MODELLING AND SIMULATING THE ASSEMBLY LINE SUPPLY BY TUGGER TRAINS

T. Staab[(a)], M. Röschinger[(b)], M. Dewitz[(c)], W. A. Günthner[(d)]

Institute for Materials Handling, Material Flow, Logistics – Technische Universität München

[(a)]staab@fml.mw.tum.de, [(b)]roeschinger@fml.mw.tum.de, [(c)]dewitz@fml.mw.tum.de, [(d)]kontakt@fml.mw.tum.de

ABSTRACT

Tugger trains are an efficient and flexible material supply concept especially for mixed-model assembly lines. However, the performance and efficiency of a tugger train system are influenced by many external factors (e.g. material throughput) and internal interdependencies (e.g. cycle times, overtaking or stopping) making a discrete-event simulation necessary to prove the feasibility of the planned systems. We present the results of a simulation study carried out on behalf of the BMW Group. For this, we used a generic simulation model which was adapted to the unique requirements and elements of the planned system. We determined the security of supply and level of service and validated tugger train routes and schedules. The congestion on roads and intersections, space for overtaking and the number of trains passing and supplying a point of need were found to be the main influencing factors.

Keywords: tugger train, in-plant milk-run, mixed-model assembly line, interdependencies of vehicles

1. INTRODUCTION

In practice, tugger trains (TT) are a very common concept for the in-plant transport of materials. As the trend towards individual customer products continues, a greater number of different products have to be produced in the same production facilities, thus it follows that more different materials have to be supplied to the different points of need. Especially, but not exclusively, manufacturing companies with a mixed-model assembly line concept find themselves confronted with the situation that this greater number of different materials cannot be supplied within the restricted space of the production facilities with the current safety stock levels and lead times (Emde and Boysen 2012). Therefore, stock levels must be reduced, and this hand-in-hand with smaller lot sizes and containers and a high-frequency provision of materials.

Tugger trains (sometimes in-plant milk-run concepts are used synonymously) are an approach to fulfil those needs. So-called TT, usually consisting of a manually-operated industrial truck and several trailers, circle on predefined routes through the production area and are loaded with whatever material is needed at the points of need assigned to this route. Often these TT are operated according to a fixed timetable similar to public transportation (Brungs 2012; Günthner et al. 2012; Kilic, Durmusoglu and Baskak 2012). The points of need are passed on each TT tour, so the recurrence period is much shorter than with typical direct transport concepts using a forklift truck, for example. As different materials are transported on the same tour, even small batches and containers can be supplied efficiently (Baudin 2004). Those are just some of the reasons why the BMW Group has decided to introduce standardised TT systems in all of its vehicle plants (Arlt 2012). Furthermore, central logistic areas for storing and sequencing the material as well as loading the TT were built close to the production areas.

While in an early planning phase, analytical models were sufficient to estimate, for example, the required number of employees and TTs, a more detailed investigation was necessary to prove the feasibility of the new logistic processes prior to their “going live”. External factors such as the material requirements or the location of the points of need as well as internal interdependencies between IT processes (e.g. call-off processing), TTs and other vehicles were seen as important factors influencing the performance and efficiency of the TT system. For this reason, a discrete-event simulation study was carried out on behalf of the BMW Group. The study’s main aspects and results are to be presented in this paper.

2. SCOPE AND STRUCTURE OF THE PAPER

This chapter provides basic information concerning the design and control strategies for TT systems, as well as a brief literature review on available methods for the planning and dimensioning of TT systems. Section 2.3. describes the procedure during the simulation study and the structure of this paper.

2.1. TT systems for material delivery

In practice, various concepts for TT systems exists which differ considerably with respect to size, process design and material equipment. However, some basic elements most TT systems have in common are shown in Figure 1. Furthermore, referring to (Günthner et al.

2012) and (Martini, Stache and Trenker 2014), typical design variants for each element are displayed.

Starting from a material source close to the production site, material is either stored or buffered. A so-called material call-off represents a demand for a specific material at a specific point of need at a specific time. To satisfy this demand, the tour on which the material call-off will be transported must be determined. While in flexible TT systems, every tour serves different points of need and tour start-times are dynamically planned, most industrial applications are operated according to fixed transportation routes and timetables. All material call-offs assigned to a tour are then taken from the material source and loaded onto the TT. This can be done either directly (e.g. by taking the TT through the warehouse), or the load is buffered within a separate station and is loaded onto the TT there. Afterwards, the delivery itself starts. For this, the driver must pass at a minimum all the points of need of the assigned material call-offs using a shortest path navigation. However, additional tasks, such as empties handling or replenishment control tasks (e.g. collecting kanban cards), could require a static routing strategy.

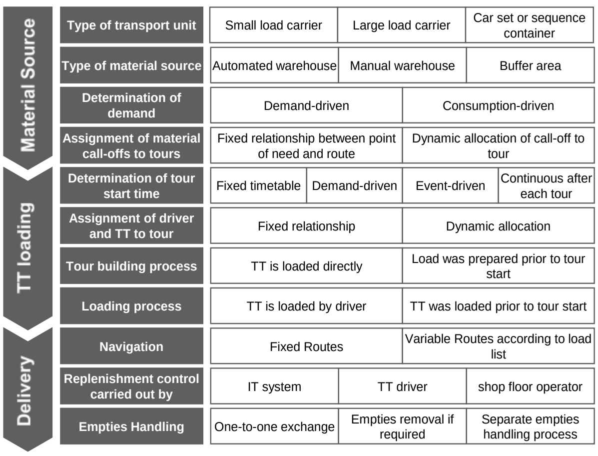

Figure 1: Basic Elements And Design Variants Of TT Systems

These design leeways, combined with many interdependencies, result in a highly complex TT system and a difficult planning task. In addition, TTs share various resources (e.g. roads, intersections, loading areas) which leads to an even greater complexity (Staab, Galka and Klenk 2013a) that cannot be analysed using analytical models, making a discrete-event simulation necessary.

