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HYBRID SYSTEM MODELING APPROACH FOR THE DEPICTION OF THE ENERGY CONSUMPTION IN PRODUCTION SIMULATIONS

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ABSTRACT

In many industrial manufacturing companies, energy has become a major cost factor. Energy aspects are included in the decision-making system of production planning and control to reduce manufacturing costs. For this priority, the simulation of production processes requires not only the consideration of logistical and technical production factors but also the integration of time-dependent energy flows which are continuous in nature. A hybrid simulation, using a continuous approach to depict the energy demand of production processes in combination with a discrete approach to map the material flows and logistic processes, shows the complex interactions between material flow and energy usage in production closer to reality. This paper presents a hybrid simulation approach combining System Dynamics, Discrete-Event and Agent-Based Simulation for energy efficiency analysis in production, considering the energy consumption in the context of planning and scheduling operations and applying it to a use-case scenario of mechanical processing of die-cast parts.

1 INTRODUCTION

Nowadays, producing companies are facing various economic and social changes. Environmental driven topics, such as global warming, CO_2 emissions and resource depletion have become strategically relevant aspects (Thiede 2012). The sustained use of energy and other resources has become a basic requirement for a company to competitively perform on the market. The design of production processes therefore requires not only the consideration of logistical and technical production conditions but also the consistent optimization of resource consumption. Based on the energy management as well as energy data acquisition systems, companies therefore record energy data and try to increase their performance in the course of their continuous improvement processes. To map the energy consumption as well as its complex interactions with material and production workflows in manufacturing, simulation models have become a common tool. They allow the process-oriented representation of the logistics and material flows in production as well as the mapping of the individual machine behavior and associated energy consumptions. Modeling different views on a production system in one approach requires the use of hybrid simulation techniques to create a holistic picture of the production. The individual simulation methods have their own graphical approaches to represent models", but they do not have obvious capabilities to depict the hybridization elements" (Brailsford et al. 2019). For this reason, one focus of this paper is placed on the conceptual model, which will be used to explain the relationship of the individual model elements of different simulation paradigms in detail. "The development of a conceptual model is a purely mental activity that involves more art than science and requires that the complexity of the physical system be reduced and controlled, keeping in mind a possible operational formalization of the model" (Trivedi and Bobbio 2017). In a hybrid simulation study, the type of hybridization and the links between the single sub-models used, have to be described, as well as the combination of modeling paradigms used. In the panel discussion on hybrid simulation at the Winter Simulation Conference 2018, Eldabi et al. (2018) stated, that conceptual modeling for hybrid simulation is not well developed. Individual simulation methods all have their own approaches for conceptual models, but hybridization elements are not modeled so far. Questions to answer with a conceptual model include how the sub-models are interrelated, what information is exchanged, and how process flow models, state charts, and stock flow models can be combined in one approach.

The paper is structured as follows. Section 2 outlines required definitions, includes a short literature review and presents the conceptual framework for the hybrid simulation model. Section 3 describes the structure of the simulation model with its single components and interaction points. Section 4 outlines the model implementation in Anylogic. Section 5 concludes with specific recommendations on future research.

2 HYBRID SYSTEM MODELING APPROACH FOR PRODUCTION PROCESSES

2.1 Definitions and Related Work

Tolk (in Mustafee et al. 2017) defines hybrid -biologically and technically speaking- as "the result of merging two or more components of different categories to generate something new, that combines the characteristics of these components into something more useful. A mule is a biological hybrid, the crossbred of a donkey and a horse with better endurance and a longer useful lifespan than its parents (…) Hybrids take two – or more – components and create something better". The reason for mixing methods is that real world problems are usually very complex and neither completely event-discrete, nor completely continuous. "They require different methods to address the multiplicity of dimensions of a problem. Additionally, all methods have different strengths and weaknesses so mixing methods can overcome the limitations of one method" (Mustafee et al. 2017). This paper follows the definition of hybrid simulation according to Brailsford (in Mustafee et al. 2017): "Hybrid simulation is one single conceptual model that, when implemented in a computer software, uses more than one simulation paradigm". The hybrid simulation is usually applied in the implementation stage of a simulation. At this point, it is important to differentiate hybrid simulation from hybrid systems modelling (HSM), which describes the combination of simulation techniques with methods from other disciplines such as Applied Computing, Computer Science, Systems Engineering, and Operations Research, to name for example problem structuring methods, forecasting, classical optimization techniques, process mining, data mining, and machine learning (Mustafee and Powell 2018). HSM is not only used in the implementation phase of the simulation study life cycle but can also be applied in the conceptual modeling phase, the model verification and validation phase, as well as in the experimental stages. In his work, Chahal (2009) defines a spectrum for modeling, analysis, and synthesis of hybrid systems, having hybrid approaches which constitute the extension of continuous systems to model discrete events on the one end and "on the other end (…) discrete models extended to represent the behavior of continuous models". In between those two extrema, mixed discrete and continuous approaches combining complementary aspects of both techniques can be found.

The way information is exchanged over time progress between sub-models has to be defined. Generally, there are two modes of interaction for sub-models, they can perform cyclic or parallel interaction. In cyclic interaction mode, the interaction takes places after completing a simulation run, when discrete outputs are used to feed the continuous sub-model and vice versa. In the parallel interaction mode, discrete and continuous models are run simultaneously and exchange information during runtime, thus continuously and discrete changing elements affect each other directly (Chahal 2009).

