APPLICATION OF DISCRETE-RATE BASED MESOSCOPIC SIMULATION MODELS FOR PRODUCTION AND LOGISTICS PLANNING

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ABSTRACT
The paper describes and analyzes the application of mesoscopic discrete-rate based simulation models for production and logistics planning tasks in comparison with microscopic discrete-event simulation models. Mesoscopic models represent logistics flow processes on an aggregated level through piecewise constant flow rates by applying the discrete-rate simulation paradigm instead of modeling individual flow objects. This leads to a fast model creation and computation.

Keywords: Discrete Rate Simulation, Mesoscopic Simulation, Production and Logistics Planning

1. INTRODUCTION
The principles and tools of discrete-event simulation (Schriber and Brunner 2008; Banks 2005; Law and Kelton 2007; Kosturiak and Gregor 1995) are utilized to implement discrete models. Discrete-event simulation models are widely used for simulation modeling in manufacturing and logistics and state of the art in production planning and logistics planning in the automotive industry (Huber and Wenzel 2011). Production and logistics planners prefer to use discrete-event models since most of the logistics processes are discrete (Scholz-Reiter et al. 2007).
The term discrete-event modeling stands “for the modeling approach based on the concept of entities, resources and block charts describing entity flow and resource sharing” (Borshchev and Filippov 2004). Since discrete-event models are able to represent workstations, technical resources, carriers and units of goods as individual objects, they can depict production and logistics systems with a high level of detail and are also referred to as microscopic models (Borshchev and Filippov 2004, Pierreval et al. 2007). Models in this class can be very complicated and slow and their creation and implementation can be time and labor consuming (Pierreval et al. 2007; Law and Kelton 2007; Kosturiak and Gregor 1995; Huber and Dangelmaier 2009; Scholz-Reiter et al. 2008).
Plant Simulation is the standard tool in the German automotive industry for the development and application of discrete-event simulation models. A survey in a German automotive OEM with 29 participating production planners (Schauf 2016) shows that 96.6 % of the production planners consider the application of simulation models in the production planning process as ‘absolutely necessary’, ‘very important’ or ‘important’. Only 3.4 % of the production planners answered that simulation modeling is not important for production planning. Production planners see the following requirements in the given order as most important for a simulation model to fulfil:

1. high quality of results,
2. quick provision of results,
3. transparency,
4. easy configuration of the simulation tool and simulation model, and
5. usability of tools and models for a production planner.

The reality though differs from the requirements and wishes of the production planners. Simulation projects to support production planning projects in the automotive industry often take quite a long time.
More than 60% of the simulation projects require more than a month and 30 % of the simulation projects even take more than six months (Schauf 2016). This contradicts the requirement of the production planners for a quick provision of the simulation results.
Problem formulation, system analysis, data collection and validation, conceptual modeling and model implementation together can require up to 85 % of the total time of a simulation project. Conducting and analyzing experiments often take less than 20 % of the total time of a simulation project. (Schauf 2016, Huber and Wenzel 2011)
One reason for long lasting simulation projects could be the application of discrete-event simulation models. Discrete-event models with a lot of entities flowing through the model or models with a too high level of detail can be associated with a high effort for modeling and computation of the model. (cf. Kuhn and Rabe 1998; Law and Kelton 2007; Feldmann and Reinhart 2000; Scholz-Reiter et al. 2008; Kosturiak and Gregor 1995).

A feasible approach to reduce the time for a simulation project is to apply simulation models with less level of detail. Reggelin (2011) and Reggelin and Tolujew (2011) describe a mesoscopic simulation approach to solve planning tasks in production and logistics systems which is based on the discrete-rate simulation paradigm (Krahl 2009, Damiron and Nastasi 2008).

A lower level of detail usually goes along with less accurate simulation results. The survey of Schauf (2016) asked the production planners which margin of error they are willing to accept, see Figure 1. The willingness to accept errors decreases with an increasing duration of a simulation project. Production planners are ready to accept errors of 5 % for simulation project which take less than a week. In simulation projects with a duration of more than six months they are willing to accept an error of about 1.5 %. These results could mean that production planners would accept to work with models which have not such a high level of detail but are capable of providing simulation results faster.