2.2. Brief literature review

Most available literature on TT systems, such as (Gyulai et al 2013), (Vaidyanathan et al. 1999) and (Emde and Boysen 2011), focus on finding an optimal route using adapted vehicle-routing problems (VRP). (Dewitz, Günthner and Arlt 2014) describe a model for calculating cycle and departure times in order to generate smoothed TT schedules. Stochastic influences, such as demand fluctuations or road blockages, as well as interdependencies between different system elements, are not taken into account.

Therefore, companies, especially in the automotive industry, use discrete-event simulation to support the planning of intralogistics processes in general, and TT systems in particular (Günthner et al. 2012). (Costa et al. 2008) and (Wiegel et al. 2013) present models and results of case studies for specific TT systems. Generic modelling approaches are presented in (Mayer and Pöge 2010), (Dreher, Nürnberger and Kulus 2009), (Roth 2012) and (Staab, Klenk and Günthner-2013b). (Mayer and Pöge 2010) introduces the so-called *VDA Automotive Library* for *Plant Simulation*, a modelling kit of currently 14 libraries with standardised modules for production systems in the automotive industry, including TT systems.

Alternatively, with the *MALAGA* commercial software product (see Dreher, Nürnberger and Kulus 2009; Roth 2012), planning and optimising TT systems is possible, but these are subject to the same restrictions of the analytical models mentioned before. An interface to Plant Simulation called *ZIP Massimo* exists to validate the results.

(Staab, Klenk and Günthner 2013b) describe an alternative approach. The generic simulation model focuses on modelling TT systems and traffic situations, rather than production systems in general. The simulation model thereby requires less standard components from the framework and can be adjusted to the unique requirements and aims of the simulation study.

2.3. Methodology and structure of the paper

In this paper, the main modelling aspects and results of a simulation study on a TT system will be presented for which the same generic modelling kit described in (Staab, Klenk and Günthner 2013b) was used.

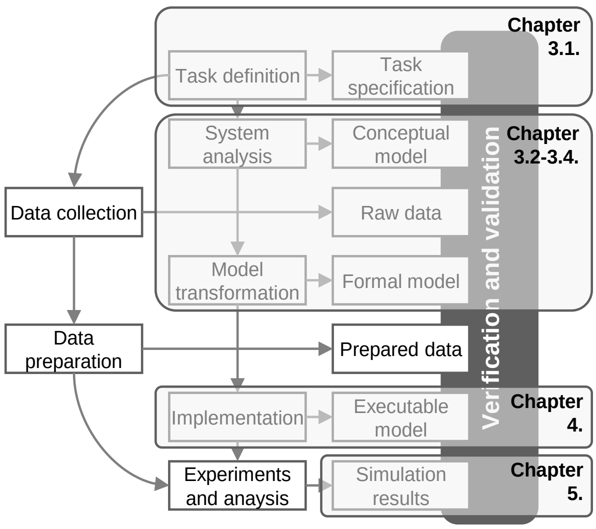

Figure 2: Procedure During The Simulation Study And Structure Of The Paper According To (VDI-Richtlinie 3633 Blatt 1 2014)

Taking into account the complexity and size of the modelled system, a structured procedure during the simulation study was essential. For this, the procedure model for a simulation according to (VDI-Richtlinie 3633 Blatt 1 2014) was used which also formed the basis for the structure of this paper (see Figure 2). The tasks and aims of the simulation study are pointed out in chapter 3.1. As part of the systems analysis, chapter 3.2.-3.4. focuses on the key information and description of the modelled system. Chapter 4 describes the executable simulation model and the implementation of specific elements which were unique to this simulation study. Further information can also be found in (Staab, Klenk and Günthner 2013b). The main results of the simulation study are presented in Chapter 5.

3. MAIN ASPECTS OF THE CONSIDERED SYSTEM

This chapter contains the description of the TT system which is investigated in the research project. The deep understanding of the system and its processes is essential, as it serves as the basis for the subsequent modelling process which is also presented in this chapter in respect of its main aspects and challenges.

3.1. Key figures for characterising the system

Due to the great complexity of the system, the discrete-event simulation was executed in order to support the current planning stage. Different key figures, which characterise the system, were defined and determined in simulation runs. The key figures can be assigned to the following categories and questions:

- Security of supply: Can the material be provided at the assembly line at the scheduled time?
- Level of service: Can all the material be provided with the planned TT routes and scheduled tours?
- Employee requirements: How many employees are necessary to handle the scheduled TT tours?
- Space requirements: How much space is necessary for departing and returning the TT in the train station area?
- Volume of traffic: How do interdependencies with other system elements influence the TT tours?

In order to understand the choice and relevance of the key indicators, the system is described closer in the next sections. Initially, a short overview of the overall process, which is visualised in Figure 3, is given. On this basis, the procedures of the IT control systems are described. Finally, the driving behaviour of TT and the corresponding restrictions are explained.

3.2. Overview and key information

Based on material requirements along the assembly lines, material call-offs are generated and sent to the central IT control system. Here, the material call-offs are collected and, according to a static timetable, assigned to a specific TT tour. At a pre-determined point in time, which refers to a tour's scheduled departure time, the loading process begins. All the material thereby assigned to the tour is loaded onto a train, with each trailer carrying a maximum of four frames each.

In this context, basically two processes have to be distinguished. On the one hand, components can be loaded manually onto the frames in a picking warehouse, whereby the material on one frame is of the same type and intended for one specific delivery point along the assembly line. On the other hand, there is an automatic process, in which the train's frames are loaded with containers for different delivery points. The containers are stored in an automatic small parts warehouse and automatically brought onto the frames by using different conveyor systems.

