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A Flexible and Generic Simulation Model for in-Bound Transport Systems

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Abstract

When planning the material flow between production and warehouse areas more precise and efficient methods are required due to the increasing complexity of logistics networks and the higher need for flexibility. In recent years simulation methods have gained in importance, since they are able to consider a wider range of factors that may influence the system performance such as vehicle interactions or stochastic effects. Simulation methods are however often associated with high development costs. In this work, we first present a generic and flexible modelling approach for in-bound transport systems. Here, we focus on three different freely movable transport vehicles: forklifts, tugger trains and automated guided vehicles. Based on this approach we then automatically create a runnable discrete event simulation model that enables analyzing the system performance and thus identifying potential optimization measures.

Keywords: generic modelling approach; multi-commodity-flow network; discrete event simulation; in-bound transport systems

1. Introduction

In-bound transport systems are an integral part of logistics networks and a crucial factor when dealing with the challenges facing logistics these days: in a dynamic environment of economic, social and political boundaries, logistics systems must be performant and reliable, while at the same time quality and flexibility are required (Handfield, Straube, Pfohl and Wieland, 2013). Furthermore, the economic success of companies is closely related to the efficiency of the transport system within its production and storage areas (VDI-2689, 2019). The design of the transport system consists of defining its three components: transport units, transport process and transport vehicles with the objective of minimizing the total costs while meeting all the relevant requirements.

Due to the high complexity of the system interactions and the stochastic nature of its processes, analytical designing methods are either inaccurate or demand a great computing effort. Simulation methods, on the other hand, allow the consideration of a large range of relevant factors, such as order assignment and routing strategies, vehicle interactions, stochastic fluctuations of the processes, etc. In doing so, they enable the analysis and prediction of the dynamic behavior of the system and provide a decision-making basis for optimization measures in practice (Mayer, Pöge, Spieckermann and Wenzel, 2020). The main drawback of using simulation methods are still the usually high costs associated with the development, application and evaluation of the models (Rudel, 2016).

The aim of this research is to develop a generic simulation model that allows for an accurate evaluation of the throughput of in-bound transport systems that use a combination of forklifts (FL), tugger trains (TT) and automated guided vehicles (AGV). The model should also allow varying levels of detail regarding input data, so that it can be used not only to design new systems but also to identify optimization opportunities in existing structures.

The structure of this paper is as follows: In section 2, we present some related works. In section 3, we first describe the developed modelling approach of input-data that we then use as a basis for creating the simulation model. In section 4, we apply the described methodology on an exemplary case study, and discuss relevant issues and opportunities related to the model in general. Finally, in section 5, we summarize the paper and give an outlook on future work.

2. Literature Review

The research conducted by Hubl, Altendorfer, Jodlbauer, Gansterer and Hartl (2011) presents a modelling approach of a flexible simulation model for analyzing shop floor structure based on BOM (bill of material) and routing information. The study covers the stochastic aspects of different parameters from the product group to the final product. Moreover, the model merges three hierarchical levels ranging from long-term to short-term view, which are used for planning and controlling actions. Thereby, the logistic operations of the complex network can be analyzed.

Similarly, another research conducted by Zhang, Wang, Wang, Cui, and Cheng (2019) present a simulation-based structuring and optimization layout that could be used to accomplish the lean design targets by production facilities. It discusses systematic procedures and a well-defined framework to deploy such an efficient manufacturing process with the aid of a simulation environment. Thereby, the study incorporates mathematical algorithms and other heuristic methods to determine the trade-off between process effectiveness and planning cost, a key aspect of risk management in every industry.

More recently, Brützel, Overbeck, Nagel, Stricker and Lanza (2020) study the possibilities for an accelerated construction of a simulation model for the evaluation of improvement measures in variable semi-automated production systems.

However, to the best knowledge of the authors, generic simulation approaches for heterogeneous in-bound transport systems, as described above, are not addressed in the scientific literature.

