Proceedings of the 2011 Winter Simulation Conference
S. Jain, R. R. Creasey, J. Himmelspach, K. P. White, and M. Fu, eds.

A MESOSCOPIC APPROACH TO MODELING AND SIMULATION OF LOGISTICS PROCESSES

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ABSTRACT

Simulation models are important for planing, implementing and operating logistics systems since they can depict their dynamic system behavior. In the field of logistics, discrete-event models are widely used. Their creation and computation is often very time and labor consuming. For this reason, the paper presents a new mesoscopic modeling and simulation approach to quickly and effectively execute analysis and planning tasks related to production and logistics systems. Mesoscopic models represent logistics flow processes on an aggregated level through piecewise constant flow rates instead of modeling individual flow objects. The results are not obtained by counting individual objects but by using mathematical formulas to calculate the results as continuous quantities in every modeling time step. This leads to a fast model creation and computation. In terms of level of detail, mesoscopic simulation models fall between object based discrete-event simulation models and flow based continuous simulation models.

1 INTRODUCTION

Enterprises have to be able to react dynamically to changing market environments, disturbances and unforeseen events. This necessitates suitable tools that immediately show the effects of changing conditions on the time-dependent behavior of the observed system so that qualified measures such as modifications of a control strategy can be devised and implemented. Simulation models are the best solution to such problems (Aufenanger, Varnholt, and Dangelmaier 2009, Borshchev and Filippov 2004). Two classes of dynamic models, namely continuous and discrete models, are widely used to depict process sequences in logistics flow systems.

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. Since discrete event models are able to represent workstations, technical resources, carriers and units of goods as individual objects, they 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). This is a disadvantage when disturbances or other changing conditions require a quick analysis of the expected system behavior and a quick derivation and evaluation of qualified measures.

Continuous models are based on differential equations and most frequently applied as system dynamics models to reproduce manufacturing and logistics processes (Pierreval et al. 2007, Scholz-Reiter et al. 2006, Angerhofer and Angelides 2000, Sterman 2000, Anderson and Morrice 1999). Since these models typically work with aggregated data on a strategic level, they are also referred to as macroscopic models (Borshchev and Filippov 2004, Pierreval et al. 2007, Größler 2007). Their level of aggregation renders them incapable of accurately representing the numerous logistics objects (products, resources, etc.) and

978-1-4577-2109-0/11/$26.00 ©2011 IEEE

control strategies, which demand consideration when resolving tactical or operational problems (Pierreval et al. 2007, Größler 2007). For this reason, logistics practitioners do not use these models very often.

The fact that the common simulation approaches do not completely meet the needs of practitioners analyzing and planning logistics systems has motivated the research on new modeling methods for logistics processes. The requirements for the new mesoscopic approach described in this paper derive from the disadvantages of the existing modeling and simulation approaches:

- Less modeling and simulation effort than in discrete event models.
- Higher level of detail than in continuous simulation models.
- Straightforward development of models.

The mesoscopic simulation approach proposed by the authors in this paper is situated between continuous and discrete event approaches in terms of level of modeling detail and required modeling and simulation effort as depicted in Figure 1. It supports quick and effective execution of analysis and planning tasks related to manufacturing and logistics networks. The principles of mesoscopic simulation of processes in logistics networks described here have been derived from the actual development of several mesoscopic models (Schenk et al. 2008, Schenk et al. 2009, Reggelin and Tolujew 2008, Savrasov and Tolujew 2008, Tolujew and Alcala 2004, Hanisch et al. 2003).

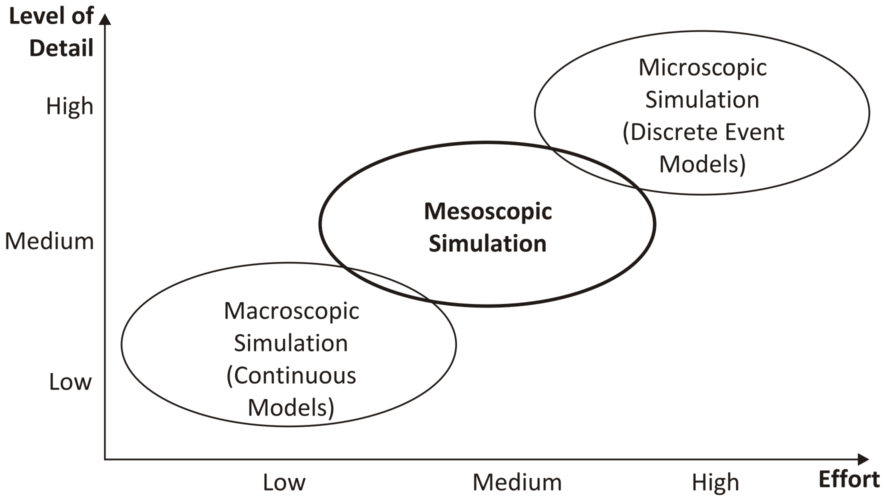

Figure 1: Classification of the mesoscopic simulation approach.

