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SIMULATING AND EVALUATING INTERNAL LOGISTICS STRATEGIES FOR SUPPLIERS IN JUST-IN-SEQUENCE SUPPLY SYSTEMS IN THE AUTOMOTIVE INDUSTRY

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ABSTRACT

The reliability of just-in-sequence supply systems depends to a large extent on the efficiency of a supplier's internal logistics distribution system. Thus, improving the logistics efficiency is a major objective for many suppliers in the automotive industry. In this paper, a discrete-event simulation model is developed to evaluate the operational implications of different logistics strategies in just-in-sequence supply systems. Building upon the case of a major automotive supplier from Germany, the implications of various transportation resources and routing approaches are investigated and analyzed when it comes to the supply of components from an internal warehouse to the assembly lines. Experimental results show that the combined, load-carrier-specific use of forklifts, pallet trucks and tugger trains holds a high potential to achieve more efficient supply operations and meet different operational performance criteria such as downsizing the vehicle fleet, improving supply reliability and punctuality at the assembly lines, or minimizing warehouse traffic.

1 INTRODUCTION

In the automotive industry, production flexibility and efficiency are fundamental for the success of Original Equipment Manufacturers (OEM) in today's dynamic and highly volatile markets. The complexity of modern vehicles calls for a huge variety of different components within the production process, while technological advancements, increasing competition, and evolving customer expectations entail ever-shorter product life cycles (Pawlewski et al. 2012). In turn, OEMs are required to implement efficient procedures in order to operate profitably under this kind of conditions. As a consequence, most OEMs have adopted just-in-sequence (JIS) production scheduling approaches, as these facilitate the efficient production of mass-customized end products by reducing inventory costs, maintaining fast throughputs, and minimizing the amount of tied-up working capital (Fisher 1997). In JIS schedules, components are delivered in frames that are sequenced in accordance with the OEMs production schedule. Hence, JIS requires a superior level of synchronization and high quality standards for the production system (Graf, 2007). While flexibility measures such as contingency plans can help to cope with short reaction times in spite of unforeseen incidents (Wagner and Silveira-Camargos 2011), the OEM's overall JIS schedule primarily depends on supply processes and their coordination (Bányai et al. 2019). In other words, suppliers play a key role for the success of JIS (Meissner 2010; Wagner and Silveira-Camargos 2011).

Yet, to conduct JIS deliveries in a reliable and cost-efficient manner, suppliers have to maintain an efficient inventory system, assure high quality production processes, have robust logistics networks in place, and be flexible and responsive to changes in the delivery requirements (Meissner 2010; Wagner and Silveira-Camargos 2010). With the associated capabilities being directly contingent on the logistics activities within the supplier's production system (Wagner and Silveira-Camargos 2011), there is an immanent need for JIS suppliers to enhance and secure logistics process quality (Pawlewski et al. 2012). Additionally, JIS suppliers are "facing more and more new challenges focusing on cost efficiency" (Bányai and Boros, 2020). Thus, improving logistics activities yields a high potential to improve synchronization, ensure timely deliveries, avoid shortages, increase customer satisfactions, and decrease operational costs.

While extant research has focused on the conceptual side of JIS production systems (e.g., Meissner 2010) or assessed the effects of external logistics strategies (e.g., Kubasáková and Kubáňová 2020) as well as supply chain configurations (e.g., Wagner and Silveira-Camargos 2011), there is a dearth of studies that deal with internal material flow strategies (e.g., Lima and Ramalhinho 2017). This is particularly true when it comes to the use and integration of individual means of transport for storage, retrieval, and shipping processes. In light of the multiplicity of available transport solutions for material flows of JIS suppliers (e.g., tugger trains, which describe industrial trucks that consist of a towing vehicle as well as multiple goods and loads carriers) as well as the variety of implications through individual solutions, it remains unclear, which means of transport contribute to more efficient operations. Furthermore, the integration of different logistics systems as well as the resulting effects on the system's overall performance require further attention in order to capture relevant interdependencies and trade-offs across transportation entities.

Drawing upon the case of one of the five largest JIS suppliers across the globe, this study opts to evaluate different logistics strategies for internal material flow processes. In this sense, the main research focus is to study and model the internal supply system, and to virtually test different means of transportation for assembly supply within the production system of the JIS supplier. In industrial practice, it is common to employ a single type of transportation unit for a variety of load carriers (e.g., small and big load carriers). Yet, automation and the advent of new means of transports such as autonomous guided vehicles (AGVs) open up new avenues for more effective and efficient material flows. Correspondingly, potential disruptions on planned production sequences can be mitigated, ultimately decreasing the risk of disintegration (Bagdia and Pasek 2005). By simulating material flow processes and evaluating the implications (e.g., traffic; production stops) of different logistics strategies, our research supports JIS suppliers in the identification of operational bottlenecks and more efficient supply flows, which holds the potential to minimize detrimental de-synchronization effects. Since the dynamic production environment of a JIS supplier is typically characterized by a high degree of complexity (Wagner and Silveira-Camargos 2011), with internal material flows being contingent on numerous factors such as tact times and container quantities, simulation is particularly suitable to imitate the real-world system and analyze various what-if-scenarios (Banks 1998).

The remainder of this paper is structured as follows: First, the background of this study is presented by outlining its underlying case and elaborating on related work (Section 2). In Section 3, the research design is presented and the conceptual logistics scenarios, model specifications, parameters, and simulation approach are discussed. Subsequently, the experimental simulation results are given in Section 4, before the paper concludes with a critical reflection on the implications of this study in Section 5.