"Variables whose values are changed or influenced by variables of the other model and variables which replace or influence the values of variables of the other models during hybrid simulation (…) [are] named (…) interaction points" (Chahal 2009). These interaction points (IP) function as interfaces between the sub-models and, in combination with the interaction mode, combine them into a holistic model. Chahal (2009) defines a three-stepped procedure to build hybrid models, which can easily be integrated in the typical lifecycle of a simulation study: (1) problem identification and justification to use hybrid approaches, (2) identification of interaction points of System Dynamics (SD) and discrete simulation paradigms (discrete event simulation (DES) and Agent-based Simulation (ABS), and (3) identification of a mode of interaction for the models (Figure 1).

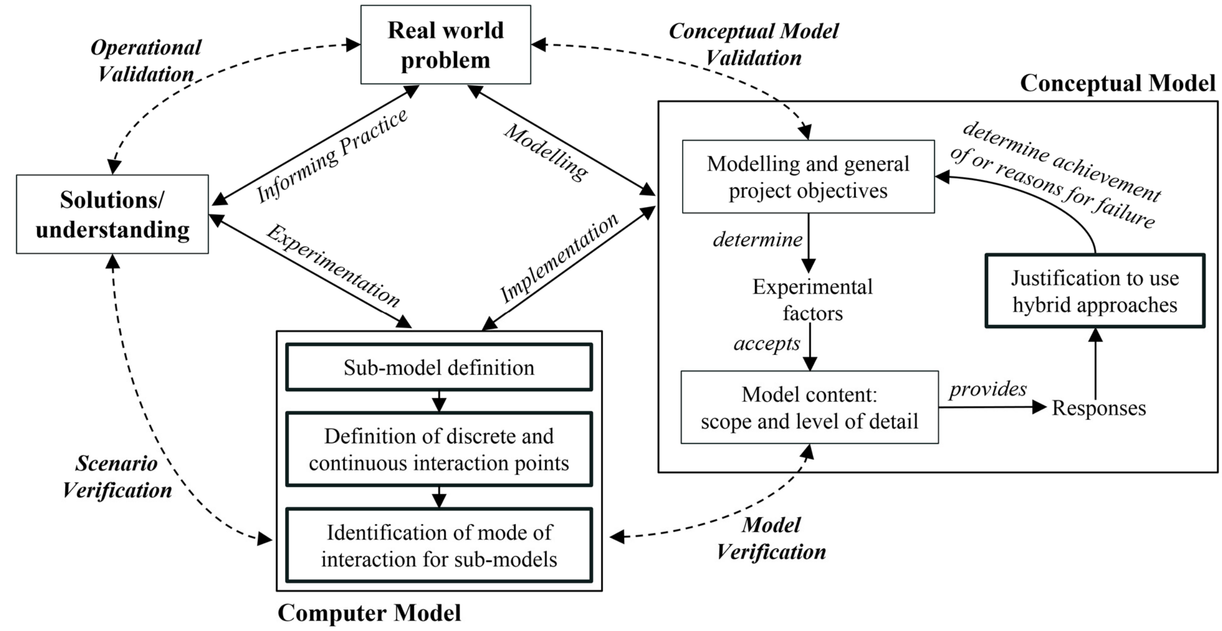

Figure 1: Stages of a hybrid simulation study (adapted from Robinson 2008; Eldabi et al. 2018; Chahal 2009).

Prior to the actual modeling process, in the conceptual phase, the modeler must think about the nature of the system to be able to find a fit between the modeling paradigms, the modeled system, and the problem (justification to use hybrid approaches). The level of abstraction as well as the views on a system must be defined, followed by a linking of paradigms to the levels of abstraction. Djanatliev and German (2015), differentiate between a horizontal and a vertical paradigm linking. The depiction of concrete implementation scenarios and the linking of certain simulation paradigms to the model structure is defined as horizontal paradigm linking. "The main task is to determine whether continuous structures are relevant (i.e. SD), processes have to be traversed (i.e. DES), or an individual behavior is necessary (i.e. ABS)" (Djanatliev and German 2015). Finally, the identified sub-models need to be connected and the interactions between the simulation paradigms SD, DES, and ABS need to be identified and made (vertical linking of simulation paradigms). Following Pritsker (1995), three basic forms for linking discretely changing and continuously changing state variables can occur in hybrid simulation models: (1) A discrete event can cause a discrete change in the value of a continuous state variable. (2) A discrete event can change the relationships that determine the behavior of a continuous state variable at a particular time. (3) Reaching a defined limit by a continuous state variable can trigger a discrete event. For a straight forward model development, especially when combining different simulation paradigms, a structured concept helps to achieve sustainable results.

A number of approaches using hybrid simulation can be found in research and industrial practice. Extensive state-of-the-art analyses have been carried out by different authors, e.g., Djanatliev and German (2015), Roemer and Strassburger (2016), and Brailsford et al. (2019). An example for the use of hybrid simulation is the depiction of the energy consumption in production simulations. The coupling of discrete-event production and continuous energy models can be seen in various research approaches in different solutions. While Schmidt and Pawletta (2014) solve the coupling of two simulation models through the use of the Discrete Event System and Differential Equation System Specification (DEV&DESS) approach from the field of systems theory in MATLAB, Peter and Wenzel (2015) and Schlueter et al. (2017) make use of a communication or control platform to parameterize, control, and synchronize bidirectional interactions between the material and the energy flow. Pawletta, Schmidt, and Junglas (2017) build a hierarchical structure of individual models with different dynamical behavior to create a dynamic hybrid model using several packages in MATLAB.