3. Methodology

3.1. Input Data modelling:

The considered transport system can be viewed as a multi-commodity flow network. It consists of a set of commodities $q_c, c \in Q$ that need to be transported with a set of vehicles $v_k, k \in V$ through a directed graph $G(N, E)$, where N denotes the set of nodes $n_i, i \in N$ and E the set of edges or arcs $e_{i,j}, i, j \in N$. For each node we define a position and a type, i.e., source, sink or intersection. An Edge $e_{i,j}$ represents a directed path between a pair of nodes n_i and n_j with some properties such as width, maximal allowed height, etc. A commodity is associated with a load unit (LU) with specified properties (e.g. load carrying equipment, weight, etc.), a source and a sink node. At the source node we specify a stochastic distribution representing the arrival process $\lambda_c, c \in Q$. Similarly, μ_c denotes the rate of the service process at the sink. Additionally, we define a buffer with limited capacity $C_{b,c}, c \in Q$ before the service station in order to accurately model adjacent processes, beyond the system boundaries. In conclusion, the transport system can be thought of as a queuing network as shown in figure 1, where μ_T denotes the (unknown) service rate of the transport system and $T_c, c \in Q$ the throughput at each sink.

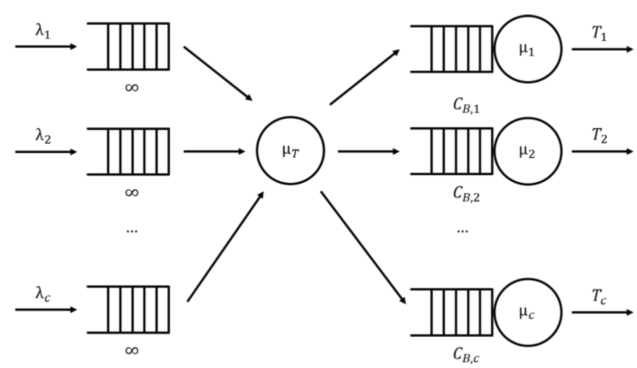

Figure 1. Representation of the transport system as a queuing network

Aside from usual parameters, such as number, type, dimensions and kinematic values, we define two stochastic distributions for the vehicles to describe the behavior of the load pick up and drop off processes. Moreover, for the purpose of modelling possible interruption, i.e., failures, charging operations and pauses of vehicle drivers, we introduce two additional distributions for the "mean time between failures" (MTBF) and the "mean time to repair" (MTTR). We also associate every interruption to a node that needs to be visited, whenever an interruption occurs. In the case of a vehicle failure, the variable is set to null. Finally, we specify a position where the vehicle can park until the next order assignment.

To achieve an even more realistic representation of the system, we define two categories of restrictions. The first category deals with restrictions of layout, and more precisely edges, on vehicles. If for example, the height of the vehicle exceeds the maximal allowed height of an edge, then the vehicle cannot drive through that edge. This is particularly the case when an edge crosses a gate that separates two areas of the plant. A speed limit can also be set on edges to model paths with human proximity, where vehicles have to drive with a lower speed. These restrictions are implicit and need to be enforced with defined rules. The second category, on the other hand, handles the restrictions of commodities on vehicles. These restrictions are explicitly imposed with Boolean variables and represent eventual incompatibilities between the vehicle and the transported LU associated with a certain commodity.

To summarize, we present a generic, scalable and extensible approach for modelling in-bound transport systems, which enables various level of details depending on the available data collection. To facilitate the data input procedure, we also used the developed structure, as shown in Figure 2, to implement a user interface. Furthermore, the user interface uses an XML schema to store the information and easily communicate with the simulation model framework.