2 BACKGROUND

2.1 Problem Description

In this study, the internal logistics activities of a Tier 1 supplier specialized in body exterior solutions in the automotive industry are modelled. The company is suffering from production stops and space shortages due to inefficient internal logistics and supply processes. Thus, the focus is on material flow processes and transportation modes related to the delivery of materials to the assembly lines. The case is based on the real-world operations of the case company and its predicted demand for the upcoming years (i.e., time horizon: 4 years). Accordingly, production plans and material requests have been projected based on historic data from the company's enterprise resource planning (ERP) system, while spatial dimensions and geographical locations have been aligned with the layout of the actual plant. As depicted in Figure 1, the associated activities of the case company can be clustered into three meta-processes: (1) Inbound logistics, (2) Transportation, and (3) Assembly. Depending on the spatial dimensions of their containers, materials and components are stored in four block storage areas (i.e., larger containers) or six high-bay racks (i.e., smaller containers) in the logistics warehouse. With each level holding 47 containers, 50 % of the shelf racks possess four levels, while the remaining 50 % possess five levels. Here, small load carriers (SLCs) and equivalent containers (e.g., cardboard boxes) are always stored at the first (i.e. bottom) storage level, while big load carriers (BLC) are stored at the upper levels. In total, the system under study features 419 material types, which are kept in six types of containers, namely pallets, SLCs, racks, lattice boxes, cardboard boxes, and BLCs. Contingent on the material, each container holds different quantities of items, ranging from nine (i.e., components: tailgate fairings) to 378,000 units (i.e., materials: flange nuts).

The assembly lines, which are located in the manufacturing plant next to the internal logistics warehouse, serve as consumption points that request materials from the internal logistics warehouse based on their production plan and the individual availability of materials at a given assembly line. Assembly volumes sum up to a weekly total of 4,102 assembled body exteriors, each being composed of a number of materials ranging from 100 to 125 unique (i.e., items that are only installed once) as well as 132 to 197 total (i.e., all items, including those that are installed more than once) material item units. Material planning is handled following a dual-container Kanban system, where two containers are sequentially made available (first-in-first-out principle) for each material on the corresponding production line (Louis 2006). As soon as all materials of a container have been consumed, a transfer order is initiated for the subsequent delivery of a container with the same material type. In accordance with production plans and availability of items, a consuming point requests different amounts of containers in different periods throughout the day. Subsequently, a suitable container is picked up by a transportation unit (e.g., forklift) from the internal logistics warehouse and supplied to the consumption point at the assembly line. Upon completion of the material request, the respective transporter picks up the empty container and transfers it to a designated waste area. The routing for transportation processes from inbound logistics to assembly line is calculated dynamically based on the shortest distance between the geographical location of the transportation unit and the source and sink of the material request. In this context, it is important to note that the routing of a transportation unit can get obstructed by other transportation units or AGVs that operate separately from the internal supply system within the assembly environment (i.e., for transportation activities between assembly lines) and may force the transporter to wait or accept detours. In the context of this study, detours describe alternative routes that are taken by transporters if one or more path segments are temporarily blocked by a production AGV or another transportation unit.

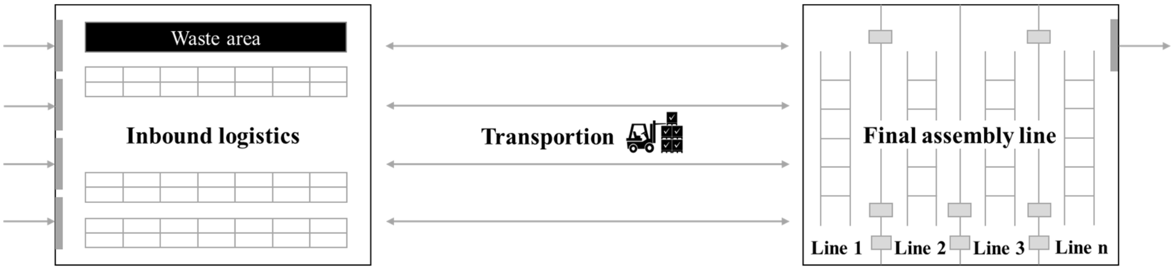

Figure 1: Simplified factory layout of the Tier 1 JIS supplier.

The main objective of this work is to improve the current material flow from the internal warehouse towards the assembly lines, applying a discrete-event simulation (DES) model to evaluate and compare the implications of different transportation modes and settings – collectively referred to as *logistics strategy* – against the current transport operations of the case company, where internal supplies are exclusively conducted by means of forklifts. Depending on the individual logistics strategy (Section 3.2), different system characteristics and Vehicle Routing Problems, such as the Capacitated Vehicle Routing Problem (CVRP) with multi-trips, time-constraints, and stochastic demand, have to be modelled (i.e., in the case of tugger trains) (Lima and Ramalhinho 2017). Thereby, in accordance with the recommendations of Wagner and Silveira-Carmargos (2011), the performance of the logistics strategies is assessed based on the following key performance indicators (KPIs) for in-house transport costs and JIS supply reliability: (1) the number of required transportation units per type, (2) the operating hours per transportation unit, (3) the total distance traveled per transportation unit, (4) the average filling levels of containers across all materials on the assembly lines, and (5) the warehouse traffic index (*WTI*) for the given scenarios *s* and the associated forklift fleet *f* or SLC transporter fleet *slc* (see Figure 4 for a scenario and vehicle fleet definition), which is averaged for two scheduling timeouts *i* (i.e., 1 = 30 minutes, 2 = 60 minutes) and conceptualized as a combined product of the number of transportation units *n*, their operating times *t* and speeds *m*, as well as the travelled distances *d* divided by a fixed factor of 1,000 (Equation 1). In contrast to the other KPIs, the WTI is not related to the avoidance of production stops by increasing supply reliability, but rather to increasing warehouse safety and available logistics space. Hence, it is particularly useful to identify scenario-specific implications on more general warehouse management objectives (Vonolfen et al. 2012).