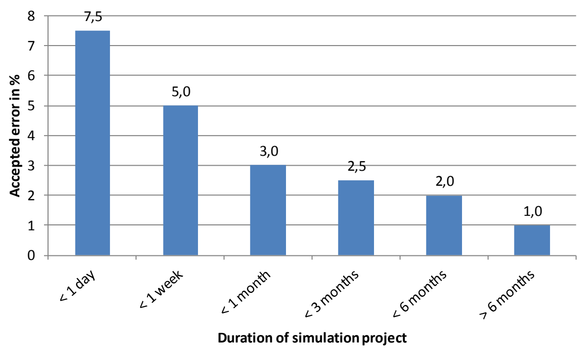

Figure 1: Accepted Errors by Production Planners in a Simulation Project (Schauf 2016)

Standard discrete-event simulation tools only support the creation of aggregated simulation models to a small degree. Simulation tools like ExtendSim (Damiron and Krahl 2014) and AnyLogic (Jain and Lechevalier 2016) easily allow the implementation of simulation models with different simulation paradigms within one model, like the combination of discrete-event elements and discrete-rate elements in ExtendSim in order to solve planning tasks in manufacturing and logistics.

However, simulation projects in the German automotive industry do not very often apply the simulation tools ExtendSim or AnyLogic. They mainly use the discrete-event simulation tool Plant Simulation. This is due to the fact that the material flow blocks of Plant Simulation allow for a very good representation of material flows in a manufacturing and logistics environment. Furthermore, the VDA Automotive Toolkit (Mayer and Pöge 2010) provides pre-build modeling blocks for the typical production and logistics processes in the body shop, paint shop, assembly and logistics in an automotive factory.

This paper describes and evaluates the application of a mesoscopic simulation approach based on the discrete-rate simulation paradigm for typical planning tasks in production and logistics systems, implemented with the simulation software ExtendSim. The modeling and computational effort and the accuracy of results of the mesoscopic discrete-rate based simulation models will be compared with discrete-event models for the same problem.

2. MESOSCOPIC MODELING AND SIMULATION APPROACH

The mesoscopic simulation approach proposed by the authors of this paper is situated between continuous and discrete-event approaches in terms of level of modeling detail and required modeling and simulation effort (Reggelin 2011). It supports quick and effective execution of analysis and planning tasks related to manufacturing and logistics networks. The principles of mesoscopic simulation models to describe processes in logistics and production networks have been derived from the actual development of several mesoscopic models (Hennies et al. 2014; Hennies et al. 2012; Tolujew et al. 2010; Schenk et al. 2009; Savrasov and Tolujew 2008; Tolujew and Alcala 2004).

Even when the term mesoscopic is not explicitly applied, a mesoscopic view often already exists from the start of production and logistics flow system modeling and simulation. Many practical production and logistics analysis and planning problems like capacity planning, dimensioning or throughput analysis describe performance requirements, resources and performance results in an aggregated form that corresponds to a mesoscopic view, see Figure 2.

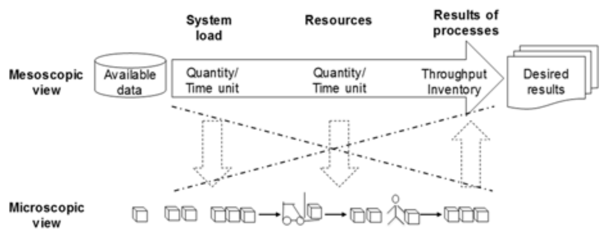

Figure 2: Mesoscopic and Microscopic Simulation Modeling Views

The basic idea of the mesoscopic approach is the direct and fast transformation of mesoscopic input data (performance requirements and resources) into mesoscopic performance results without the detour of object based event-driven process modeling. In order to fulfill the requirement of a quick provision of simulation results mesoscopic models employ a flow based approach for the direct computation on a mesoscopic aggregation level.