Manually-loaded TTs are provided on defined departure tracks in the train station area punctually before the scheduled departure time. As soon as this time is reached, a driver takes the train and leaves the train station area. Automatically-loaded TTs, however, need to pick up the loaded frames before leaving the train station area. The train which, at this moment, consists of four trailers with each one carrying an empty frame, drives into an automatic frame-converter device. Therein, empty frames are removed from the trailers and full frames, which are provided by a conveyor system, are moved onto the trailers. Afterwards, the TT leaves the device and finally, at the scheduled departure time, the train station area.

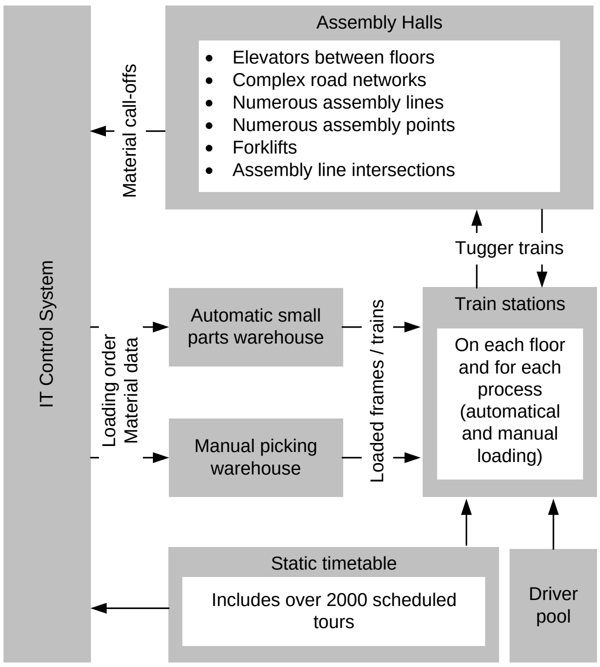

Figure 3: Overview Of The Considered TT System

All the TTs run on several determined routes through the assembly halls where they stop at the delivery points for which they are transporting materials. In the case of manually-loaded trains, full frames are exchanged with empty frames at the delivery point, whereas in the case of automatically-loaded trains, containers are exchanged. After delivering all the contained materials, the TTs return to the train station, where they stand by for the next tour. So, in the course of one day, over 2000 tours supply about 1000 assembly points.

3.3. Call-off processing in the IT control system

The main task of the IT control system is the processing of material call-offs. These are generated in different ways along the assembly line, which is why the three types of call-offs represented in the following sections have to be differentiated.

3.3.1. Call-offs for sequenced components

At each individual assembly point, a defined component, which belongs to a certain material type but exists in several variants, is added to the product. Therefore, all the variants of a component, which are to be assembled within the next assembly cycles, must be available at each assembly point, namely in the sequence they are installed. In order to achieve this, corresponding material call-offs are generated at specific call-off points along the assembly lines. These points are located at a pre-determined distance from the points where the material is needed for installation. When defining the distance between assigned call-off and assembly points, sufficient time for delivering the material in time is considered and ensured.

For a pre-determined period of time, the IT control system collects all the call-offs for one individual assembly point. It then looks for a TT route which passes this point. As there are several tours within one route, the next step is to select an appropriate tour from the timetable. The scheduled time of each tour, at which the TT returns to the train station, is considered in this. Only if this time is before the time at which the material is needed at the assembly line, and the tour's planned loading and departure time have not yet elapsed, is the tour viable. The component needed earliest is thereby decisive. Finally, the last but one tour, which fulfils the described requirements, is chosen. This is because, in the next step, it might be that the capacity needed for delivering all the requested material exceeds the capacity provided by one TT. In this case, the material is assigned to the latest possible tour. This is, in other words, the last tour which returns to the train station before the point in time at which the material is needed. In this context, it has to be taken into account that the materials for other assembly points also passed by the route might already be attached to the selected tour. Furthermore, a TT contains a maximum of four frames, whereby each one is loaded with material for one specific assembly point. So, if it is not possible to assign the material to a scheduled tour, the IT control system initialises an additional special tour.

After a tour is planned, the data is forwarded to the picking warehouse where the frames are loaded with the required variants of the components. Due to pre-determined time management, it can be ensured that the loaded TT is ready in the train station at the scheduled departure time of the tour at the latest.

3.3.2. Demand-driven automated call-offs for containers

As mentioned above, in addition to the manual loading process, there is also an automatic loading process in which containers stored in an automatic small-parts warehouse are automatically conveyed onto the frames. The corresponding material call-offs for the containers are generated at specific points along the assembly line. Each of these points is located at a defined distance from the material's assembly point as already described above. If the product which passes the call-off point requires the material at the assigned assembly point, the stock of the respective material is proactively reduced by the required number of components. When, as a result, the defined minimum stock falls below a pre-determined value, a container call-off is generated.

The further planning corresponds largely to the already-specified methodology (see 3.3.1.). Thus, the container is booked onto the tour passing the assembly point and is the second to last tour which guarantees a punctual delivery. At a pre-determined time, referring to a tour's scheduled departure time, the tour is closed. Thus, no more material can be assigned onto the tour and the removal of the already attached containers from the automatic small parts warehouse is initiated. Whilst loading the frames, the sequence of unloading the containers is considered. This means that the storage shelves of the frames are filled, beginning with the containers which are removed first at a delivery point. Thus, the frames are loaded and unloaded on different sides.

3.3.3. Consumption-driven Kanban call-offs for containers

Not all containers are called off automatically as described in the last section, there is a kanban-based method, too. Nevertheless, the processing of the call-offs does not differ significantly, other than that the kanban call-off is generated directly at the assembly point. A sign there indicates that a container has run empty. Afterwards, the call-off is generated by a passing TT's driver. The IT control system then looks for when the next tour is leaving, which is not already closed for loading, and assigns the required container onto this tour.