2.2 Concept Objectives and Requirements

Derived from an extensive literature analysis, the requirements for a hybrid simulation approach for the dynamic depiction of energy consumption in production can be determined (Roemer and Strassburger 2016). The methodology shall contain all relevant material and energy flows and their dynamic interdependencies to increase transparency in production towards improvements and to outline conflicts and contradicting requirements, to support the optimization of critical parameters. Ideally, the hybrid simulation paradigms are implemented in one software tool to provide a holistic view without the complexity of interface management, complex data exchanges, and synchronization requirements. The methodology shall be build up modular in order to allow for flexible coupling and fast adaptation of single system components. A high grade of configuration and parameterization elements is desirable to ensure an uncomplicated implementation for a wide range of production cases without causing high efforts for case-specific adaptations. The integration of existing database data sets shall be included to support a forecasting of energy requirements for unanalyzed combinations of operating machines, process scheduling tasks and process parameters. A dynamic visualization of results is required for a full documentation of improvements. To avoid unnecessary repetitions of implementation steps, to support the individual implementation phases by means of proven procedures, and to minimize the overall implementation time as well as expenses for system and data maintenance, application guidelines have to be formulated.

2.3 Conceptual Framework

The simulation of the material and energy flows in a production requires the use of different simulation paradigms for a realistic depiction of the various aspects. Djanatliev and German (2015) introduced a user guide for hybrid modeling and validated it with an example of a problem in the healthcare sector. In this paper, we apply the methodology on a hybrid simulation model for the energy consumption modeling in production (Figure 2). As in the healthcare example, four abstraction levels are identified. On a macro level, the total energy consumption of the entire production is being relevant. The energy consumption flow is continuous in nature and therefore SD is the appropriate simulation paradigm. Besides, it is possible to perform input data updates using DES. The material flow and the production process landscape are presented on the meso level, represented by the process-oriented DES. While the machine behavior is treated as a black box on the meso level, the detailed structures, i.e. the process behavior of the single machines, are presented on the micro level. In addition to the machine states triggered and demanded by the material flow, the behavior of the machines includes the self-determined change of the machine states in production-free times (e.g. switching from idle to standby or from standby to off mode). ABS state charts are used to model the machine behavior. Again, single input data updates are performed using DES techniques. While the agents can act actively on the micro level, the internal level processes are usually passive. The energy consumption process on single machine level is again continuous in nature and can be represented using the SD paradigm.

Material flow and process changes on meso and micro level affect the total energy consumption of the production. Changes on macro level, e.g. the definition of a new total allowed energy consumption in form of restriction will affect the workflow on meso level by demanding more efficient processes. Interactions between meso and micro levels take place, when the work flow entities (parts) run through the processing by the agents (machines). The agents can cause delays on the meso level when their state is not production ready as demanded by the workflow. On the other hand, the workflow can affect the agent's behavior by not delivering entities and forcing the agent to adapt its machine behavior due to process changes, making them behave as efficient as possible with regards to the overall objectives defined on macro level.