Mesoscopic models represent flow processes in production and logistics systems through piecewise constant flow rates. This assumption is valid since logistics flows do not change continuously over time. The control of resources is not carried out continuously but only at certain points of time like changes of shifts, falling below or exceeding inventory thresholds. The resulting linearity of the cumulative flows facilitates event scheduling and the use of mathematical formulas

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for recalculating the system‘s state variables at every simulation time step.
The simulation time step is variable and the step size depends on the occurrence of scheduled events. This leads to a high computational performance. The principles of event-based computation of linear continuous processes are employed in the discrete-rate simulation paradigm implemented in the simulation software ExtendSim (Krahl 2009, Damiron and Nastasi 2008) and the hybrid simulation approach described by Kouikoglou and Phillis (2001).
However, a pure linear continuous representation of logistics flow processes is too abstract and aggregated for many analysis and planning tasks in production and logistics systems. Therefore, the mesoscopic modeling and simulation approach applied in this paper expands the event-based computation of linear continuous flow processes as described below. A more detailed description of the mesoscopic modeling and simulation approach can be found in Reggelin (2011) and in Reggelin and Tolujew (2011).

2.1. Mesoscopic Product Model

Since one single variable reproduces the flow between two nodes of a network structure in a flow-based model, a flow's individual segments are neither identifiable nor traceable. Therefore, a mesoscopic model may employ different product types in parallel through all nodes and edges of the logistics network and in order to differentiate between flow objects with different characteristics. Features like resource consumption and required routes through the logistics network distinguish the individual product types from one another. Every product type is assigned to its own channel at the model's components.
Furthermore, so-called product portions are introduced in order to sequentially differentiate a flow of a product type. Their number is specified during the conceptual modeling phase. Certain quantities of products, e.g. lot size, cargo size, number of goods in a shipment or number of people in a group, may be modeled as product portions. Thus, the path of individual product portions that may be spatially distributed throughout the network can be tracked and relevant events that may occur along this path can be captured.

2.2. Mesoscopic Process Model

In addition to piece-wise continuous flows (discrete-rate modeling), a mesoscopic model may employ impulse-like flows (object-based discrete-event modeling) to represent the flow of objects through a production or logistics system in order to increase the level of detail. Impulse-like flows allow to represent bundled movement of objects like bundled transports or the movement of production batches.

2.3. Mesoscopic Modeling Components

The mesoscopic model components allow to model the basic functions of a production and logistics system: transformation, storage and transportation. A mesoscopic model may employ the basic components of source, sink, funnel and delay to represent a material flow structure. Flows may be additionally modified with the components of assembly and disassembly. Multichannel funnels are a mesoscopic model‘s main components because they properly represent the processes of parallel or sequential processing and storage of several product types and product portions in a real area of operations. The use of a multichannel funnel as a mesoscopic model's main component facilitates a straightforward modeling.

3. TYPICAL PLANNING TASKS IN PRODUCTION AND LOGISTICS SUPPORTED BY SIMULATION MODELING

Schauf (2016) also asked which tasks do production planners already solve or would like to solve with the help of simulation models in the future. The results are grouped into the typical applications of simulation modeling of systems in materials handling, logistics and production according to (VDI 2014) and depicted in Table 1. Furthermore, Table 1 shows whether or not mesoscopic discrete-rate based simulation models seem to be suitable to solve these analysis tasks.
Mesoscopic simulation models seem to be a possible choice for most of the typical planning tasks which planners already solve with the help of simulation modeling. However, they are not capable solving tasks that relate to the analysis of order sequences due to the fact that discrete-rate models cannot represent individual flow objects in a simulation model. Schauf (2016) analyzes more detailed the suitability of the mesoscopic simulation approach for typical tasks of a production planner.
Even when almost 97 % of the asked production planers stated that simulation modeling is 'absolutely necessary', 'very important' or 'important' (see section above), the application and planned application of simulation modeling seems to fall behind this figure. One reason as already mentioned above could be the gap between the desired quick provision of results and the often long durations of a simulation project. The next section describes which advantages the use of mesoscopic discrete-rate based simulation models can have in terms of duration of a simulation study by applying the approach for three typical tasks of a production planner.