$$\mathrm{WTI_s} = \frac{\frac{1}{2} * m_f * \sum_{i=1}^{2} n_f * t_f * d_f + \frac{1}{2} * m_{slc} * \sum_{i=1}^{2} n_{slc} * t_{slc} * d_{slc}}{1000} \tag{1}$$

2.2 Related Work

The literature regarding just-in-time and just-in-sequence supplies can be clustered into three related streams of research, which focus on (1) purchasing and supply chain management strategies (e.g., Wagner and Silveira-Carmargos 2011), (2) scheduling and production principles (e.g., Urnauer et al. 2019), as well as (3) internal material flow processes of suppliers (e.g., Pawlewski et al. 2012). In this study, the focus is on the third research area, which is particularly relevant for JIS suppliers in order to identify operational bottlenecks and ensure efficient supply flows that help to minimize detrimental de-synchronization effects.

In the context of internal material flow processes, scholars have employed a variety of simulation-based studies to analyze the effects of production and logistics strategies on various performance metrics. For example, Lima and Ramalhinho (2017) employed a combination of mathematical modelling and Monte Carlo simulation to design internal supply routes for tugger trains in a car-assembly factory. Their results suggest that solving the Warehouse Shipping Problem as an instance of the Capacitated Vehicle Routing Problem can help to manage different levels of production in a more efficient and cost reductive way. Similarly, Saez-Mas et al. (2020) analyzed the logistics flows of different assembly lines in an automobile factory and proposed a mathematical model to support strategic decision-making regarding assignment policies, transportation strategies, and material handling devices. Moreover, Staab et al. (2016) employed DES to analyze traffic situations in in-plant milk-run systems, whereas Korytkowski and Karkoszka (2016) developed a DES model to evaluate interactions between milk-run operators and an assembly line. Filz et al. (2019) used an agent-based simulation to compare different material supply strategies in matrix-structured manufacturing systems, proving AGVs as particularly effective. Finally, Wang et al. (2014) conducted a simulation-based analysis and optimization to reduce the traffic on a shop floor with path constraints and improve the overall utilization of transportation resources.

Despite the conducive insights from existing studies, there is a dearth of research that compares the implications of different internal logistics strategies within the same reference system. Moreover, to the best of our knowledge, few studies have elaborated on routing effects that occur due to the interplay of transportation units as well as confounders such as other production units, which is highly suitable for simulation-based analysis, as it features a high level of complexity and interdependence.

3 METHODOLOGY

3.1 Research Design

In order to address the priory outlined research objective, a three-stage research design is utilized. A synopsis of the overall research approach can be found in Figure 2. First, the general framework for the simulation study (*Planning* phase) has been determined. In doing so, two half-day workshops have been conducted with our industry partner. During the workshops, the participants worked out a detailed problem specification and defined the operational framework for the simulation study. The main objective is the identification of more-efficient and reliable means of transport for the internal material flows between internal warehouse and production environment (i.e., assembly lines). Based on the problem specifics, the overarching research approach was established and four conceptual logistics strategies were derived (Section 3.2). Subsequently, the *Data Collection* process was initiated. Data collection is particularly important to understand all aspects of the problem, such as the decision on relevant input data, and to provide a reliable basis for simulation modelling and analysis (Onggo and Hill 2014). The *Data Collection* process was informed by interviews with plant structure/logistics planners and logistics managers of our industry partner as well as primary (e.g., historic data from ERP system) and secondary data (e.g., product data sheets). In accordance with the information from the *Planning* and *Data collection* phase, in the *Simulation* phase, the real-world environment has been modelled on a conceptual basis, before an iterative development approach was employed to design, validate and implement the technical simulation model (Section 3.3). Following the analysis of 100 experiments per logistics strategy (Section 4), strategy-specific implications as well as the scientific and practical knowledge of the findings were synthesized (Section 5).

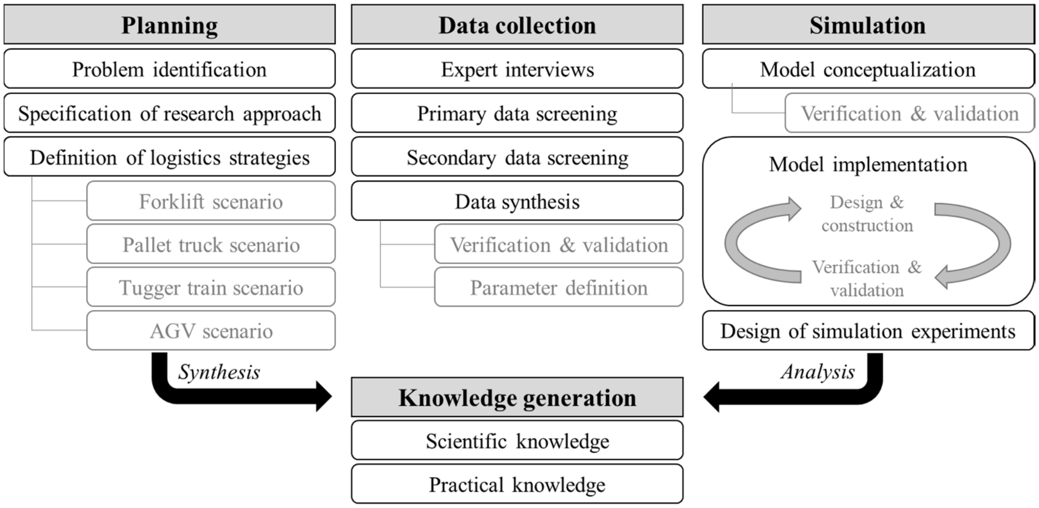

Figure 2: Research design for this simulation study.