2 MESOSCOPIC APPROACH

Even when the term mesoscopic is not explicitly applied, a mesoscopic view often already exists from the start of logistics flow system modeling and simulation (see Figure 2). Many practical 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 (Schenk et al. 2008).

As depicted in Figure 2, microscopic simulation is often employed to arrive at pure mesoscopic results from problems presented in the pure mesoscopic view. This “detour” is quite complicated and costly because it involves the decomposition and aggregation of data. Data loss and deformation seem unavoidable. The aggregated results of a macroscopic simulation do not suit most logistics analyzing and planning tasks.

The basic idea of the mesoscopic approach is the direct and fast transformation of mesoscopic input data (performance requirements and/or resources) into mesoscopic performance results without the detour of object based event-driven process modeling (see Figure 2). In order to fulfill the requirement of effort reduction mesoscopic models employ a flow based approach for the direct computation on a mesoscopic aggregation level.

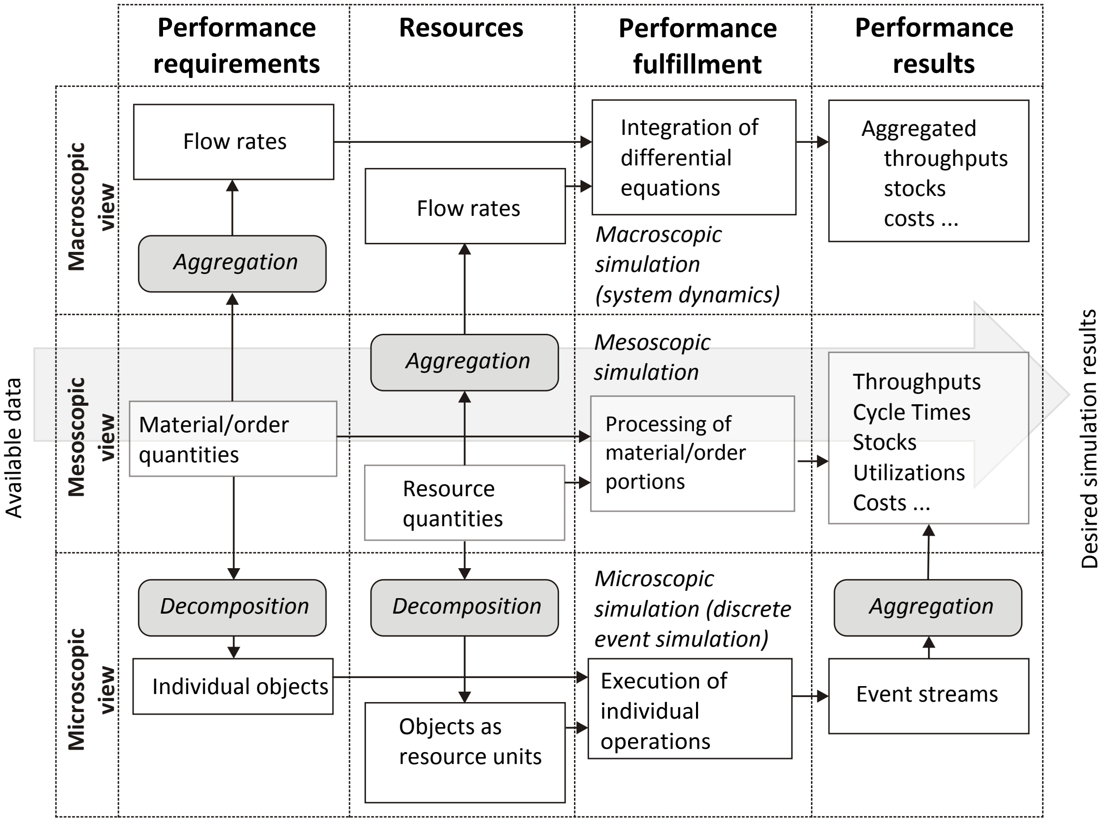

Figure 2: Microscopic, mesoscopic and macroscopic simulation views.