4. APPLICATION AND EVELUATION OF MESOSCOPIC SIMULATION MODELS

This section compares the application of mesoscopic discrete-rate based simulation models with discrete-event simulation models in terms of duration of a simulation study and deviation in results by applying these two modeling paradigms for three typical tasks of a production planner:

1. Determination of the number of load handling devices for a an assembly line
2. Verifying the throughput of a final assembly

3. Verifying performance of the goods receiving processes of an assembly plant.

Table 1: Fields of Analysis in Production and Logistics Planning and Use of Simulation Models

	Already use simulation modeling	Plan to use simulation modeling in the future	Mesoscopic discrete rate based simulation model suitable?
Order sequences	8 %	14 %	no
Throughput	15 %	11%	yes
Management Strategies	11 %	18 %	yes
Verifying function and performance	11 %	18 %	partly
Dimensioning	30 %	18 %	partly
Performance limits	2 %	4 %	yes
Bottlenecks	5 %	4 %	partly
Examination of variants	9 %	7 %	party

The authors chose ExtendSim to implement the mesoscopic simulation models, since ExtendSim facilitates combining discrete-rate model elements and discrete-event model elements by using the Rate library and the Item library within one model. Furthermore, the Rate library supports a close modeling of the mesoscopic modeling elements described in the section before.

4.1. Determination of the Number of Load Handling Devices for an Assembly Line

A typical task for a production and logistics planner is to determine the required number of resources for a process. Already 30 % of the asked production planners use simulation modelling for this task, see Table 1. In this example, the planner has to determine the number of load handling devices that need to be provided for a total of five sections of an assembly line. Figure 3 depicts the mesoscopic discrete-rate based simulation model to solve this task. The model mainly comprises the blue Rate Library blocks and the yellow Value Library blocks.

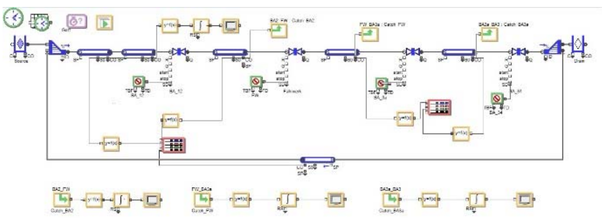

Figure 3: Mesoscopic Simulation Model in ExtendSim based on Rate Library and Value Library Blocks for Determining the Number of Load Handling Devices for an Assembly line

The model was compared to a discrete-event model implemented with the Plant Simulation VDA toolkit. Table 2 shows the comparison of results and simulation run time. The deviation of the results of the mesoscopic simulation model compared to the discrete-event model is about 1 % and lies within the accepted margin of error of the interviewed production planners (see Figure 1). The use of the discrete-rate based model leads to an enormous reduction of simulation runtime. Furthermore, the modeling effort for the discrete-rate based model is also lower than for the discrete-event model. That implicates that mesoscopic discrete-rate based simulation models could be a good alternative for a production planner to get quick planning results in a sufficient quality.

Table 2: Comparison of Simulation Effort and Results for the Microscopic and Mesoscopic Simulation Model

	Number of required load handling devices	Deviation of result	Duration of a simulation run
Microscopic discrete-event model with VDA toolkit in Plant Simulation	417	0 %	720 minutes
Mesoscopic discrete-rate model with own toolkit in ExtendSim	421	1 %	1 minute

4.2. Verifying the Throughput of a Final Assembly

For the same assembly line that was analyzed in the section before, the task of the production planner was to verify that the final assembly can guarantee a throughput of 60 products per hour. For this tasks the simulation model shown in Figure 3 was modified to solve this task and then compared to a discrete-event model implemented with the Plant Simulation VDA toolkit. Table 3 shows the results of the comparison.

Table 3: Comparison of Simulation Effort and Results for the Microscopic and Mesoscopic Simulation Model

	Output per hour	Deviation of result	Duration of a simulation run
Microscopic discrete-event model with VDA toolkit in Plant Simulation	60.02	0 %	103 minutes
Mesoscopic discrete-rate model with own toolkit in ExtendSim	60.14	0.2 %	0.04 minutes

The comparison shows that margin of error with about 0.2 % lies within the accepted margin of error of the interviewed production planners (see Figure 1) and the use of a mesoscopic discrete-rate based simulation model gains a huge reduction in simulation runtime and also helps to reduce the time required for building the model.