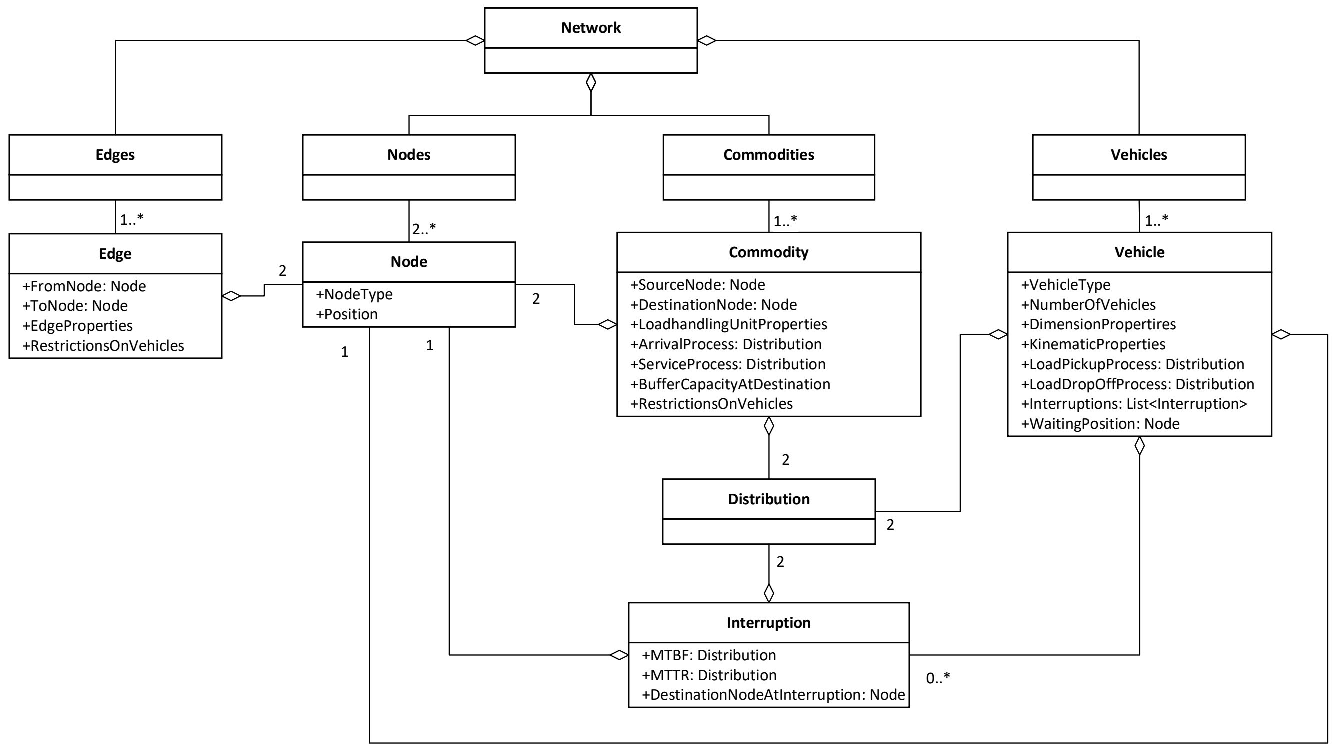

Figure 2. Representation of the developed data input structure using a simplified UML class diagram.

3.2. Simulation model

The simulation model is implemented in the discrete event simulation software Tecnomatix Plant Simulation. The modeled transport system consists of a set of tracks linking the sources to the sinks. A source is modeled as a queuing network with multiple arrival processes that correspond to those of the commodities starting at that node, and that are connected to a buffer with unlimited capacity. Each time a load unit enters the buffer, a transport order that inherits the related commodity properties (e.g. restrictions on vehicles) is created. Sinks, on the other hand, are basically G/G/$C_{B,c}$/∞/FIFO queues. LUs are first delivered on the buffer, then transferred to a station with a defined service process and finally removed from the system. The station represents the process of moving LUs to some adjacent system, beyond our system boundaries, e.g. warehouse, assembly station etc. At every source and sink we create a sensor that detects the presence of vehicles and initiates, when applicable, the load handling process. Note that additional congestions may appear at sinks if the buffer capacity is not adequately designed.

For order assignments, we implement a vehicle-initiated strategy, i.e., every time a vehicle delivers a LU at a sink, an event triggers the order assignment method. In the presence of orders that can be executed by the vehicle at that time, a route will be calculated and assigned to the vehicle. Otherwise, the vehicle drives to its waiting position, if defined, or wait at the last visited sink for the next order. The routing procedure uses vehicle-specific static routes calculated with a modified version of the Floyd-Warshall-Algorithm (Floyd, 1962) that considers the different restrictions between vehicles and edges. Furthermore, a 2-opt-algorithm (Croes, 1958) is deployed to optimize the initial solution, which consists of a first-come-first-served ordered set of transport orders with a size less or equal to the vehicle capacity. Unlike the original version of the algorithm, unfeasible solutions have to be avoided at each iteration, as introduced in (Psaraftis, 1983).