3.2 Logistics Strategies, Model Parameters, and Assumptions

Within the scope of our simulation study, four logistics scenarios have been assessed (Figure 3). In the *Forklift* scenario, forklifts are employed to transfer both BLCs as well as SLCs from the internal warehouse to the assembly lines. The referenced forklift vehicle is a *Cesab R112* with an acceleration and deacceleration of 0.28 m/s^2, maximum speed of 10 km/h, lifting speed of 0.37 m/s, lowering speed of 0.50 m/s, and a carrying capacity of 1 load carrier. In contrast, the *Pallet truck* scenario employs different modes of transportation for BLCs and SLCs. Here, forklifts are used to transfer BLCs to the assembly lines, while pallet trucks (*Jungheinrich AM22* with 0.12 m/s^2 acceleration and deacceleration, 4 km/h maximum speed, 0.15 m/s lifting speed, 0.20 m/s lowering speed, and a carrying capacity of 3 load carriers) are utilized for the transportation of SLCs. Pallet trucks depart from the internal warehouse in line with a timeout of 30 or 60 minutes or based on a pooling concept, which schedules a transportation activity as soon as sufficient material call-offs are available to utilize the capacity limit (i.e., 3 load carriers) of a given pallet truck. Similarly, the *Tugger train* scenario features a combination of forklifts that are responsible for the transportation of BLCs and a tugger train that moves SLCs from the internal warehouse to the assembly lines in the production plant. The tugger train consists of an electric drive vehicle and four trailers, each featuring space for three SLCs. The referenced tugger train is a *Still Liftrunner* with *C-Frame* trailers and

0.16 m/s^2 acceleration and deacceleration, a maximum speed of 6 km/h, and a removal time of 6 seconds per SLC. Within the capacity limits of its trailers, the tugger train can carry any combination of SLCs and has access to the same path network than forklifts, pallet trucks and AGVs. Again, transportation activities are scheduled based on a fixed timeout (i.e., 30/60 minutes) or as soon as material call-offs equal the capacity limits of the transportation unit. Ultimately, the *AGV* scenarios uses forklifts for BLCs and AGVs for SLCs. AGVs have been modelled based on the *Active Shuttle* concept of *Bosch Rexroth* with 0.1 m/s^2 acceleration and deacceleration, 3.6 km/h maximum speed, 5 seconds removal time per SLC, and a carrying capacity of 3 load carries. Removal processes from the rack storage are fully automated.

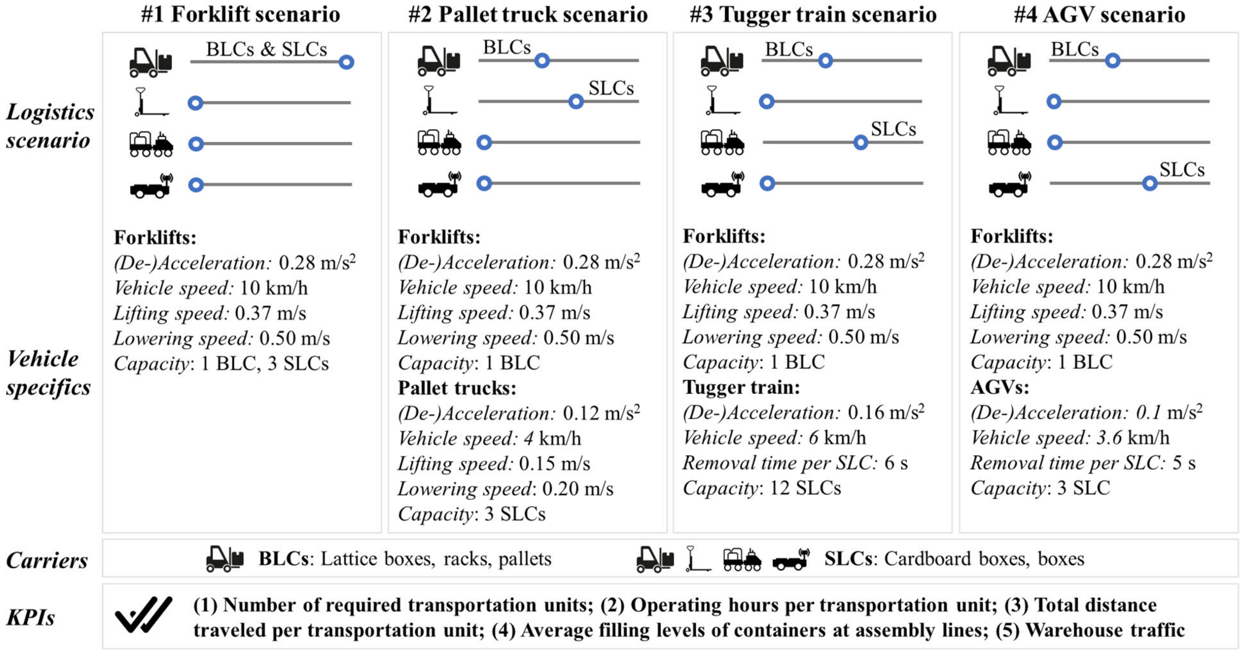

Figure 3: Overview of logistics strategies (scale indicates share of transportation units).