4.3. Verifying Performance of the Goods Receiving Processes of an Assembly Plant

The task of the planer was to verify that the throughput of the receiving process of an assembly plant meets the required performance. Figure 4 shows the main processes of the goods receiving department. Between 6:00 a.m. and 11:30 p.m., one to three trucks arrive at the goods receiving department every half an hour and will be allocated to one of the three unloading gates. The number of loading units on each truck depends on the type of loaded products. A truck has loaded one loading unit up to 90 loading units. After the quality check, the loading unit have to be transported by forklifts to sort lanes. The storage process can only be started, if all loading units of a truck are sorted in the corresponding sort lanes.

Figure 4: Goods Receiving Process of an Assembly Plant

The main challenge for mesoscopicly modeling the logistics processes is to determine which processes can be aggregated to the discrete-rate paradigm in a reasonable way (transforming single process durations into flow rates) and which processes need to be modeled object-based with the discrete-event simulation paradigm. Figure 5 presents the conceptual mesoscopic simulation model with a combination of discrete-rate and discrete-event processes.

The created entities in process stage I represent arriving trucks in the goods receiving department. Every entity has an attribute, which represents the number of loaded units on the truck. After going through one of the three preparation processes, entities move into the corresponding interchange block, which symbolizes a gate for unloading. In the gate, the attribute of the entity is transformed into a discrete-rate stock to model the unloading process. The unloading work cycles with a forklift are aggregated to a rate process by taking into account the process times for all work cycles to unload one truck, depending on the current number of allocated forklifts to the process, the speed, loading capacity, loading and unloading time of each forklift, the average stacking time for each loading unit, the distance between gate and buffer zone, and the number of loading units in the truck. After a truck is unloaded, it goes through the follow-up process, before it leaves the system and unblocks the gate for the following trucks.

For the quality check, the discrete-rate stock in the buffer area will be retransformed into an attribute of a discrete-event entity. The reason for this is that in the real system a restriction exists, which postulates that loading units of a truck load are only allowed to be sorted, if all of them pass the quality check. Therefore it is possible to save more computational and modelling effort, if only one entity is processed instead of applying a complex rate equation.

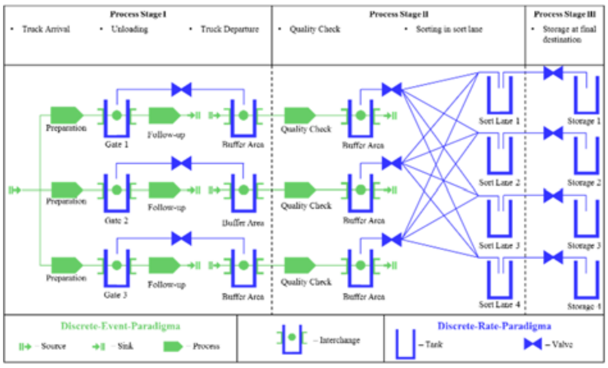

Figure 5: Conceptual Mesoscopic Simulation Model with Discrete-rate and Discrete-event Processes in the ExtendSim Notation

The runtime of the mesoscopic model is nearly 87 % lower (see Table 4) compared to the microscopic model. In terms of the queue length in front of the gates and the daily system throughput of loading units, there are only slight deviations between the mesoscopic and microscopic simulation models.

Table 4: Comparison of the Simulation Results of the Mesoscopic and Microscopic Model

	Throughput (loading units/day)	Max. queue length in front of gates (trucks)	Duration of a simulation run
Microscopic discrete-event model with VDA toolkit in Plant Simulation	3,445	3	201 seconds
Mesoscopic discrete-rate model in ExtendSim	3,464	3	27 seconds

5. CONCLUSION

The results of the simulation experiments show that mesoscopic simulation models based on the discrete-rate simulation paradigm are capable to support planning tasks in production and logistics systems. For several typical planning tasks, their results differ only slightly from the results of a discrete-event simulation model. The results deviation stays within a margin that is accepted by production planners.

Mesoscopic simulation models can save enormous amounts of modeling and computational time compared to discrete-event models and thus comply with the requirements of production planners to receive simulation results within a short period of time.

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