Mesoscopic models represent logistics flow processes 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 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 still too abstract and aggregated for many logistics analysis and planning tasks. Therefore, the mesoscopic modeling and simulation approach described in this paper expands the event-based computation of linear continuous flow processes as follows:

- **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.

- **Process Model**
  In addition to piece-wise continuous flows, a mesoscopic model may employ impulse-like flows to represent the flow of logistics objects through a logistics system in order to increase the level of detail. Impulse-like flows allow to represent bundled movement of logistics objects like bundled transports or the movement of production batches.
- **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 facilitate a straightforward modeling.
- **Simulation Software**
  Since there is no existing simulation software to directly implement models with the described mesoscopic approach, a specific mesoscopic simulation software has been developed.

More detailed descriptions of the mesoscopic modeling and simulation approach can be found in (Tolujew et al. 2010, Schenk et al. 2010b, Schenk et al. 2010a, Schenk et al. 2008). Table 1 summarizes the main characteristics of the different simulation approaches.

3 APPLICATION OF THE MESOSCOPIC APPROACH: RESOURCE ALLOCATION AT A LOGISTICS HUB

Figure 3 depicts the application area of the described mesoscopic modeling and simulation approach. Mesoscopic models are mainly used for tasks on a middle abstraction level. Mesoscopic models are particularly suited for the analysis of large-scale logistics processes with a large number of objects. In most cases, an item-based discrete event simulation would be overly complex for these applications because of the disproportionate amount of computation required. This section describes the application of the mesoscopic approach for the derivation of resource allocation strategies at a logistics hub.

Figure 4 presents the structure of the mesoscopic model developed. The mesoscopic approach was applied to model and simulate some of the processes in a logistics service provider's hub. The example shows that the mesoscopic approach is a suitable method for quickly dealing with analysis and planning tasks, calculation of key performance indicators and comparison of different variants of control strategies in production and logistics systems. In order to keep the model clear, only a small part of the distribution network of a logistics service provider is modeled. However, the mesoscopic approach allows easily handling models of any size since the computing time does not depend on the number of represented flow objects. The model represents the receiving area, the intermediate storage, the consolidation, the shipping area and the transportation to the next processing center. Three two-channel funnels are the main components of

Table 1: Characteristics of the mesoscopic modeling and simulation approach in comparison with discrete event simulation, discrete rate simulation and system dynamics simulation.

	Discrete Event Simulation	**Mesoscopic Simulation**	**Discrete Rate Simulation**	**System Dynamics Simulation**
Application	Logistics processes on the individual object level	Logistics processes on an aggregated mesoscopic level	Linear continuous processes	Aggregated logistics processes
Software Tools	Plant Simulation, AutoMod	MesoSim	ExtendSim	Vensim, Powersim
Level of detail	High	Medium	Low - medium	Low
Effort	High	Medium	Low - Medium	Low
Representation of logistics flow processes	Entities that flow through a system of resources	Quantities of goods that flow through the model both as flows and impulse-like flows	Homogeneous bulk flows that flow through the model (rate based flow system)	Values (stocks and flows, feedbacks)
Product model	Individual objects	Distinguishes between product types within a flow and product portions within a product type	One variable for flow between two network's nodes	One variable for flow between two network's nodes
Main modeling components	Logistics specific resources, queues	Multichannel funnels, multichannel delays	Tanks, valves, conveys	Containers, valves
State change through	Events concerning movement and status of entities	Events concerning change of flow rates and occurrence of impulses	Events concerning change of flow rates	Time change
Time step	Variable	Variable	Variable	Constant