Based on the real-world system and its operational peculiarities, it is supposed that SLCs are stored at the lowest level of a given high-bay storage area, while BLCs are stored at the levels two to tens. Supply processes are modelled as black box, ensuring unlimited supplies of consumed goods in the internal warehouse. Transportation units, regardless of their type, share one common home location in the internal logistics warehouse and always return to this location if they have not been assigned with any transportation request. It is assumed that the entire fleet is electric and that battery levels are recharged at the home location when transportation units are inactive. Moreover, to allow for comparing the required number of transporters for different scenarios and objectives, the maximum number of transportation units have not been restricted and the fleet sizes have been determined based on the given demand in the system. For this purpose, a dynamic insertion algorithm constantly checks the mean utilization rate of a given fleet (e.g., forklifts) and adds an additional transportation unit to this fleet if a certain threshold (e.g., 80 %) is reached.

The operational warehouse system is analyzed on a daily basis and features three work shifts, each of which consists of seven hours. Order quantities and sequences from the consumption points (i.e., the assembly lines) are modelled based on three different settings. In setting 1 (Historical Data), demands are projected based on historical ERP data. In setting 2 (Positive Peak), material requests from the assembly lines are set based on a hypothetical high level of requests, while setting 3 (Negative Peak) assumes a hypothetical low level of material requests. In setting 2 and setting 3, the demand of each consuming point is randomly generated based on variations of the historical data that decrease (setting 2) or increase (setting 3) the total number of material requests by 50 % (setting 2) or 100 % (setting 3). In line with the dual-container Kanban system, two containers are present at the assembly lines at the beginning of each working day. As soon as all materials from one container have been consumed, a material request is scheduled and the second container is employed within the production process to avoid delays. Accordingly, at the beginning of a working day, there are always two containers at a workstation, whereby the initial fill level of the containers differs depending on the material type and range from 50 % to 70 %. The distance from the home location of the transportation units in the internal warehouse to the assembly lines differs by route as well as consumption point and ranges from 178 (i.e., shortest route) to 286 meters (i.e., longest route). Furthermore, within the production environment, a set of 20 production AGVs with fixed routings (see bold lines in Figure 4) and timings is modelled and may obstruct supply vehicles that opt to fulfill a material request from a given assembly line. A synopsis on relevant model parameters can be found in Table 1.

Table 1: Model parameters.

Paramater	**Value**	**Unit**	**Type**
Block storage space/Small parts high-bay storage space	1,312/4,800	Materials	Fixed
Collision detection timeout	2	Seconds	Fixed
Consumption points	11	Workstation	Fixed
Container capacity	4-85,000	Materials	Variable
Fleet utilization threshold	70/80/90	Percentage	Variable
Initial container fill levels	50-70	Percentage	Variable
Large parts high-bay storage space	678	Materials	Fixed
Material unloading duration (min/mean/max)	10/20/30	Seconds	Stochastic
Production AGVs	20	Vehicles	Fixed
Production areas	4	Assembly lines	Fixed
Transportation scheduling timeout	30/60	Minutes	Variable
Waste unloading duration (min/mean/max)	5/10/15	Seconds	Stochastic
Working hours per shift	7	Hours	Fixed
Working shifts	3	Shifts	Fixed

3.3 Discrete-event Simulation Model

Since the assignment, routing and choice of transportation units is part of a dynamic production environment that features a high degree of interdependence and complexity, an analytical solution would not be feasible. Instead, a simulation model has been developed to imitate the operations of the real-world system over time and evaluate different logistics strategies in terms of multiple what-if analyses (Banks 1998).

To analyze the operational implications of the proposed logistics strategies, a DES model has been built in AnyLogic Professional (v. 8.8.1). Here, the synchronous time advancing mechanism in the model is triggered by a sequential list of events that represent the internal operational logic of the simulation. The central components of the simulation model are the storage facilities (block and high-bay storages), the transportation units as well as the eleven assembly lines that act as consumption points for the material requests. As depicted in Figure 4, initially, materials are loaded from the database and assigned to the given storage areas. At the beginning of each working day, containers with random fill levels between 50 % and 70 % are initialized at the assembly lines to account for the remaining filling levels of the previous working day. In line with the dual-container Kanban system, a material request is scheduled as soon as a given container is empty. Depending on the type of material and scenario, the material request is assigned to the respective vehicle fleet. For SLCs, requests are collected until the vehicle-specific transportation capacity is met or the predefined timeout is reached. Upon material drop-off, vehicles collect the empty container(s) at the assembly lines und transfer them to the waste area. Afterwards, they check for additional material requests. While pallet trucks, tugger train and AGVs return to their home location if there no material requests are left, forklifts check whether there are containers at the inbound docks that need to be stowed. In reference to the higher-level material call-offs from the internal logistics warehouse to the external outdoor storage area, inbound deliveries take place according to a black-box scheme that spawns inbound deliveries if a specific number of BLC containers (i.e., 20) has been removed from the storages. If there are no containers left for storage at the inbound docks, forklifts check if there are empty cells at the bottom of the high-bay storages and refill these cells from upper areas of the same storage as needed. Operations of the vehicle fleets are monitored continuously and a dynamic insertion algorithm adds an additional transporter to the fleet if the pre-specified utilization threshold (e.g., 80 %) has been reached.