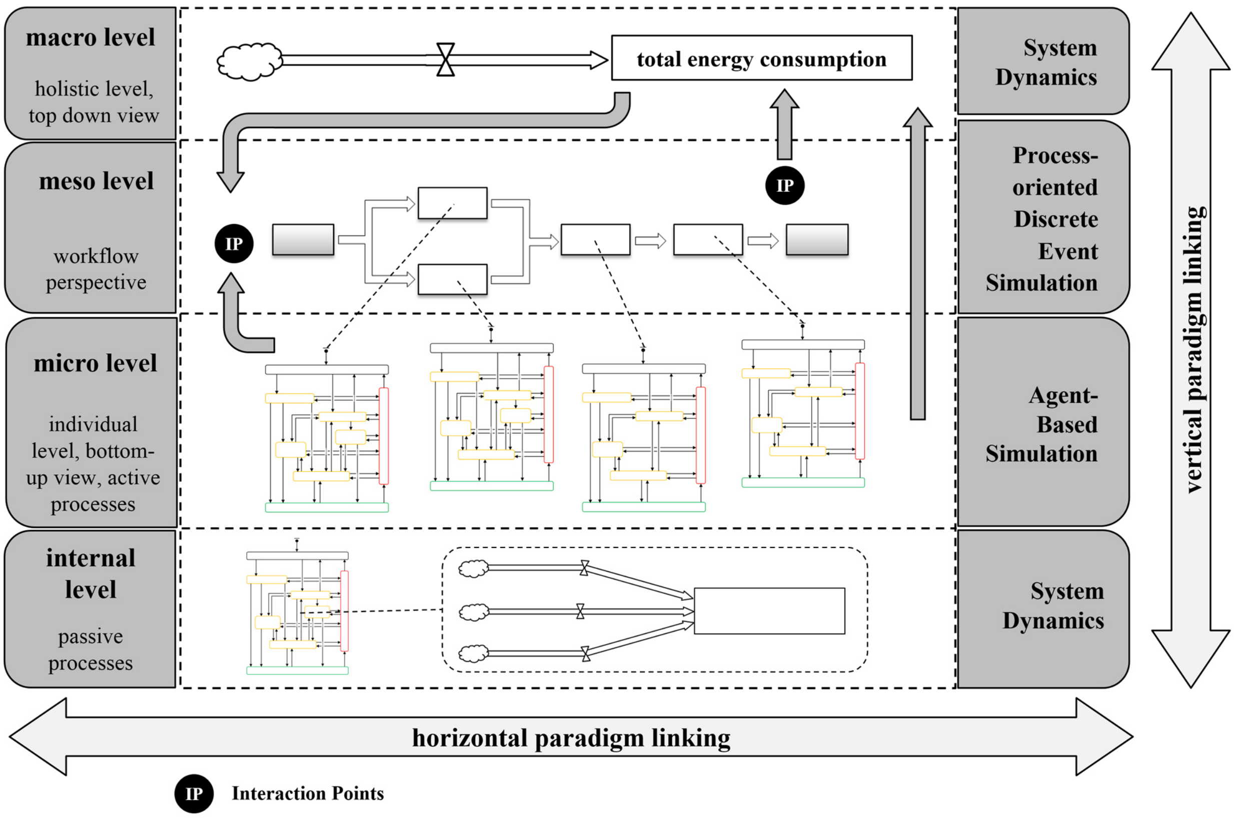

Figure 2: Overview of the hybrid simulation approach for the energy consumption model of a production (adapted from Djanatliev and German 2015).

For the implementation of the simulation approach in Anylogic, the concept described above implies the need to define three building blocks, a production flow brick to depict the meso level, a machine brick to picture processes on micro level, and an energy brick for the depiction of the macro level and passive processes, all based on different simulation paradigms as shown in Figure 2 and described in detail in section 3.

3 STRUCTURE OF THE SIMULATION MODEL

3.1 Production Flow Brick

The production flow brick describes the event-based flow of parts through machine components and machines and comprises relevant production flow and production planning parameters. The structure of the entity-based production flow model includes all main electrical consumers that make a significant and immediate contribution to the execution of the production processes. To meet the minimum requirements needed to depict the behavior of the production on the one hand and to keep the model as simple as possible on the other hand, supporting processes such as the transport and storage of material are initially only considered in the model with the time delay they cause, but not for the calculation of the energy consumption as their share of the total energy consumption is low compared to the production processes. The process flow can generally be modeled and visualized using the standard blocks of available simulation software solutions. The model of the considered production area must have a defined start and a defined ending and should not include reverse flows, as they normally do not occur in production. Upstream and subsequent processes of the defined viewing area are represented by a source or sink symbol. Thus, the material flow and the model boundaries are defined. The modeling of the material flow requires the specification of batch sizes and, associated therewith, the installation of buffers and blockers to ensure compliance of batch sizes in the production line. In connected production flows with multiple processing options, flow dividing and combining elements are implemented with a defined splitting logic. The number of parameters and data to be collected is highly dependent on the model purpose and defined investigation targets. Following the VDI standard 3633 (VDI 2014) for production simulation, the required simulation input data for the material flow simulation is divided into system load, organizational and technical data.

3.2 Machine Brick

The machine brick is used to model the process control operations of the production and functions as a control unit for the different production states of the modeled production machines. It also comprises all relevant parameters and required information to assess the system behavior of single production machines. The machine brick represents the operational inside of the machines shown in the material flow.

The machine behavior can be depicted using state graphs and is subsequently referred to as "machine logic". The machine logic includes all possible operational machine states as well as allowed transitions between single states. Three basic types will be defined which can easily be customized through various parameters and specified restrictions for each machine (Figure 3). Every machine enters its machine logic through the initial state, which does not consume any model time or energy. Depending on the operation complexity of the machine, the complexity type of the machine logic is chosen and can be assigned to the machine in the DES model.

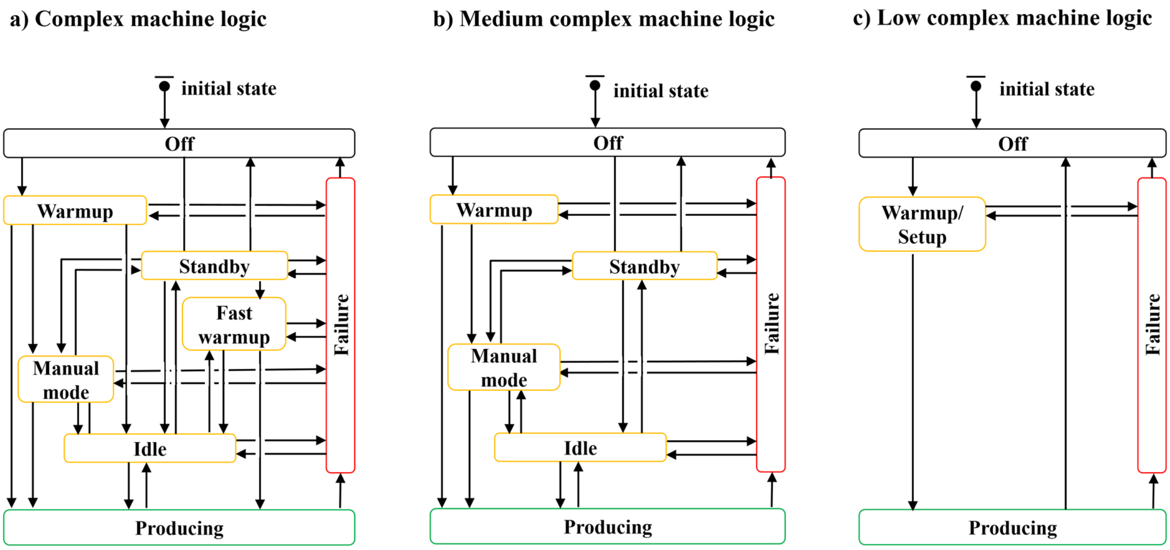

Figure 3: Machine logic types.