3.4. Vehicle's driving behaviour and restrictions

After a TT leaves the train station area, it goes into the assembly halls. The TTs can move between the floors using a vehicle elevator. Coming from a train station, a TT always follows the pre-determined route, to which the tour is assigned, across the assembly hall.

On its way along the assembly lines, a TT stops at the assembly points where material has been loaded onto the frames. An unloading TT standing at an assembly point can be overtaken by another TT whose next destination is not the same assembly point. However, in the case of one-way roads along the assembly lines, this is only possible if the road is wide enough. As this is not always given, corresponding restrictions referring ranges of road widths are stated in a traffic concept. Furthermore, the admissibility of overtaking depends on the type of the TT, above all in terms of its trailer´s width. For example, a TT transporting containers must overtake all other TT on medium and wide roads whereas a TT transporting sequenced components must only overtake on wide roads. In case of roads with oncoming traffic the same restrictions are valid. Additionally, a TT´s driver must assure that no oncoming train is hindered before overtaking.

Besides TT other vehicles also move around in the assembly halls. These vehicles, e.g. forklifts, deliver large components and containers, and present obstacles for the TT as they move more slowly and cannot be overtaken.

According to the arrangement of the assembly lines, the road networks include a few dead ends where TTs have to turn around. This represents one particularity of the road networks. Another one is the existence of numerous intersections due to the roads having been designed along mainly parallel assembly lines flowing into orthogonally-arranged main roads. Hence, there are intersections with up to four adjoining roads and therefore the definition of the rights of way becomes inevitable. These definitions are shown in Figure 4 and state that a TT coming from a road along an assembly line has priority when turning onto the main road. This is because at the end of a few of the roads along the assembly lines, there are crossing gates which close according to the assembly cycles. Thus, it can be ensured that no TTs block assembly line crossings and the material flow of the products which are conveyed on a parallel running line. For the same reason, TTs intending to turn from the main road onto a road along an assembly line have secondary priority, providing there is enough space behind a crossing gate. The last priority is assigned to TTs moving straight on the main road. Apart from the priority rules, there is the regulation that, if the intended turning directions allow turning without collision, more than one TT may turn at the same moment.

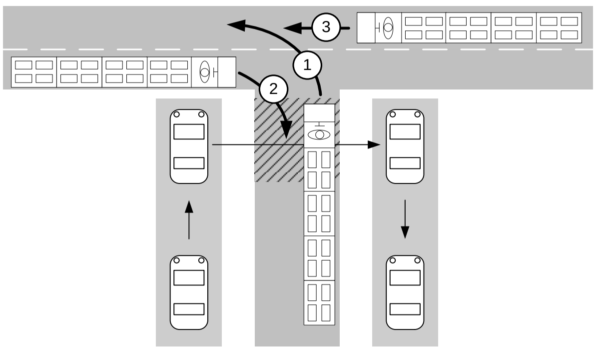

Figure 4: Priorities For Driving Across Intersections

The restrictions described for overtaking and turning in intersections, in combination with further interdependencies between TTs and other vehicles, result in a dynamic, complex and unpredictable system status (i.e. traffic jams) and affect the scheduled duration of a tour. Amongst other things, these aspects are examined by a dynamic simulation of the presented TT system. For this purpose, the system was reproduced and implemented in a simulation model which is described in the next chapter.

4. IMPLEMENTATION OF THE SIMULATION MODEL

The simulation model was implemented using the discrete-event simulation software, *Plant Simulation*, whose use is widespread within the area of production and logistics. The software offers various customisable modules, i.e. roads, warehouses, working stations and vehicles. The control of information and material flows is realised by procedures programmed by the user and assigned to a specific event (i.e. reaching a defined time or a vehicle passing a pre-determined point).

The subsequent sections deal with a closer description of the simulation model, focussing on the model’s level of detail, as well as its basic structure. Moreover, main challenges and adequate solution proposals are presented, in order to inform readers dealing with related issues.

4.1. Basic structure and processes of the simulation model

The simulation model consists of different networks which are arranged in two hierarchy levels. At the top level, the IT control system is modelled in order to generate and process material call-offs which is why various input data is integrated into this network. Two examples for the required input data are a timetable including all the tours and their corresponding scheduled times, as well as a quantity structure of parts containing data for each material, such as container capacities, route assignment, parts per product, assembly point and the likelihood of installation into a product. On the basis of the latter, a procedure monitors and adjusts the material stock and demand for each material and assembly point and, if necessary, generates a material call-off. As the material flow of products along the assembly lines is not modelled, the procedure is executed at intervals of the assembly cycles when material is used. The further processing of material call-offs is implemented according to the described IT control system (see 3.4.) and realised by several procedures accessing various tables and variables.

After the planning of a tour is completed, a procedure initialises the provision of a TT in one of the train station networks depending upon which floor the route runs. The generated object thereby receives all the necessary information, such as contained material, delivery points, scheduled times and route. The loading of the TT is not simulated, but respected in the form of time restrictions. At the scheduled departure time, the

TT leaves the train station network and moves along its route into one of the assembly halls.

In order to facilitate the implementation process, as well as the understanding of the simulation model, real layouts are deposited in the background of each network. The essential processes in the assembly hall networks are surveyed in the following explanations.

4.2. Main challenges and solution proposals

In conclusion of the chapters 2 and 3 the high degree of complexity of TT systems can be stated. In order to address this fact, a main challenge consisted in implementing a transparent and comprehensible simulation model which serves as a basis for future projects. Therefore, typical elements of TT systems are implemented as stand-alone and general components which can easily be parametrised. However, there are a few elements of a TT system which must be implemented according to specific requirements of a particular use case. The provided simulation model gives a clue how these elements can efficiently be implemented and combined with the general components.