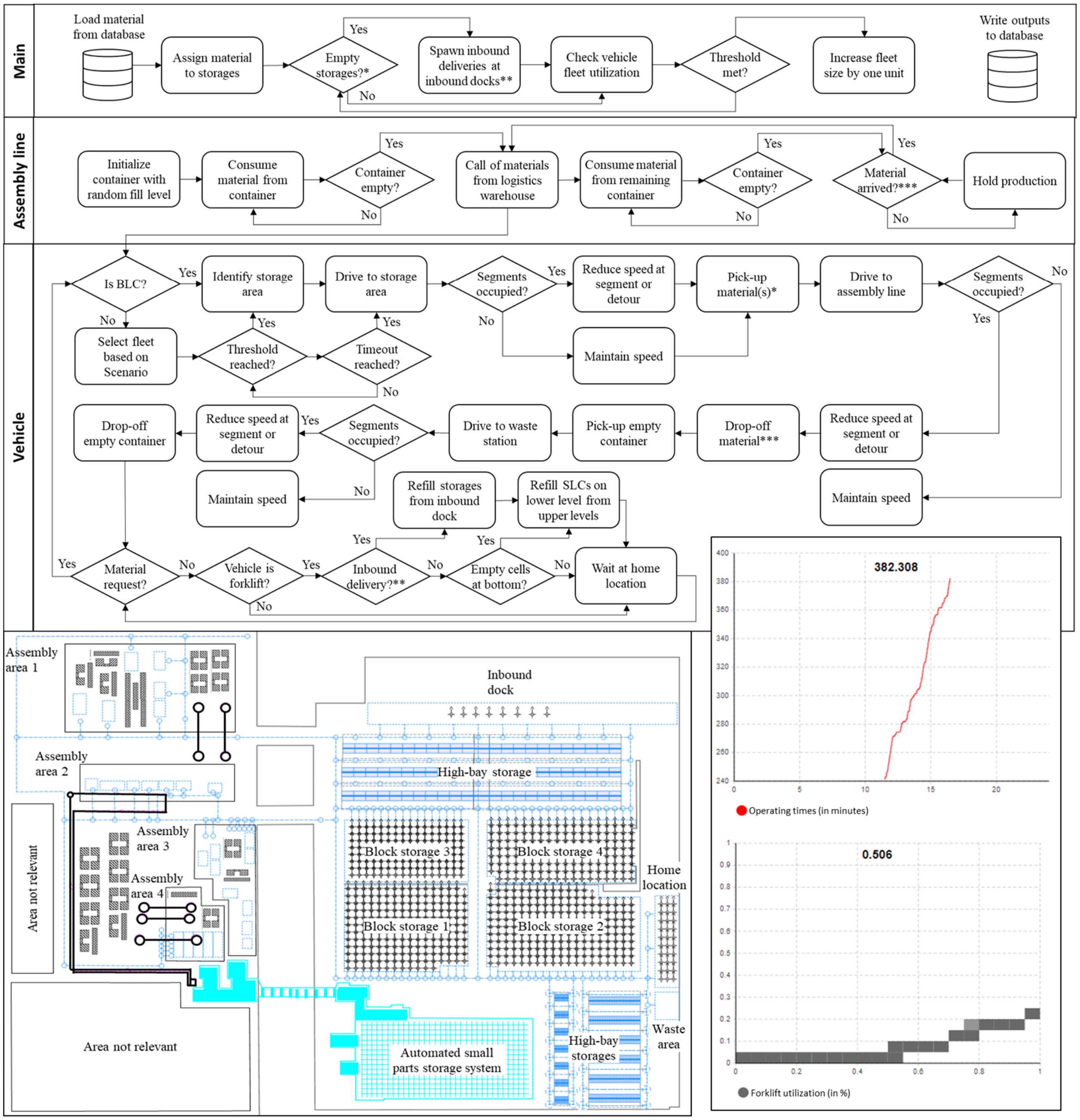

Figure 4: Environment and flowchart chart of the DES model.

Vehicle routing is based on a path network within the production environment (dotted lines in Figure 4). The paths of a route can be shared my multiple vehicles. However, a collision detection algorithm has been implemented to delay vehicles that have to bypass (i.e., meet in opposite directions) each other on a given path. To account for safety restrictions due to narrow transportation paths, which are typical for JIS production environments (Meissner 2010), vehicles cannot overtake each other. If a path segment is blocked by a slower vehicle (i.e., AGV), faster vehicle units have to adapt their speed on the respective path segments until they reach a segment that is not occupied in the same direction. Moreover, the plant layout features two routing bottlenecks, namely the two locks between the lower logistics hall and the upper production hall. Here, even bypassing is not possible. Therefore, the routing algorithm blocks these areas for other transportation units whilst they are occupied by a given transporter. To solve the individual routing problem for forklifts, pallet trucks, tugger train, and AGVs, a CVRP (Crainic and Laporte 1998) has been formulated, where a set of routes needs to be found that start and end at the vehicle's home location, visit and serve each consumption point only once, without exceeding each vehicle's capacity, while minimizing the total transportation costs in terms of distance (i.e., sum of the costs of the arcs related to the routes). For solving the CVRP, Google's OR-Tools were used and the routing model imported to AnyLogic. Finally, the DES model and its components were calibrated and validated by comparing historical operations data to the results of setting 1 in the *Forklift* scenario, showing no deviations in terms of fleet size and minimal deviations (< 5%) concerning material request volumes (i.e., demand), operating times, and mileages.