The production machines go through different operating states, whose time sequence and duration are affected and determined by technical requirements and dependent on production quantities and time tables. An exception is the failure state, which is usually entered unplanned. Rohrer (1998) proposes four options to handle machine downtimes. They can either be ignored, which is probably the most chosen variant, they can be included by adjusting processing times, considered as constant values for time-to-failure and time-to-repair, or as a fourth option, statistical distributions for time-to-failure and time-to-repair can be used.

The energy requirements of the individual operating states of a machine can vary greatly in terms of height and curve progression. While some operating states might rather be constant over a longer period of time, others have a highly volatile energy consumption profile. Some operating states, e.g. the warm up and setup state, have a defined length which is technically required to set the machine ready for production, while for others the retention time of a machine in that state is dependent on the production task and quantity. The required parameters to map the machine behavior in a realistic manner, need to be included in the machine logic. To structure the machine behavior, allowed machine state transitions must be defined. Equally important is the definition of machine state restrictions, e.g. a minimum duration of a state. Besides structural data, production data is required to picture the production processes. Important production parameters for a simulation are setup times, production cycle times, as well as data on performance, capacity, throughput, and batch sizes.

3.3 Energy Brick

The energy brick is used to model the energy consumption behavior of production machines continuously for any possible moment in time. The mapping of the energy consumption is done using stock and flow elements of the SD library. Every machine has its energy consumption profile, which can be split up in sequences and then be assigned to different energy states which are differentiated according to time and optimization aspects and can be split up into three groups, technically relevant operations, value-adding, and non-value-adding operations. The sum of all productive machine times is included in the energy flow which represents the value-adding machine operations, the energy flow for the technically required operations includes the warmup, fast warmup, and setup times of all machines, and the energy flow of the non-value-adding operations summarizes all machine times of standby or idle mode. The single energy consumption profiles of the machines sum up to an energy consumption flow of a production line and finally to the total energy consumption of the entire production area. The load profiles of a machine can be created in three ways. They can either be measured and assigned using real production data, they can be represented in form of mathematical functions, or it is possible to work with individual energy values, which were formed as an average and are assumed to be constant over the duration of an entire energy state. The use of mean values instead of the real energy consumption profile is going strong at the expense of a realistic representation of the energy consumption but has the advantage of low data acquisition and storage efforts. The creation of mathematical functions to describe the energy consumption profile requires a lot of effort in the process of function approximation, but also brings the big advantage of simple storage options with it, since only single function parameters and no big data tables must be stored. Nonetheless, the predictive quality of mathematical functions is highly dependent on the approximation quality. The usage of value tables or table functions causes probably the most accurate prediction quality and the least creation efforts even though the required technical installations for measuring the data as well as the required memory to store the data is higher and the implementation of the data access in the simulation model might be more complicated.

While the machine behavior is expressed using the machine logic with its machine states, the energy consumption behavior can be represented adding up different energy states over time. Continuous variables for the energy state are created by considering the ratio of the passed time in a state and the remaining time. Those variables are required to be able to picture the consumption behavior at any moment in time, even in between single events of the event-based part of the simulation model. They can also be used for the optimized timing of machine startups in the production line, as they allow the calculation of the remaining time until a waiting machine has to be ready for its production process.

3.4 Interaction Point Definition

The three presented sub-models describe different aspects of a production. In order to combine the three sub-models to a holistic production simulation, it is required to define all necessary interaction points. The process and the energy brick are coupled via the machine and the energy state. With the defined system throughput, shift and working schedules, material requirements and production orders, the production flow brick functions as a pace maker for the entire simulation module. The production flow brick is directly linked to the machine brick. It triggers the machine logic with events which are planned or taking place in the production flow (Figure 4). Planned production orders for example affect the process logic of the production machines, as the machines must be in a production-ready state, as soon as the production order processing time starts.

