ time-discrete simulation value at time t

x_i ≙ time-continuous simulation value at time t

i ≙ discretized time step

Another method which is often used is the root of the mean square deviation and is calculated as follows (Willmott and Matsuura, 2005):

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{x}_i - x_i)^2} \tag{6}$$

Due to the quadratic weighing of individual simulation values, large and small deviations are disproportionately strongly included in the evaluation (Willmott and Matsuura, 2005).

With the help of the tolerances, a statement can be made as to whether time-discrete models can adequately map energy flow systems. The permissible tolerances are 10% for MAE and 30% for RMSD (Parsons, 1997).

When looking at the deviations of the electrical capacitor, it is noticeable that the values for MAE and RMSD are relatively high in both the first and second simulation runs and are no longer within the tolerance range. Thus, the time-discrete model of the electrical capacitor cannot sufficiently represent real models. It should be noted that time-discrete and time-continuous models are simplified, which can be a reason for a significant difference.

In addition, a physical model is used for the time-continuous simulation. Furthermore, it can be observed that the values of the MAE deviate more strongly from the specified tolerances than those of the RMSD. Similar results are achieved with the flywheel, whereby the deviations of the flywheel in comparison to the electrical capacitor deviate less from the tolerance values, but still, do not lie within the tolerance range.

Table 3 shows the determined deviations of the time-discrete and time-continuous simulation of both simulation runs.

***Table 3**: Deviation of time-discrete and time-continuous simulation*

	First simulation run		Second simulation run	
	MAE	RMSD	MAE	RMSD
Capacitor	33,38%	41,09%	43,08%	54,13%
Accumulator	0,69%	0,90%	0,95%	1,25%
Compressed air supply	2,39%	5,83%	0,44%	0,65%
Flywheel	28,77%	34,50%	19,58%	24,53%

Here, physical models were also used for the time-continuous simulation and strong simplifications were assumed, which can explain the large difference. Only in the second simulation run of the flywheel, the value of 24.53% is reached with the RMSD, which is still within the tolerance range. The reason for this could be the operation between the lower and upper charge limits of 20% and 80%, which are 10% and 90% for the first simulation run. Similar effects can be observed with the electrical capacitor, where the deviation is less with a lower and upper charge limit of 10% and 90%, than with the second simulation run, where the charge limits are 1% and 99%.

With the accumulator and the compressed air reservoir, it is evident that the values show only a slight deviation between the two types of simulation. This can be explained by the fact that the same formulas were used to simulate the energy flow with the time-discrete and time-continuous models.

6 Conclusion and outlook

In this paper, the loss of information of the time-discrete simulation compared to the time-continuous simulation was investigated using the example of energy flow systems. The results of the investigations have shown that time-discrete models cannot adequately map energy flow systems and therefore too much information is lost in comparison to time-continuous simulation.

Up to now, the validation of the models for the production infrastructure is not possible due to a construction phase at the learning factory. In addition, the accumulator and the compressed air supply are shown in simplified form, which means that a physically correct representation of these two storage elements is not required (differential equations were used for the time-continuous modelling of the electrical capacitor and the flywheel).

Further research needs are divided into two main areas: On the one hand, the library of production infrastructure components presented in this article should be expanded, on the other hand, the use of co-simulation tools in connection with Plant Simulation should be researched with the aim of energy flow simulation.

Acknowledgement

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Bibliography

Alexander Sauer; Sebastian Weckmann, 2017: Dezentrale Steuerung von Energieflexibilität in der Produktion. Hg. v. Industrie 4.0 Management. Online verfügbar unter http://www.industrie-management.de/node/64.

Andres, P.; Spiwoks, M.: Prognosegütemaße: State of the Art der statistischen Ex-post-Beurteilung von Prognosen. Darmstadt: Sofia 2000.

Beier, J.; Neef, B.; Thiede, S.; Herrmann, C.: Integrating on-site Renewable Electricity Generation into a Manufacturing System with Intermittent Battery Storage from Electric Vehicles. Procedia CIRP 48 (2016), pp. 483–488.

Beier, J.; Thiede, S.; Herrmann, C.: Increasing Energy Flexibility of Manufacturing Systems through Flexible Compressed Air Generation. Procedia CIRP 37 (2015), pp. 18–23.

Europäische Kommission: Rahmen für die Klima- und Energiepolitik bis 2030: Rahmen für die Klima- und Energiepolitik bis 2030. Online verfügbar unter https://ec.europa.eu/clima/policies/strategies/2030_de.

Fuss, E.; Beißert, U.: Beitrag zur Energie- und Materialflusssimulation in Produktion und Logistik. Tagungsband 19. Magdeburger Logistiktage »Sichere und nachhaltige Logistik« (2014), pp. 39–48.

Krausz, M.: Methode zur Abschätzung der Ergebnisqualität von modularen Gesamtfahrzeugsimulationsmodellen. Wiesbaden: Springer Fachmedien Wiesbaden 2017.

Lutz, H.; Wendt, W.: Taschenbuch der Regelungstechnik: Mit MATLAB und Simulink. Haan-Gruiten: Verl. Europa-Lehrmittel Nourney Vollmer 2014.

Robert Parsons: ASHRAE handbook: 1997 fundamentals. Atlanta GA: ASHRAE 1997.

Schlegel, A.; Stoldt, J.; Putz, M.: Erweiterte Integration energetischer Betrachtungen in der Materialflusssimulation. In: Simulation in Produktion und Logistik 2013, 2013, pp. 187–196.

Schulze, C.; Blume, S.; Herrmann, C.; Thiede, S.: Energy Storage Technologies to foster Energy Flexibility in Learning Factories (2019).

Solding, P.: Increased energy efficiency in manufacturing systems using discrete event simulation, Dissertation, 2008.

Stahl, B.; Taisch, M.; Cannata, A.; Müller, F.; Thiede, S.; Herrmann, C.; Cataldo, A.; Antonio, F.C.: Combined Energy, Material and Building Simulation for Green Factory Planning. In: Nee, A.Y.; Song, B.; Ong, S.-K. (Hrsg.): Re-engineering Manufacturing for Sustainability. Singapore: Springer Singapore 2013, pp. 493–498.

Steffen, H.; Bausch, H.: Elektrotechnik: Grundlagen. Wiesbaden: B. G. Teubner Verlag / GWV Fachverlage GmbH Wiesbaden 2007.

Stoldt, J.; Prell, B.; Schlegel, A.; Putz, M.: Modellierung von volatilen erneuerbaren Energieerzeugern und Energiespeichern in der Materialflusssimulation. In: Simulation in Produktion und Logistik 2017, 2017, pp. 49–58.

Stoldt, J.; Schlegel, A.; Franz, E.; Langer, T.; Putz, M.: Generic Energy-Enhancement Module for Consumption Analysis of Manufacturing Processes in Discrete Event Simulation. In: Nee, A.Y.; Song, B.; Ong, S.-K. (Hrsg.): Re-engineering Manufacturing for Sustainability. Singapore: Springer Singapore 2013, pp. 165–170.

Wenzel, S.; Peter, T.: Simulation in Produktion und Logistik 2017. Kassel: Kassel University Press GmbH 2017.

Willmott, C.J.; Matsuura, K.: Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. Climate Research 30 (2005), pp. 79–82.