4 EXPERIMENTAL RESULTS

Following a Monte Carlo approach, the results of 100 simulation replications with random sampling per logistics scenario, setting, and scheduling timeout were averaged, with each simulation run equaling one working day (i.e., 21 hours). To improve usability, case analyses were performed based on the respective scenario, setting, and timeout for scheduling SLC transportation activities. Table 2 synopsizes the required transportation units per type (KPI 1), the average demand in terms of transportation/discard (SA) and refill (RS) requests, as well as the average filling levels of all containers at the assembly lines.

Table 2: Required transportation units and transportation requests for each configuration.

Scenario	**Setting**	**Scheduling timeout**	**Demand (SA/RS)**	**Average filling level %**	**No. forklifts**	**No. pallet trucks**	**No. tugger trains**	**No. AGVs**	**No. total vehicles**
Forklift	Setting 1 – Historical data	30 minutes	820/369	18.3	5	0	0	0	5
		60 minutes	820/370	18.3	5	0	0	0	5
	Setting 2 – Negative peak	30 minutes	436/177	18.1	3	0	0	0	3
		60 minutes	434/177	18.1	3	0	0	0	3
	Setting 3 – Positive peak	30 minutes	1564/738	18.0	13	0	0	0	13
		60 minutes	1562/743	17.9	13	0	0	0	13
Pallet truck	Setting 1 – Historical data	30 minutes	820/369	18.2	4	5	0	0	11
		60 minutes	820/370	18.2	4	4	0	0	8
	Setting 2 – Negative peak	30 minutes	434/177	18.1	3	3	0	0	6
		60 minutes	434/176	18.1	3	3	0	0	6
	Setting 3 – Positive peak	30 minutes	1572/753	18.0	8	7	0	0	15
		60 minutes	1578/745	18.0	9	8	0	0	16
Tugger train	Setting 1 – Historical data	30 minutes	586/361	17.5	3	0	1	0	4
		60 minutes	584/361	17.4	3	0	1	0	4
	Setting 2 – Negative peak	30 minutes	346/175	18.0	2	0	1	0	3
		60 minutes	320/174	17.9	2	0	1	0	3
	Setting 3 – Positive peak	30 minutes	1064/625	7.8	7	0	1	0	8
		60 minutes	1062/626	7.8	6	0	1	0	7
AGV	Setting 1 – Historical data	30 minutes	816/369	18.1	4	0	0	5	9
		60 minutes	818/368	18.2	4	0	0	5	9
	Setting 2 – Negative peak	30 minutes	436/176	18.1	2	0	0	3	5
		60 minutes	432/176	18.0	2	0	0	3	5
	Setting 3 – Positive peak	30 minutes	1576/746	17.9	9	0	0	9	18
		60 minutes	1568/742	17.8	9	0	0	11	20

While the *Tugger train* scenario features the lowest number of total transportation units across all settings, the average filling levels are rather low compared to the other scenarios, especially when material requests are peaking. This is a cause for concern as it represents a high risk of production stops due to an absence of materials at the assembly lines. In contrast, the *Forklift* scenario encompasses a comparably low number of transportation units for all settings, while also ensuring reasonable filling levels at the assembly lines. Still, it is noteworthy that forklift operations come with several drawbacks such as the need for a skilled, costly workforce and more volatile, expensive equipment (Min 2007). Thus, despite the higher total number of required transportation units, also the *Pallet truck* scenario appears to be a favorable choice for JIS suppliers, as it features a low number of forklifts for different settings, with moderate requirements for the pallet truck fleet and high filling levels. In contrast, the *AGV* scenario is less advisable under the given conditions, as it is rather inflexible and thus requires a high number of AGVs, while reducing the required number of forklifts to a similar extent than the use of pallet trucks (but requiring the introduction of a new logistics system). In terms of operating time (KPI 2), Figure 5 shows that the *AGV* scenario results in the highest number of operating minutes across all settings, while the *Forklift* scenario features the lowest total operating time. Interestingly, using pallet trucks or a tugger train seems to be particularly effective for low volumes and can notably decrease the operating times of forklifts, whereas high volumes are best handled solely by forklifts. In turn, pallet trucks enable robust operations and, only excelled by the *Forklift* scenario, show low fluctuations on operation time when facing different request volumes and scheduling timeouts.