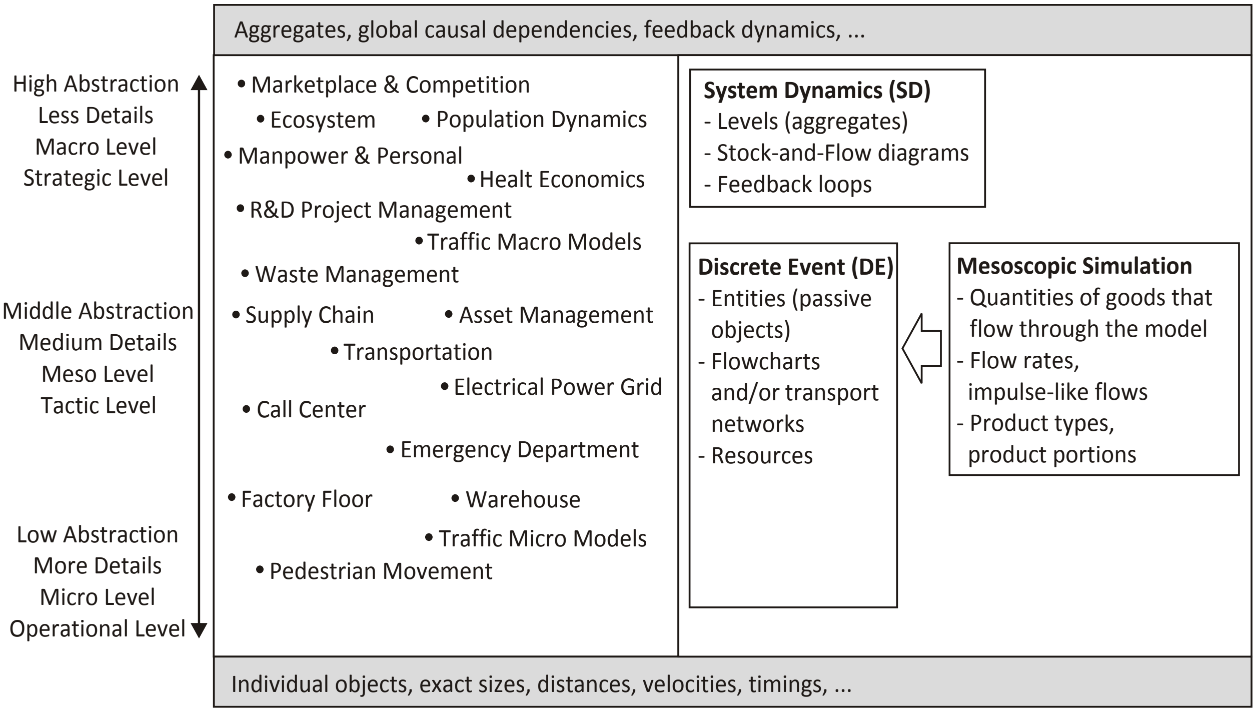

Figure 3: Classification of the mesoscopic modeling and simulation approach in the overview of Borshchev and Filippov (2004).

the model. Furthermore, two delay elements for modeling the transport to the two destinations are used. The two product types represent the two different destinations of the outgoing goods.

In every time step the preceding component determines the input stream of the succeeding component (funnel or delay) and the resource control determines the output stream of a component. The content of a component (funnel or delay) is the difference of these two streams. The input data of the model have been prepared according to the choice of the time step of one hour. Figure 5 shows the input stream of the logistics hub for the two product types and depicts the maximum throughputs of the forklift team in pallets/h distributed over the day. The maximum throughputs do not depend on the location in the hub where the forklifts are doing their jobs. The capacity of the resource of outgoing trucks is limited to 1 truck/h that can leave to destination 1 and 2 trucks/h to destination 2. A truck is only allowed to leave the hub if the content of funnel 3 reaches 50 pallets. The resource forklifts determines the maximum throughput of funnel 1 and 2. The resource of outgoing trucks determines the maximum throughput of funnel 3. In every time step a change of the assigned capacities allows the control of the model. The input data in this example are not stochastic.

Exemplary, the following three control strategies of the resource forklift in funnel 1 and 2 are compared. The model allows also for the representation of any other resource allocation strategies.

- Strategy 1 assigns fixed fork lift capacities. The same capacity is assigned to every funnel for every product type.
- Strategy 2 assigns to funnel 2 only as much capacity that maximum one truck per hour and per product type can leave the hub. The remaining capacity is assigned to funnel 1.
- Strategy 3 assigns the capacity proportionally to the contents of the funnels.

For any component of the model and any product type, the variables shown in Table 2 are sequentially calculated for every time step.