In this context, apart from the detailed implementation of the IT control, the greatest challenges consisted in the modelling of the vehicles' driving behaviour as there are various interdependencies to be considered. The following sections therefore highlight the realisation of navigation and overtaking processes, as well as the consideration of interdependencies between TTs and forklifts in the simulation model.

4.2.1. Navigation to delivery points along routes

The navigation of TTs along their routes within the modelled road networks is based upon the sequential arrangement of intersections whereby each intersection, which represents an instance of the according network class, automatically determines its direct successive intersections when starting a simulation run. Additionally, the sequence of intersections, which must be passed through, is made available in a table for each route. Hence, any road networks can be modelled using the provided intersection element.

As soon as a TT arrives at one of an intersection's maximum of four accesses, a procedure designates the intersection - by checking the above-mentioned table - which the TT must pass through next on its way along its route. For this purpose, each TT carries the information on which intersection is just now being passed through. As it is possible to pass through the same intersection back-to-back (i.e. in case of dead ends), the TT does not carry the explicit identification of the intersection, but a pointer to the corresponding row in the table. Hence, the procedure checks the entry in the next row and routes the TT to the equivalent exit of the intersection, whereby the above mentioned priority rules are considered (see 3.5.). Furthermore, the pointer is updated so that the described process reruns over and over in the coming intersections until the TT finally returns to the train station.

The navigation of TTs not only involves driving along determined routes, but also stopping at delivery points for which material is transported. This is why the sequence of delivery points is documented in a table for each route. After generating a TT in the train station, a procedure identifies the first delivery point to be approached along the corresponding route. This is done by comparing the list of delivery points contained in the TT object with the content of the above-mentioned table. The name of the first delivery point is then written into a corresponding attribute of the TT object.

Pursuant to the real assembly layout, each delivery point's position is considered in the simulation model. Hence, at such positions, a so-called sensor can be found on the respective object of the modelled road networks. When a TT passes a sensor, a procedure compares the name of the delivery point assigned to the sensor with the TT's delivery point attribute. If both match, the TT is stopped for a pre-determined time in line with the real duration for stopping, dismounting, unloading, as well as boarding and starting again. Afterwards, the next delivery point is detected and the attribute updated. Finally, the process just described is repeated until all the material is supplied.

Eventually it can be stated that the algorithms controlling a TT´s navigation to delivery points along defined routes operate independent of certain road networks and are therefore easily transferable on other simulation models.

4.2.2. Overtaking delivering TT

As already mentioned, a delivering TT may be overtaken taking into account a few restrictions. The applied simulation tool, however, does not allow overtaking actions on a road object. For this reason, a TT is transferred onto an object next to the road object as if supplying material at the just-reached delivery point as shown in Figure 5. Thereupon, a sensor is generated on the road object at a position which meets the TT's rear position. The front position of the TT correlates to the above-mentioned sensor at which the need for stopping at the assigned delivery point is examined.

As soon as another TT arrives at the sensor representing the rear position of a delivering TT, a procedure which verifies the possibility of overtaking is activated. The various restrictions described in section 3.4 are thereby checked. If overtaking is not allowed, i.e. because of a too narrow road section, the TT must wait until the delivering one continues running on its route. In this case, the waiting TT's explicit ID is written into a table where it is assigned to the corresponding delivery point. Once a TT completes the delivery process, it is transferred back onto the road object and the sensor representing its rear position is deleted. At the same time, the table is scanned for a waiting TT and its starting at the appropriate time initiated.

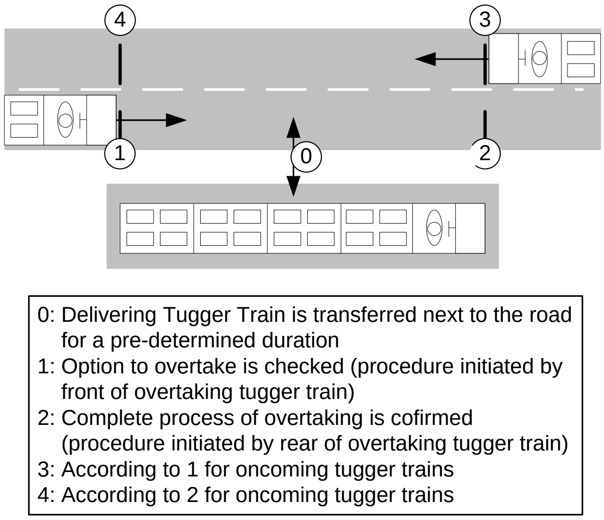

Figure 5: Sensor Positions For Delivering And Overtaking Processes

If, however, overtaking is possible, the TT does not stop but drives on and passes the delivering TT. In doing so, an entry stating that, at the moment, there is an overtaking in process along the delivery point, is made into the table. The entry is deleted as soon as the overtaking TT's rear has passed the sensor which represents the delivering TT's front positions. Consequently, before a delivering TT is transferred back onto the road object, a procedure, which uses the table, checks if the TT is being overtaken at that moment. Where necessary, it has to wait until the overtaking TT has completely passed by, or if the corresponding table entry has been deleted.

In the event of roads with oncoming traffic, the implemented overtaking process is analogically organised. Although, before overtaking, a procedure checks if there is oncoming traffic between the front and rear position of the delivering TT, it is not until this has been ascertained as not being the case, that the overtaking process can start, and the lane for oncoming traffic is locked at the front position of the delivering TT until the process is concluded. This is done by using sensors as shown on Figure 5, and tables as described above for one-way roads.

As described in this section, the process of overtaking delivering TT is implemented according to specific restrictions and configurations of the investigated system. Nevertheless, the basic idea and structure of the algorithms can be used for other simulation projects.