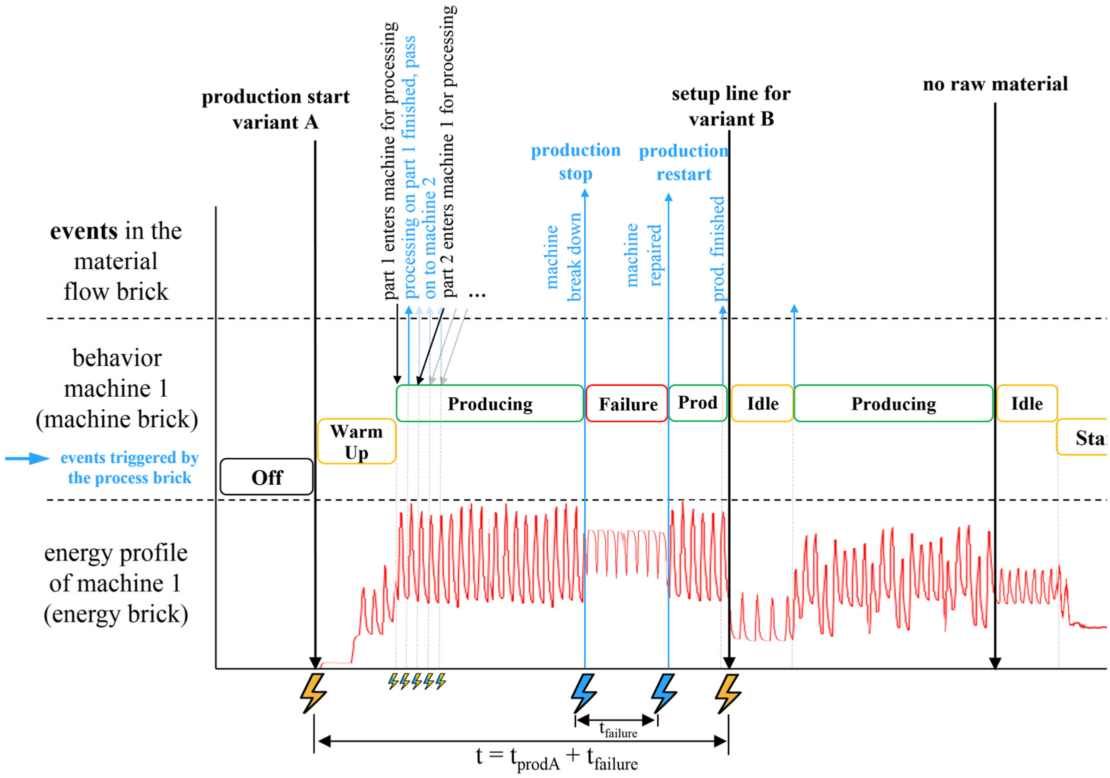

Figure 4: Effects of events triggered in the process brick on the material flow.

The machine logic is triggered again, when parts actually enter the individual machines of the production line. The delay in material flow a machine causes is not defined in the DES material flow model, as it would be done in a purely event-based simulation model but is calculated summing up the process times of the single operating states of the machine logic. Parallel to the machine state sequence running in the machine logic, the load profile of the simulated machines is displayed in the energy brick. The information about the completion of the machining process on a part must then be given back to the material flow brick in order to trigger the next steps of the material flow, such as transferring the part from the machine to a parts buffer or the next machine accordingly. In principle, every event that occurs in the material flow brick triggers a change of the machine and the energy state in the other two bricks. Likewise, the processes in the machine brick influence the events of the material flow. In the machine logic, all steps of processing every individual part are shown. If the processing time of part x is over, this information is transferred to the material flow brick. Subsequently, part x leaves the machine and the next part y is brought to the machine for processing. The two bricks are in a permanent exchange of information through which actions and reactions in form of events are created. While the lack of raw material forces the machine to stop producing and switch to an unproductive state, the change of states initiated by the machine, e.g. in the case of a machine breakdown, will unlikely interrupt the material flow and can postpone material flow events.

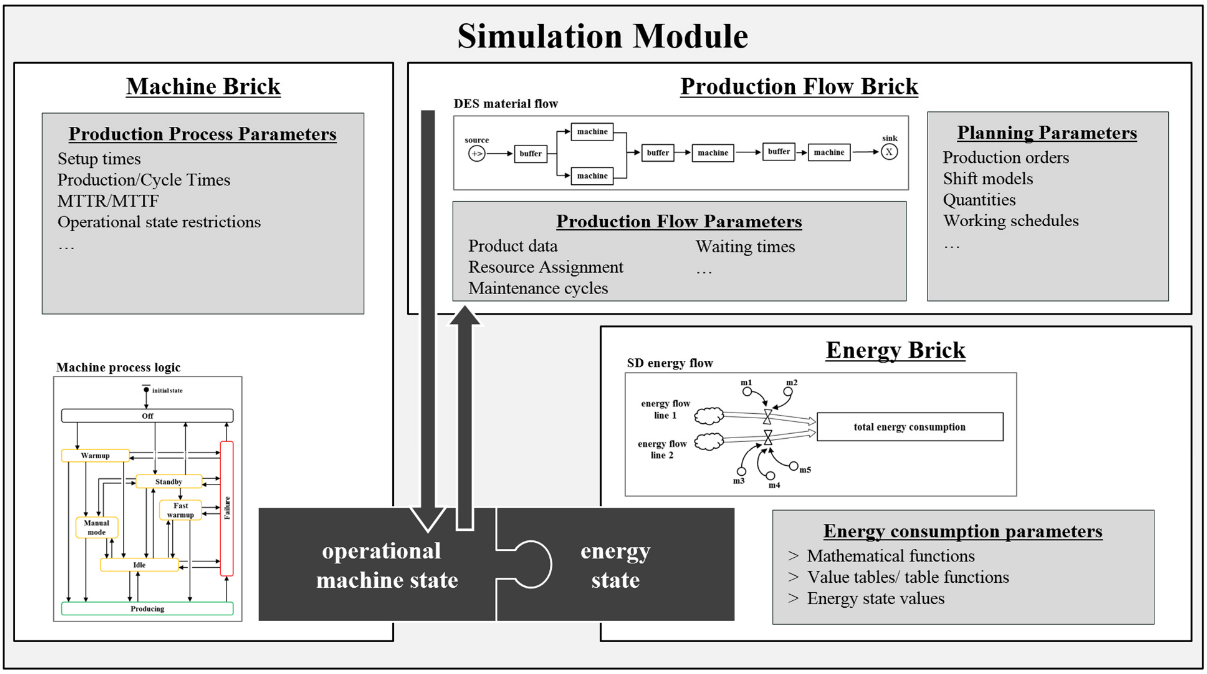

Figure 5: Conceptual structure of the simulation module.