In order to identify bottleneck situations and consequently derive some appropriate optimization measures, various key performance indicators can be monitored during the simulation. For each commodity we calculate and update throughput, cycle time and buffer utilization values. Furthermore, we determine utilization rates of vehicles, which we additionally subdivide with respect to their possible states, namely: driving, load handling, blocked, waiting and failed. Note that the state "blocked" refers to the case, in which the vehicle is located at a sink, whilst the buffer at that sink is full. Last but not least, we create a heat map that shows the congestion values for paths and intersections.

Each of the described aspects of the simulation model was validated by means of extreme condition tests and sensitivity analysis. The Simulation framework enables also the visualization of all relevant interactions, which ensure a better reliability of the model.

4. Evaluation

In this chapter, we evaluate the generic model by performing a simulation of an exemplary heterogeneous in-bound transport system. The goal of this experiment is to illustrate the efficiency of the model in analyzing the system performance and identifying potential optimization measures.

4.1. Parameters

The considered example consist of a 10x10 Manhattan grid layout with one-way roads. 20 vehicles from 3 different vehicles types are deployed to transport LUs from 9 sources to 9 sinks located on both sides of the grid and uniformly distributed across the edge of the square. Vehicle parameters are shown in table 1. For the purpose of simplicity, load handling times are constants, interruptions are not being considered and all vehicles are able to go through every edge in the graph. Furthermore, in order to reduce congestion, we define different waiting positions for each vehicle type. Table 2 shows the different commodity parameters. Note that the abbreviations "exp." and "const." refer to negative exponential and deterministic distributions, respectively. Besides, "x" and "-" values in columns 5-7 represent the restrictions between commodities and vehicles. "x" means, that a commodity can be transported with a vehicle type and "-" otherwise.

Table 1. Vehicles parameters

Vehicle	Capacity	Speed loaded/ unloaded [m/s]	Acceleration loaded / unloaded [m/s^2]	Load handling time [s]	Number of vehicles
FL	1	5 / 5	1,05 / 0,89	5	6
AGV	1	1,5 / 1,5	0,5 / 0,5	10	10
TT	5	3,6 / 2,08	0,72 / 0,42	7	4

Table 2. Commodities parameters

Commodity	Arrival rate [LU/h] / Distribution	Service rate [LU/h] / Distribution	Buffer capacity	FL	AGV	TT
1	35 / exp.	40 / exp.	5	-	-	x
2	35 / exp.	40 / const.	5	-	-	x
3	35 / exp.	40 / exp.	5	-	x	-
4	35 / exp.	40 / const.	5	-	x	-
5	35 / exp.	40 / exp.	5	x	-	-
6	35 / exp.	40 / const.	5	x	-	-
7	35 / const.	40 / exp.	5	x	x	-
8	35 / const.	40 / exp.	5	x	-	x
9	35 / const.	40 / exp.	5	-	x	x

4.2. Simulation results

In this section, we analyze the throughput of each commodity as well as the mean utilization of vehicles and Buffers.

Figure 3 shows the shares of orders, which were completed within the simulation time (100 hours). We can see that the required throughput could not be achieved with the current parameters. We also observe that the percentage of completed orders is almost the same. This is due, on one hand, to the fact that transport orders are executed on a FIFO basis, and on the other hand, to the restrictions chosen for commodities 7-9. In fact, these commodities are shared between all vehicle types, which allows balanced throughput values.

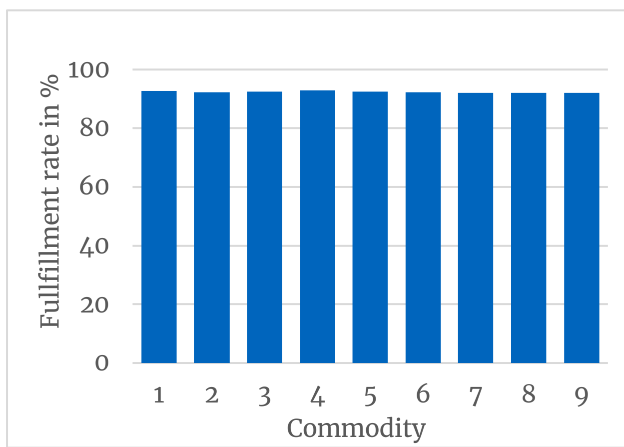

Figure 3: Percentage of completed orders

The first reason that can explain why the required throughput could not be achieved, is the high utilization levels of the three vehicle types (approx. 99,8 %) as shown in Figure 4. Furthermore, we observe that, due to their higher capacity, tugger trains have a higher share of load handling time and also, a higher probability to be blocked by service stations at sink nodes, since the arriving LUs have a higher variation, which results in longer queues.