4.2.3. Consideration of forklifts and crossing gates

Forklifts move on defined road sections at various times at which no other vehicle can be on these sections, as forklifts need the complete road width in order to shunt. As there is no such thing as a timetable allowing the modelling of the forklift-runs in accordance with the real system, these are modelled in a simplified way. This means that at defined intervals, which are calculated on the basis of the forklift's appearance in the real system, the road sections concerned are locked. After an analogously calculated duration, the road sections are released and potentially waiting TTs moved on. Forklifts themselves are not modelled by means of a moving object, but visualised on the road sections.

In comparison with forklifts, the gates at the assembly line crossing are modelled more accurately as they close according to the assembly cycles. So, an object is inserted into the road networks corresponding to the real position of intersection gates. The status of the object (open or closed), as well as the colour (green or red), is set according to the assembly cycles. Arriving TTs trigger a procedure which checks the current status of the gate object and either allows the TT to move on, or stops it until the status changes.

As the elements for forklifts and crossing gates are implemented separately and parametrisable, they can easily be integrated in other simulation models. Moreover, the forklift element can also be applied for considering any periodically moving element interdepending with TTs.

5. RESULTS

The implemented simulation model offers various functionalities to record and calculate key figures which are shown above (see 3.1.). The key figures are summarised in several tables and variables. These are filled with procedures which are initiated by the respective events in the TT's process. For example, the actual delivery time at the assembly points is measured and compared with the planned delivery time.

The implemented functionalities do not only serve the model validation and verification, but also as a basis for evaluating the real system and deriving optimising measurements which are presented in the following chapter. In addition, they provide valuable information for a potentially needed economic evaluation of the system. For example, savings by reducing the number of employees and TTs could be compared with costs for additional unplanned transports to maintain the security of supply.

As the planning of the system presented in the paper at hand is still in progress, the numbers given in this section are anonymised simulation results.

5.1. Security of supply and level of service

Security of supply is defined as the share of material call-offs provided in time at the point of need. To guarantee a sufficient supply of the assembly line and stable production, call-offs have to be provided in time. As the time between the creation of a call-off and the provision thereof depends on dynamic effects, it is useful to plan additional buffer time.

In the simulation model described above, each call-off is given a target time. Once the TT has finished its tour, the time of supply of each call-off is compared to the target time.

To prove a security of supply of 100 percent is a central requirement for the simulation study. If any missing parts are detected, further analysis is necessary on how to optimise it to 100 percent. Even then, the real system might not reach that security of supply as there are additional hardly calculable influencing factors, e.g. mistakes, such as supply at the wrong point of need or the wrong picking in the warehouse. With a 100 percent security of supply, the buffer times planned in advance between call-off generation and the estimated time of supply are sufficient to compensate for any queues and disturbances occurring during the whole process, whereas each late call-off bears the risk of stopping the assembly line or causing a rework, as the missing part has to be assembled once the product has left the assembly line. In both cases, additional high costs would be incurred.

The level of service is another important performance figure for measuring the supply quality: it is defined as the share of call-offs provided by default processes (see 3.2 and 3.3). Typically, a default process is designed to cope with the estimated number of material call-offs. Due to system dynamics like call-off peaks or queues, this process design can sometimes be insufficient. To cover such cases, a back-up routine is defined using a substitute TT to deliver this material. Along with the supply time measurement, each activation of a back-up process is logged and evaluated in the simulation.

In the case of fluctuating material demands and low default process reserves, a level of service of less than 100 percent is likely to be seen. As each activation of the back-up process leads to an additional vehicle driving through the road networks, the next question would be whether the overall traffic is increased to such an extent that it affects the material supply. Again, the security of supply can be considered for that: if it reaches 100 percent for the default and back-up process, the back-up process itself has been reliably designed, too.

5.2. Employee requirements

Once the supply of the assembly line is ensured, the next aim is to use as few employees as possible. Thus, the employee requirement is defined as the number of drivers needed to cover all the tours. In the analysed system, drivers are organised into pools, whereby one pool corresponds to one train station and every driver in a pool is trained for each route starting at that station. If too few regular drivers are planned for a pool, the schedule may be delayed. On the other hand, too many drivers in a pool lower the average workload per driver and cost more.

To get the data needed for an evaluation of the employee requirements, the number of drivers available in each pool is logged and converted into a distribution graph (see Figure 6). If the pool size is not limited, each tour starts in time and the maximum value in the graph shows the number of active drivers needed at once. Each driver who is not available at the station, but currently on the way on a certain tour, is defined as active.

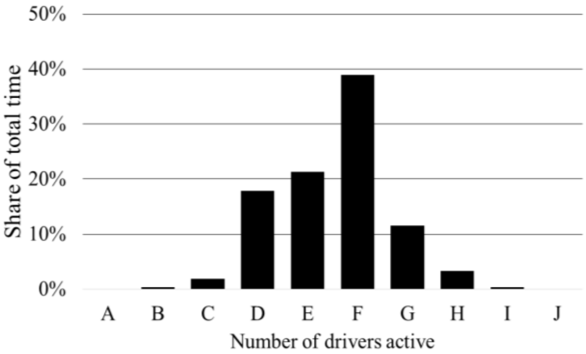

Figure 6: Distribution Of Employee Requirements Over Time

The frequency distribution serves as a useful basis for further optimisation. If the distribution is even quite near the upper boundary, the average workload per driver is low most of the time. In the visualised example, a maximum of J drivers are needed, but only for a very short time. In this case, the distribution shows how much time is covered by reducing the number of employees available: if H drivers are used, only a little time is “lost” in which the number of drivers is insufficiently low. When only using G drivers, a significantly higher amount of about 5% of all the time is not covered. The results on the schedule, as well as material supply, must then be additionally analysed.