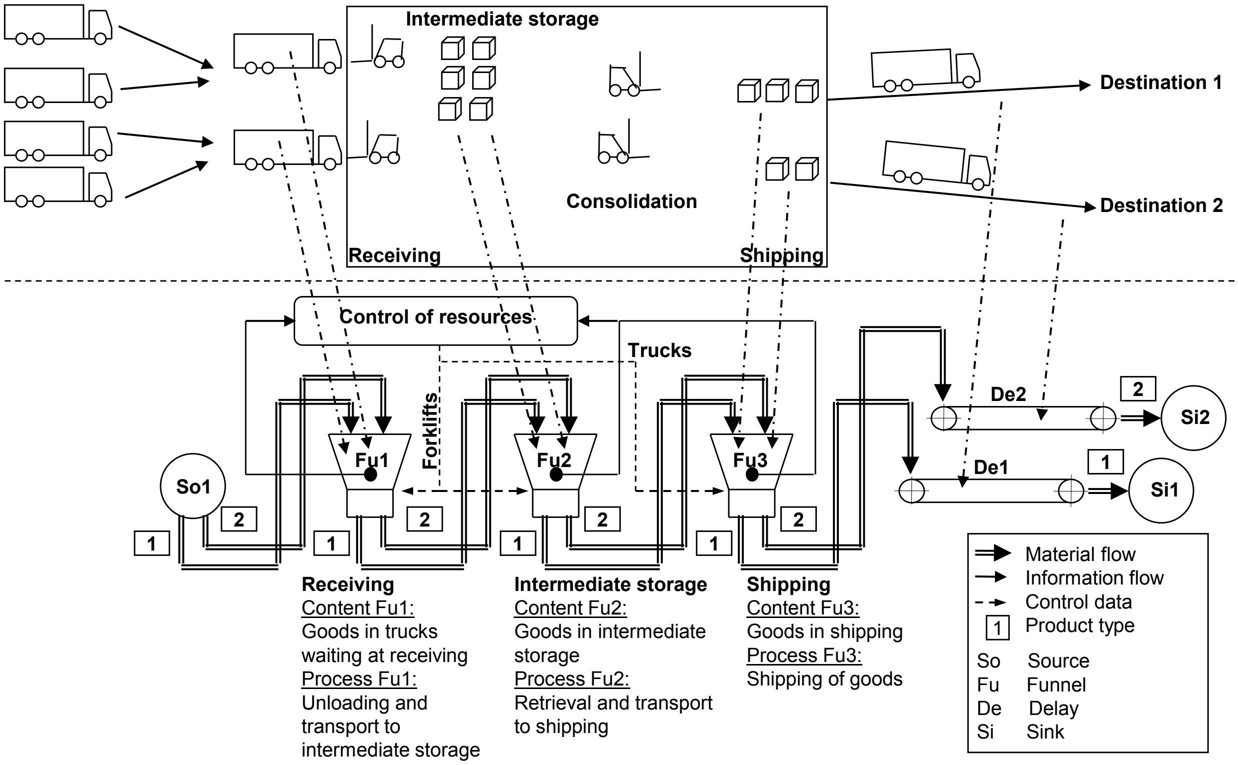

Figure 4: Mesoscopic model of processes in a logistics hub.

Table 2: Variables of the mesoscopic model.

Variable	Description
$S(t_i)$	Content of a funnel's channel at the beginning of interval Δt
$C^{in}[t_i, t_i + \Delta t]$	Amount of incoming products at a funnel's channel during interval Δt
$\mu(t_i)$	Assigned maximum throughput of a funnel's channel during interval Δt
$C^{out}[t_i, t_i + \Delta t]$	Amount of outgoing products at a funnel's channel during interval Δt

Figure 6 depicts the contents of the funnels for the three different resource allocation strategies. Strategy 3 works best since all the goods can be loaded onto the outgoing trucks during the work day. In strategy 1, content remains in funnel 1 (waiting trucks at the receiving) and in strategy 2, content remains in funnel 2 (intermediate storage).