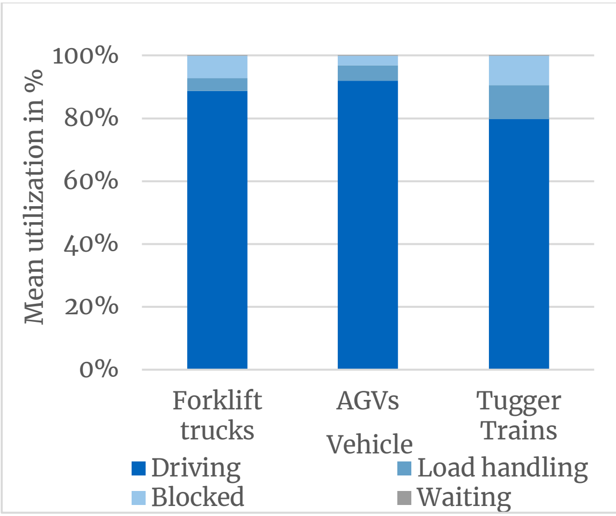

Figure 4: Mean utilization of vehicles

Increasing the number of vehicles in the system, may not be the right choice in order to achieve the required system performance. Indeed, we added two vehicle from each type to the system and performed another simulation run with the same parameters and still, did not reach the throughput required (95,6%). This is mainly explained by the increased congestion in the network caused by the interactions occurring at each sink of the system, since they represent some adjacent elements with defined (finite) service rates.

Figure 5 shows mean utilization values of the buffers associated with each commodity. The buffers have a mean waiting percentage of 82,3%, with some differences explained by the different distributions of arrival and service times. That means that a vehicle has to wait on average 17,8% of the time before it can drop off the load and execute the next order, which reflects negatively on the overall system performance. To achieve the required throughput we increased the service rates at the sink nodes from 35 LU/h to 45LU/h for Commodity 2-6 and from 35 LU/h to 50 LU/h for the remaining ones and added one tugger train to the system.

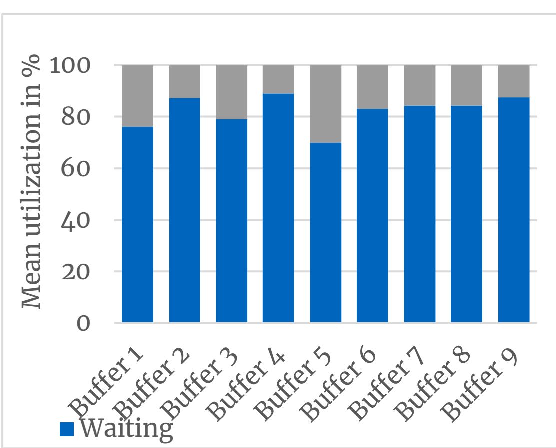

Figure 5: Buffer utilization

4.3. Discussion

The simulation model described in this paper provides a quick and easy method to study the performance of material flow systems and identify potential optimization measures. In order to achieve a more precise analysis however, a minimum of statistical knowledge is required. Moreover, the model does not cover all the numerous design and control aspects that may emerge in such complex systems. Thus, the role of logistic planners remains of capital importance when using this approach in checking the plausibility of the assumptions and results in the first place and secondly, in identifying further improvement and development opportunities.

5. Conclusions and future work

In this work, we first present a scalable and structured modelling approach for the required input data for simulating in-bound transport systems with freely movable vehicles. Based on this approach, we then create a generic and flexible discrete event simulation model that allows the system performance analysis by means of various indicators. By means of an exemplary case study, we finally evaluate the described model with regards to both the simplicity of its application, and to the versatility it provides when dealing with input data.

In future work, new transport-order-initiated assignment strategies will be implemented, which enable a more efficient optimization of material flow. Furthermore a dynamic routing will be applied in order to balance congestion through the network. Finally the simulation model will be extended to include bidirectional lanes. To tackle the problematic of deadlocks that arise as a result of this design aspect, appropriate strategies will be developed.

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