If the employee requirement is not estimated using the simulation results as in Figure 6, but is adapted from the schedule only, the number of drivers needed would be underestimated. Although the schedule contains all the information on the start and planned return for each tour, and therefore allows the derivation of the time efficiency of each driver, this static calculation is based on the assumption that all the tours are executed exactly in time with any dynamic effects being factored out. By using simulation, these dynamic effects (e.g. queues and disturbances) are taken into account and increase the time needed per tour. In such cases, the driver’s availability at the station is decreased and more drivers are needed to compensate for possible delays in subsequent tours. As an alternative, the dynamic effects on the time needed per tour, e.g. traffic jams, could be reduced in different ways to increase the drivers’ availability.

5.3. Space requirements

Besides the employee requirements, train station design contains the calculation of space required for the handover between the picking warehouse and the road networks. Similar to the employees, the space requirement is defined as the number of handover places needed to cover a certain percentage of all tours. As the system described above is installed in an already existing plant, space is scarce. Too few handover places cause queues in the train station and can delay the departure of subsequent tours.

In the case of the space requirement, the number of handover places available is logged and converted into a frequency distribution graph, too.

As with the employee requirement, the maximum number of handover places should be installed if possible. On the other hand, if there is not enough space, a distribution, such as in Figure **6** 6, shows the effect when the available space is reduced.

5.4. Volume of traffic

Dynamic effects like queues and disturbances were identified as reasons for increased employee and space requirements. For a further analysis, the volume of traffic is evaluated to derive possible approaches to lower their influence.

The first performance figure needed is the number of vehicles per hour passing each road section. The higher this congestion measure, the higher the risk that disturbances will develop. Secondly, the waiting time per hour is calculated for each road section. This figure reveals the reasons for delays as shown in an analysis of the time needed per tour. In total, the time between departure and the arrival back at the station consists of three parts: driving, supply, and waiting due to disturbances. The driving time is constant as is the route and thus the distance per tour is fixed. Secondly, the time needed to supply the TT's load depends on the capacity efficiency and thus varies slightly. However, compared to driving and waiting, this time period is short. The duration of waiting caused by disturbances fluctuates and is therefore uncertain. When creating a schedule, this time is calculated using an overhead. If this overhead is insufficient on a certain tour, the planned time is exceeded and the schedule delayed.

In the simulation, each road section is able to detect passing trains. This information is collected after each experiment for further analysis. In addition, as soon as waiting is caused, each vehicle affected is logged, including its position, as well as the duration of waiting. For this, procedures initiated by all the sources are used for the waiting in the modelled system, e.g. intersections, supply processes and vehicle elevators.

For a visualisation and parallel evaluation of the volume of traffic, road sections can be coloured. The darker the grey, the higher the value of the represented performance figure. Figure **7** shows a section of the road networks where a high number of vehicles pass and sources of waiting occur.The right vertical road is the main transit section, which explains the high number of passing vehicles. Regarding waiting, the number of waiting vehicles is only one part of the analysis. Some sections in Figure **7** show a high number of stops, but the duration of each stop is important, too, because less, but longer, waiting processes could have more effect on the road networks and other vehicles. In the example at hand, the waiting time per stop is long, when many vehicles have to wait. Thus, the section shown in the figure shows a high volume of traffic and should be considered for optimisation.

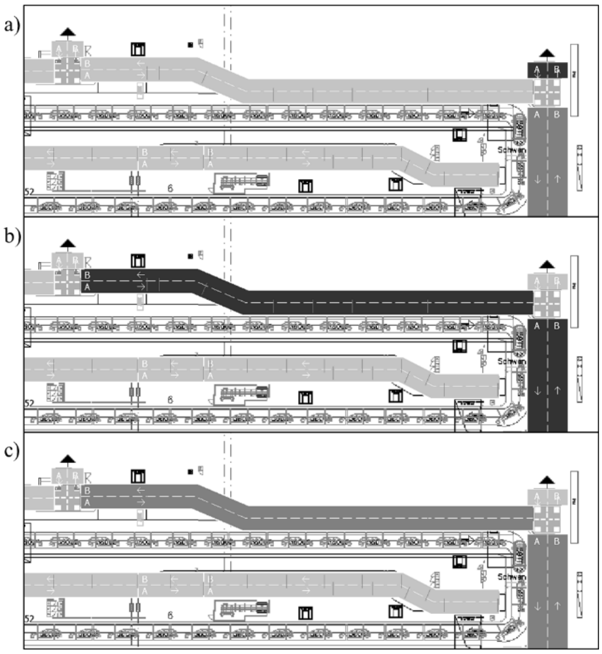

Figure 7: Visualisation Of Passing Vehicles (a), Waiting Vehicles (b) And Waiting Time (c)

As in the example in Figure 7, the whole road network should be checked for such sections. Beginning with the sections with the highest congestion, the road networks should be optimised. Based on the number of passing vehicles, roads can be merged to sectors with a high risk of disturbances. In the current planning status, such sectors exist, but are used for transit only, which means that no points of need are arranged alongside. For the future planning of routes and supply, sectors should be considered which neither increase the congestion, nor create new reasons for delays, especially if obstacles of any kind are added. In addition, this volume of traffic could be critical for safety at work, for example, in case workers have to cross between their workplace and any other points of interest.

To derive recommendations for sections with a high waiting risk, an individual analysis of the reasons is necessary. In front of obstacles, like elevators between the first and second floors, queues also affect passing trains if there is only one lane for all vehicles. By adding a second lane exclusively for waiting vehicles, transit traffic remains unaffected. In some areas, roads are too narrow for vehicles to overtake, if a precursor stops to supply material. By widening the roads in sections that were found to have potential, waiting can be reduced. A way to avoid waiting, especially in dead ends, would be to split the applicable routes there: assuming a route A supplies material inside a dead-end section, as well as outside (see Figure 8), it could be split into a route A1 supplying only the points of need outside, and a route A2 which would only supply inside the dead-end: the capacity efficiency of A1 and A2 would be reduced, as the amount of material to be supplied is defined by the quantity structure of the parts, and their sum equals the capacity efficiency of A. This would allow for the trains to go less frequently, but to be loaded with more material. Thus, the number of vehicles inside the dead-end is reduced while material supply is unaffected.