The three sub-models can be combined to form a holistic production model (Figure 5). The energy consumption is closely linked to the machine behavior. The interaction point clearly consists of the assignment of the corresponding energy load profiles to the machine states. The machine conditions are in turn influenced by the material flow in the production line. Likewise, the behavior of the machines influences the occurrence of events in the material flow, such as the failure of a machine. To ensure a smooth interoperability of the sub-models, all interdependencies must be clearly defined and considered via events, dynamic parameters, functions, and restrictions in the simulation model.

The hybrid simulation model is build up, using historical production and energy data. If the model realistically reproduces the processes in production and the associated energy consumptions data, it can be run using forecast data to simulate future energy consumption profiles of the production area. These data can then be used in terms of energy efficiency optimizations for peak load avoidance, energy-efficient machine scheduling, as well as for the reduction of non-value-adding machine times.

4 MODEL IMPLEMENTATION AND EXPERIMENTAL VALIDATION

4.1 Implementation of the Hybrid Simulation Method in Practice

The implementation of the simulation methodology was performed in Anylogic 8, a simulation tool which supports multi-paradigm simulation. The prototypical implementation is done using an anonymized production scenario from a foundry, focusing on the final processing steps of pre-fabricated parts. The production scenario comprises a production line for the mechanical processing of large die-cast parts with a total of five machines. First, the parts are machined on one of the two CNC (Computerized numerical control) machines. Subsequently, holes and threads are drilled in the drilling machine, followed by a sandblasting process. Afterwards, the parts are grouped in lots of twelve and are cleaned in an industrial washing machine. The production line is operated in a two-shift mode. For all five machines, a preventive maintenance schedule exists with weekly occurring services. The produced quantities are highly dependent on the customer’s orders, but a maximum quantity of 60 parts per shift cannot be exceeded. Processing times, durations of technically required machine states and other relevant key figures are considered in the simulation model. The matching of machines states and energy consumption profiles is done comparing two options. All machines went through a controlled state simulation to be able to precisely allocate the energy consumptions to the respective machine states. This method is very time consuming, as it causes the shutdown of a production line for the duration of the tests of all states. To avoid manual machine state simulations, Teiwes et al. (2018) developed a load profile clustering (LPC) algorithm using only electrical load profiles and processing times to identify different load levels such as processing and waiting times of machines. The five-step approach is based upon a k-means clustering algorithm and aims at a simplification of energy allocation. The automated extraction of state-based machine information from available load profile data in combination with a manual processing cluster assignment saves time compared to the machine status simulation and leads to reliable results.

The hybrid model is built up in Anylogic using the process modeling and the SD library as well as the agent components and the state charts. Several variables, parameters and functions are in use to capture relevant interactions between the different model levels. For the model validation, the model logic has been crosschecked several times before it was used to reproduce a number of production days of historical data. After repeated fine-tuning of the modeled material flow parameters as well as multiple revisions of the entered machine state transition rules the hybrid simulation reproduced the production data with a deviation of less than 3.2 percent.

Through different simulation experiments with a varying machine scheduling, batch size variations for individual machines of the production line and the deliberate avoidance of non-value-added machine states, it was possible to test how the energy consumption of the production can be reduced without negatively affecting the total daily output. By starting the CNC machines with a slight offset, peak loads in the total consumption of the production line have been reduced by nearly 7 percent.

4.2 Simulation Results and Discussion

The practical implementation has shown that it is possible to build a hybrid simulation model, using the three modeling paradigms SD, DES, and ABS for representing the energy consumption behavior in production on the basis of historical data. It was also pointed out that the simulation model, in combination with forecast figures regarding quantities and planned schedules, can be used to map the future consumption very precisely with its upcoming peak loads and non-value-adding production phases.

The occurring deviation of 3.2 percent per shift can be explained considering machine failures in the real production. As the machine failures can hardly be predicted correctly, they have not been considered in the hybrid model. As they occurred in practice, but not in the model, the part numbers produced in the simulation runs have been slightly higher than in practice. For future simulation runs, it is possible to consider a failure probability for all machines in the machine logic if the focus is on getting the output numbers of the model closer to the ones in the real production. In this test we have not considered failures, as the timing of failures in the model will always be different from their actual future occurrence in production. Therefore, our focus was clearly on the detection of possible consumption peaks, which might stay undetected due to a machine failure occurrence in the model.

While energy monitoring systems are gradually being recognized and installed as efficiency tools in many companies, an accurate tracking of the energy consumption on machine level in a very detailed resolution is rather the exception. To grant flexibility in case load data is not available, the simulation approach has been tested with mean values instead of energy load profiles. For each machine state a mean value has been added as a parameter, which is taken as the consumption value for the entire duration of the state. While this did not have any influence on the detection and avoidance of unproductive states and only a small deviation regarding the total energy consumption of the line through the use of mean values was noticed, the existing peak loads in the consumption profiles disappeared (Figure 6). The model accuracy should therefore be chosen depending on the objective of the investigation. A combination of the use of energy data tables and mean values is also conceivable if, not all machines have yet been connected to the energy data acquisition in a production, but should already be taken into account.

Figure 6: Comparison of the accuracy of the production line data with and without the SD in the simulation model.