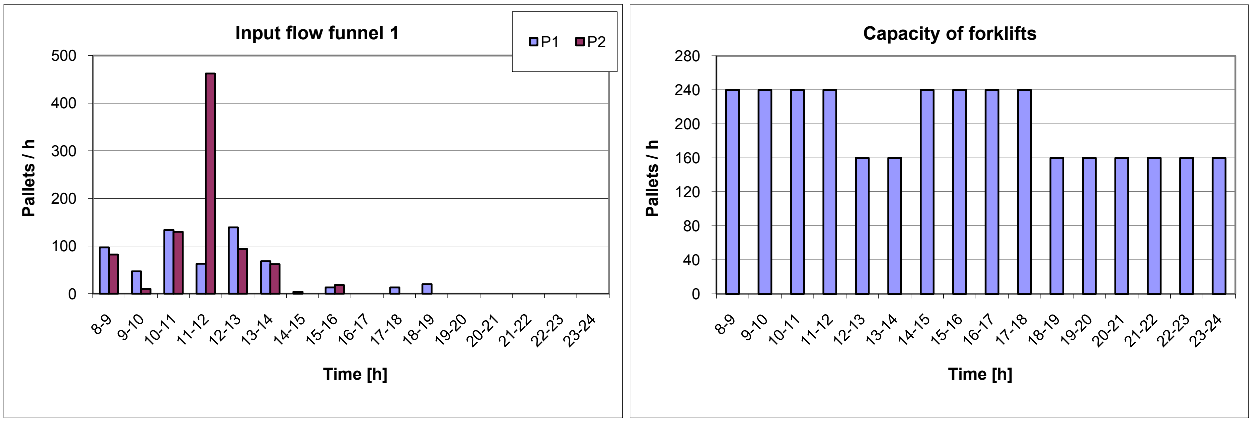

Figure 5: Input data of the mesoscopic model.

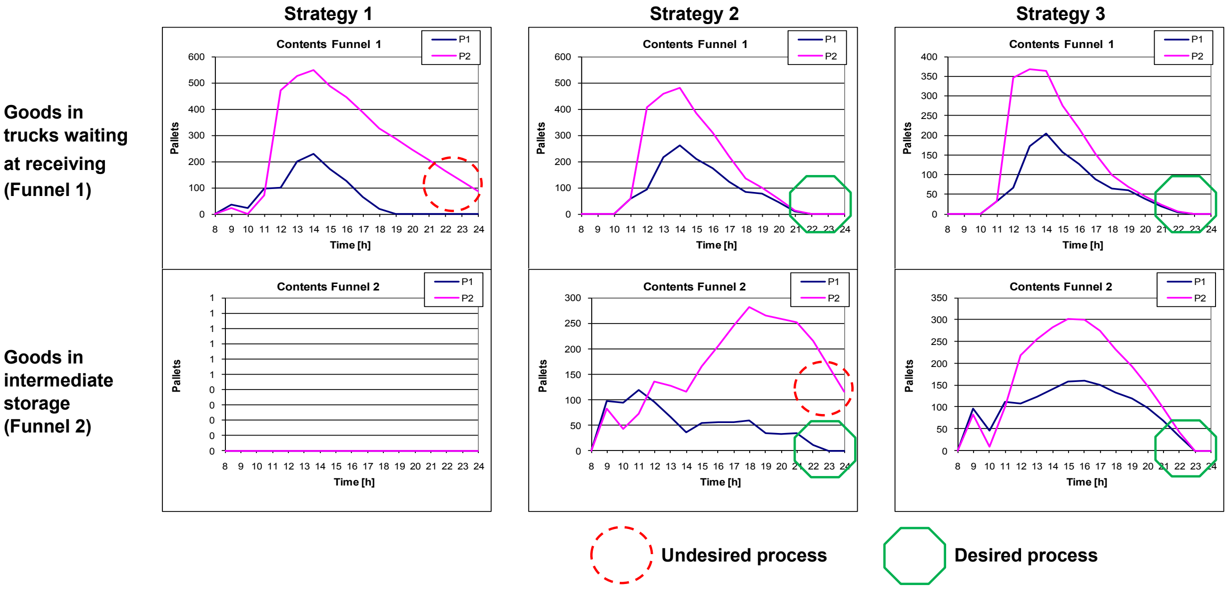

Figure 6: Outcome for three different resource allocation rules.

4 CONCLUSION AND OUTLOOK

The mesoscopic simulation approach described here expands the present set of tools for logistics systems simulation. It has two main advantages:

- Flow processes are modeled with a simple and universal form of representation (piecewise constant flow rates and impulse-like flows) that is suitable for many real manufacturing and logistics processes.
- Models employing variable time steps perform significantly better and require less computing time than continuous or discrete event models.

The presented mesoscopic modeling and simulation approach leads to the following future research tasks:

- The computing performance of the mesoscopic simulation approach facilitates an on-line simulation of logistics systems. Thus, an integration of the mesoscopic approach into concepts of on-line planing, on-line control and on-line optimization of logistics processes should be pursued.
- Integration into logistics event management concepts like the one of Brandau and Tolujew (2010): The logistics event management system can trigger new simulation runs to devise adequate measures to cope with disturbances or other changing operating conditions.
- The mesoscopic approach can be used to automatically derive control strategies for the logistics processes under examination since the fast computation of a mesoscopic model facilitates the testing of many different control rules within a short time.

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