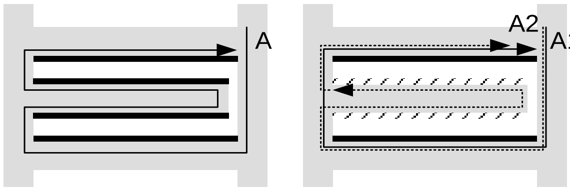

Figure 8: Route-splitting For Efficiency Optimisation

6. SUMMARY

The paper on hand describes the modelling and implementation of a TT system supplying several automotive assembly lines with more than 2000 tours on various routes. The focus of the simulation model lies on the IT system with three types of call-off processing, as well as on reproducing the vehicles' driving behaviour. Specific elements, like restrictions on overtaking and turning, were taken into account to facilitate meaningful results. For this, five important performance figures were derived from the main aims of the research: security of supply, level of service, employee and space requirements, as well as the volume of traffic. Firstly, the required security of supply of 100 percent has to be proved. For further analysis, the level of service helps to check the default process design. Employee and space requirements can be analysed using a histogram to find the requested balance between high security and a low need of resources. Due to the complex road networks with specific restrictions and a large variety of vehicles, the volume of traffic reveals highly-congested sections which need to be considered in further optimisations.

In summary, the requirements of creating a simulation model with a reusable framework were met. Universal objects like vehicles or roads were combined with specifically adaptable elements like overtaking behaviour or IT-processes. Thus, the model can easily be adjusted if further questions arise during future planning or if different TT systems with deviating properties are to be analysed in the future.

REFERENCES

Arlt, T., 2012. Neue Wege in der Automobillogistik bei BMW, *21. Deutscher Materialfluss-Kongress*. 29.03.2012, Garching bei München.

Baudin, M., 2004. *Lean logistics - The nuts and bolts of delivering materials and goods*. New York, Productivity Press.

Brungs, F., 2012. *Der Milkrun in der Produktionslogistik*. Aachen: Shaker.

Costa, B.; Dias, L. S.; Oliveira, J. A.; Pereira, G., 2008. Simulation as a tool for planning a material delivery system to manufacturing lines. *2008 IEEE International Engineering Management Conference*, pp. 1–5, 28-30.06.2008, Estorial.

Dewitz, M., Günthner, W. A., Arlt, T., 2014. Fahrplanoptimierung für innerbetriebliche Routenverkehre. *Logistics Journal* Vol. 2014, 2014, pp. 1-14.

Dreher, S., Nürnberger, A. and Kulus, D., 2009. *Routenzugoptimierung in der Produktionslogistik*. *ZWF*. 3-2009, pp. 131–135.

Emde, S., Boysen, N., 2012. Optimally locating in-house logistics areas to facilitate JIT-supply of mixed-model assembly lines. *International Journal of Production Economics* 135: pp. 393–402.

Emde, S., Boysen, N., 2011. Optimally routing and scheduling tow trains for JIT-supply of mixed-model assembly lines. *European Journal of Operational Research* 217: pp. 287-299.

Günthner, W. A.; Klenk, E.; Galka, S., 2012. *Stand und Entwicklung von Routenzugsystemen für den innerbetrieblichen Materialtransport - Ergebnisse einer Studie*. München: fml Lehrstuhl für Fördertechnik Materialfluss Logistik.

Kilic, H. S.; Durmusoglu, M. B.; Baskak, M., 2012. Classification and modeling for in-plant milk-run distribution systems. *The International Journal of Advanced Manufacturing Technology* 62: pp. 1135–1146.

Martini, A.; Stache, U.; Trenker, F., 2014. *Planung von Routenzugsystemen - Übersicht möglicher Gestaltungsalternativen und Vergleich von Planungsmethoden*. *ZWF* 109, pp. 50–55.

Mayer, G.; Pöge, C., 2010. Auf dem Weg zum Standard - Von der Idee zur Umsetzung des VDA Automotive Bausteinkastens. *Integrationsaspekte der Simulation: Technik, Organisation und Personal*. pp. 31–36, 07-08.10.2010, Karlsruhe.

Roth, S., 2012. Virtuelle Logistik- und Materialflussplanung - Beispielhafte Anwendungen. Integrationsaspekte der Simulation. *Zusammenarbeit im Umfeld der Digitalen Fabrik*, 21.09.2012, Hannover.

Staab, T.; Galka, S.; Klenk, E., 2013a. Effizienzsteigerung für Routenzüge. *15. ASIM Fachtagung Simulation in Produktion und Logistik*, pp. 167–176, 09-11.10.2013, Paderborn.

Staab, T.; Klenk, E.; Günthner, W. A., 2013b. Simulating Dynamic Dependencies And Blockages In In-plant Milk-run Traffic Systems. *27th European Conference on Modelling and Simulation*, pp. 622–628, 27-30.05.2013, Aalesund.

Vaidyanathan, B., Matson, J.O., Miller, D., Matson J.E., 1999. A capacitated vehicle routing problem for just-in-time delivery. *IIE Transactions* 31: pp. 1083–1092.

Wiegel, F.; Immler, S.; Knobloch, D.; Abele, E., 2013. Simulationsgestützte Optimierung innerbetrieblicher Milkruns. *PRODUCTIVITY Management* 18: pp. 51–54.

VDI-Richtlinie 3633 Blatt 1, 2014. *Simulation of systems in materials handling, logistics and production*. Berlin: Beuth.