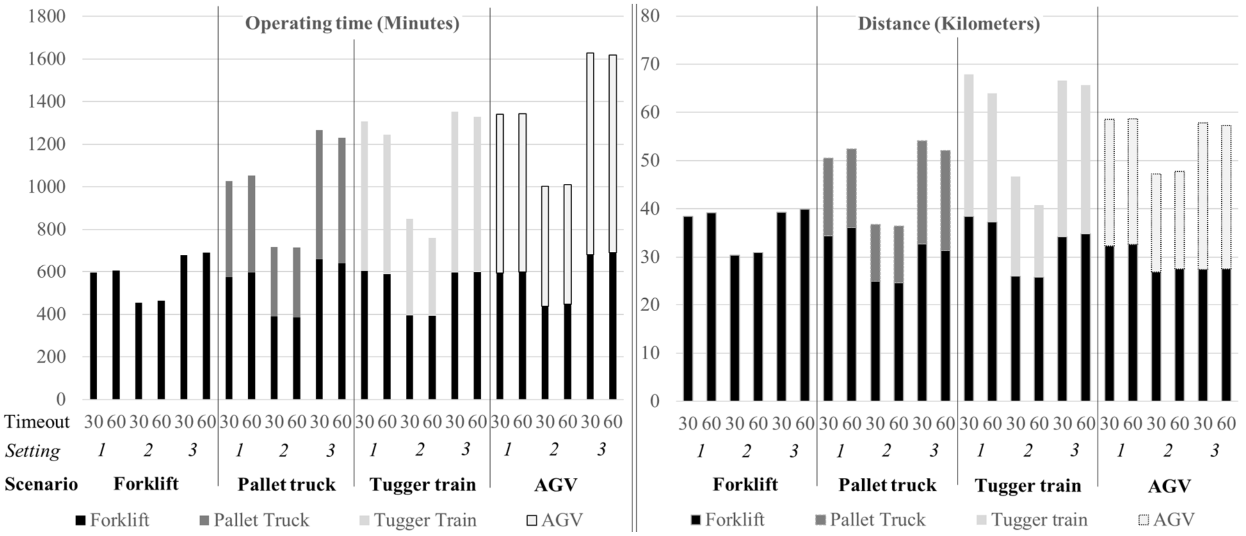

Figure 5: Operating time and distance traveled of vehicles in the supply system.

Concerning distances, Figure 5 indicates that mileages can be kept at minimum when using forklifts as sole transportation unit. Furthermore, the *Pallet truck* scenario appears to result in rather little distances, while the *Tugger train* scenario features the highest number of travelled kilometers across all scenarios and settings. However, in this context, it needs to be mentioned that distance traveled alone is not a realistic proxy for warehouse traffic. Instead, warehouse traffic needs to be conceptualized as a combined product of the number of transportation units, their operating times and operating speeds, as well as the travelled distances. Now, looking at the combined indicator for warehouse traffic (Table 3), it becomes obvious that both, the *Pallet truck* as well as the *Tugger train* scenario are capable of outperforming the traditional *Forklift scenario* in terms of warehouse traffic when it comes to negative and positive peaks. Moreover, these scenarios also perform similar to the *Forklift* scenario in the setting that is based on historical data.

Table 3: Warehouse traffic indices across the investigated scenarios (best result per setting in bold).

Setting	**Forklift scenario**	**Pallet truck scenario**	**Tugger train scenario**	**AGV scenario**
Setting 1 – Historical data	**1187**	1358	1200	1381
Setting 2 – Negative peak	465	**342**	406	537
Setting 3 – Positive Peak	3636	2540	**2414**	3687

Overall and across all KPIs, it seems beneficial to employ rather short scheduling timeouts for forklifts and pallet trucks, while long scheduling timeouts yield more operational benefits for tugger trains and AGVs.

5 DISCUSSION AND CONCLUSION

Proper material flows are highly important for production systems in general as well as JIS environments in particular. Thus, this work studies the real case of an internal material supply and routing problem in a JIS environment. A DES model has been developed to investigate the implications of four distinct logistics strategies under different circumstances. The strategies are compared to each other based on five KPIs that are typically employed to assess the effectiveness of internal material flow processes in research and practice (Wagner and Silveira-Carmargos 2011), namely (1) number of transportation units, (2) operating hours, (3) total distance traveled, (4) average filling levels at assembly lines, and (5) projected warehouse traffic, which is conceptualized through several indicators such as mileage, speed, and operating time.

Traditionally, forklifts are employed as main transportation unit in JIS production environments because they allow for a high degree of flexibility and scalability (Vonolfen et al. 2012). However, forklift operations come with several pitfalls. On the one hand, they raise traffic and feature a higher risk for traffic congestion, which can be linked to unforeseeable delays and safety threats (e.g., accidents). On the other hand, their operations are more expensive since they require a skilled workforce. While forklifts may feature the most benefits in terms of absolute numbers, our simulation has shown that other logistics systems such as pallet trucks and tugger trains can also be beneficial in different settings to cope for the disadvantages of forklifts without entailing major drawbacks for relevant KPIs such as fleet size and operating times. Even though the use of AGVs seems to be rather inadvisable based on our results, it also needs to be mentioned that they feature additional benefits that have not been investigated in this study. Logistic systems that are based on manual processes are generally more vulnerable to inefficiencies such as information loss, bad oversights of the work in process level, missing parts, wrong parts delivered, and excessive inventories. In turn, the use of automated solutions such as AGVs can cope for these risks, which may feature additional benefits beyond the investigated KPIs. In addition, the decision for manual or automated logistics systems is also based on the contractual time frame of the supplier. Since Tier 1 suppliers often have long-term contracts with OEMs, it may still be worthwhile to invest in automation and long-term restructuring programs rather than manual transport systems and short-term process changes.

Overall, our results correspond to insights that have been generated by prior research under similar circumstances and in similar environments (e.g., Filz et al. 2019; Wang et al. 2014). Since the conditions, constraints, and assumptions of this study have been derived from the real case of a major JIS-supplier in Germany, its propositions are highly valuable for research and practice. On the one hand, they contribute to a more thorough understanding of operational interdependencies and implications that are directly related to the choice of logistics strategies for internal material supplies. On the other hand, our DES model can be used by practitioners to test the influence of various logistics strategies on their supply and production processes. The main question arising from our research is to what extent the investigated scenarios really contribute to dissolve the everlasting dilemma of productivity and flexibility when extending the scope to an intralogistics end-to-end view, or whether they are not just allowing for more flexibility at the expense of higher inventory levels. In future research this needs to be addressed in an amplified simulation and by using different combinations of supply strategies to increase the usability of our model and results.

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