5 CONCLUSIONS AND FUTURE WORK

The aim of the presented approach is the depiction of combined material and energy flow simulation in production to create a realistic model showing the dynamic behavior of the energy consumption in production process. The use of a multi-method simulation software simplifies the hybrid modeling process. The complexity of interface management, complex data exchanges, and synchronization requirements are reduced compared to the usage of different software packages for the single simulation paradigms. Occurring peak demands and time-continuous energy consumption can be shown closer to reality compared to DES models based on measured operating states, which are considered to be constant over a defined period of time. Our future work is to extend the hybrid simulation approach by an integrated optimization to focus on the simulation-based optimization of complex production lines with its interactions and dependencies. Energy efficiency optimizations for peak loads, energy-efficient machine scheduling, and the reduction of non-value-adding machine times are only three scenarios that can be used to reduce energy consumption in an existing production area to reduce manufacturing costs.

REFERENCES

Brailsford, S. C., T. Eldabi, M. Kunc, N. Mustafee, and A. F. Osorio. 2019. "Hybrid Simulation Modelling in Operational Research: A State-of-the-art Review." *European Journal of Operational Research* 278(3):721–737.

Chahal, K. 2009. *A Generic Framework for Hybrid Simulation in Healthcare*. Ph.D. thesis, School of Information Systems, Computing and Mathematics, Brunel University, London. https://bura.brunel.ac.uk/bitstream/2438/4711/1/FulltextThesis.pdf. Accessed 19.07.19.

Djanatliev, A. and R. German. 2015. "Towards a Guide to Domain-specific Hybrid Simulation." In *Proceedings of the 2015 Winter Simulation Conference,* edited by L. Yilmaz, W. K. Chan, I. Moon, T. M. Roeder, C. M. Macal, and M. D. Rossetti, 1609–1620. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Eldabi, T., S. Brailsford, A. Djanatliev, M. Kunc, N. Mustafee, and A. F. Osorio. 2018. "Hybrid Simulation Challenges and Opportunities: A Life-Cycle Approach." In *Proceedings of the 2018 Winter Simulation Conference,* edited by M. Rabe, A. A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, 1500-1514. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Mustafee, N., S. Brailsford, A. Djanatliev, T. Eldabi, M. Kunc, and A. Tolk. 2017. "Purpose and Benefits of Hybrid Simulation: Contributing to the Convergence of its Definitions." In *Proceedings of the 2017 Winter Simulation Conference,* edited by W. K. Chan, A. D'Ambrogio, G. Zacharewicz, N. Mustafee, G. Wainer, and E. H. Page, 1631–1645. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Mustafee, N. and J. H. Powell. 2018. "From Hybrid Simulation to Hybrid System Modelling." In *Proceedings of the 2018 Winter Simulation Conference,* edited by M. Rabe, A. A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, 1430–1439. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Pawletta, T., A. Schmidt, and P. Junglas. 2017. "A Multimodeling Approach for the Simulation of Energy Consumption in Manufacturing." *SNE Simulation Notes Europe* 27:115–124.

Peter, T. and S. Wenzel. 2015. "Simulationsgestützte Planung und Bewertung der Energieeffizienz für Produktionssysteme in der Automobilindustrie." In *Proceedings of the Simulation in Production and Logistics 2015*, edited by M. Rabe and U. Clausen, 535–544. Stuttgart: Fraunhofer Verl.

Pritsker, A. A. B. 1995. *Introduction to simulation and SLAM II,* 4th ed., New York: Halsted Press.

Robinson, S. 2008. "Conceptual Modelling for Simulation Part I: Definition and Requirements." *Journal of the Operational Research* Society 59(3):278–290.

Roemer, A. C. and S. Strassburger. 2016. "A Review of Literature on Simulation-based Optimization of the Energy Efficiency in Production." In *Proceedings of the 2016 Winter Simulation Conference,* edited by T. M. Roeder, P. I. Frazier, R. Szechtman, and E. Zhou, 1416–1427. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Rohrer, M. W. 1998. "Simulation of Manufacturing and Material Handling Systems." In *Handbook of Simulation,* edited by J. Banks, 519–545, New York, Wiley; Co-published by Engineering & Management Press.

Schlueter, W., M. Henninger, A. Buswell, and J. Schmidt. 2017. "Schwachstellenanalyse und Prozessverbesserung in Nichteisen-Schmelz- und Druckgussbetrieben durch bidirektionale Kopplung eines Materialflussmodells mit einem Energiemodell." In *Proceedings of the Simulation in Produktion und Logistik 2017*, edited by S. Wenzel and T. Peter, 19–28. Kassel: Kassel University Press GmbH.

Schmidt, A. and Pawletta T. 2014. "Hybride Modellierung fertigungstechnischer Prozessketten mit Energieaspekten in einer ereignisorientierten Simulationsumgebung." In *ASIM 2014, 22. Symposium Simulationstechnik; Tagungsband,* edited by J. Wittmann and C. Deatcu, 109–116. Wien: ARGESIM /ASIM.

Teiwes, H., S. Blume, C. Herrmann, M. Rössinger, and S. Thiede. 2018. "Energy Load Profile Analysis on Machine Level." *Procedia CIRP* 69:271–276.

Thiede, S. 2012. *Energy Efficiency in Manufacturing Systems*, Berlin Heidelberg: Springer-Verlag.

Trivedi, K. S. and A. Bobbio. 2017. *Reliability and availability engineering. Modeling, analysis, and applications*, Cambridge: Cambridge University Press.

VDI Verein Deutscher Ingenieure e.V. *VDI 3633:2014-12: Simulation of systems in materials handling, logistics and production. Fundamentals* ICS 03.100.10, Last modified 12.2014 Accessed 12.02.18, Berlin: Beuth Verlag.

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