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Development of a Simulation Library for the Planning of Tugger Train Systems

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AFFIDAVIT

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Abstract

In the area of material supply for internal logistics, a change can be observed in the recent years. Many large automotive manufacturers are switching from the forklift trucks they used until now, to a tugger train system. For the planning of these tugger train systems, there are already many different methods in the literature available, some of them also include simulations. The reasons for the inclusion of simulations are the evaluation and optimization of the tugger train system. The simulation software Plant Simulation enables the creation of a digital model of production plants and their logistics processes. However, the simulation of tugger train systems in Plant Simulation is only possible to a limited extent because the software only provides rudimentary tugger train elements for this purpose. This master thesis addresses this problem by developing a simulation library for tugger train systems in Plant Simulation.

In order to achieve this goal and to be able to simulate as many practice-relevant tugger train systems as possible with the simulation library, a wide variety of planning approaches are discussed and compared with each other, as the first step. With the help of this comparison, a catalog of requirements is created that contains the most important aspects of the different planning methods. The simulation library with the underlying catalog of requirements enables the planner to simulate a variety of tugger train systems, which are used in praxis, and to evaluate them with the help of key figures. Based on these key figures, such as utilization, number of tugger trains, tour times, delivered loads, etc., the planned tugger train system is evaluated. However, not only the evaluation of the key figures, but also the graphical representation of the tugger train system brings various advantages. This is because the graphical representation enables a quick plausibility check of the routes.

The simulation library is demonstrated and evaluated by applying it to various case studies. It is shown that a large number of practice-relevant tugger train systems can be represented and optimized with the help of the simulation library. However, since there are not only standard cases but also special cases in practice, the goal of further research must be to implement these special cases as well and to further improve the simulation library.

Kurzfassung

Im Bereich der Materialversorgung für die interne Logistik ist in den letzten Jahren ein Wandel zu beobachten. Viele große Automobilhersteller steigen von den bisher eingesetzten Gabelstaplern auf ein Routenzugsystem um. Für die Planung dieser Routenzugsysteme gibt es in der Literatur bereits viele verschiedene Methoden, die zum Teil auch Simulationen beinhalten. Gründe für diese Einbeziehung sind die Bewertung und Optimierung des Routenzugsystems. Die Simulationssoftware Plant Simulation ermöglicht die Erstellung eines digitalen Modells von Produktionsanlagen und deren Logistikprozessen. Die Simulation von Routenzugsystemen in Plant Simulation ist jedoch nur bedingt möglich, da die Software nur rudimentäre Routenzugmodule für diesen Zweck bereitstellt. Die vorliegende Masterarbeit greift dieses Problem auf und begegnet ihm mit der Entwicklung einer Simulationsbibliothek für Routenzugsystemen in Plant Simulation.

Um dieses Ziel zu erreichen und um möglichst viele praxisrelevante Routenzugsysteme mit der Simulationsbibliothek simulieren zu können, werden zunächst verschiedenste Planungsansätze diskutiert und miteinander verglichen. Mit Hilfe dieses Vergleichs wird ein Anforderungskatalog erstellt, der die wichtigsten Aspekte der verschiedenen Planungsmethoden enthält. Die Simulationsbibliothek mit dem zugrundeliegenden Anforderungskatalog ermöglicht es dem Planer, eine Vielzahl von praxisrelevante Routenzugsystemen zu simulieren und mit Hilfe von Kennzahlen zu bewerten. Anhand dieser Kennzahlen, wie z. B. Auslastung, Anzahl der Routenzüge, Tour Zeiten, ausgelieferten Ladungen usw., wird das geplante Routenzugsystem bewertet. Doch nicht nur die Auswertung der Kennzahlen, sondern auch die grafische Darstellung des Routenzugsystems bringt verschiedene Vorteile mit sich. Denn die grafische Darstellung ermöglicht eine schnelle Plausibilitätsüberprüfung der Routen.

Die Simulationsbibliothek wird durch die Anwendung auf verschiedene Fallbeispiele demonstriert und auch evaluiert. Dabei zeigt sich, dass eine große Anzahl der in der Praxis relevanten Routenzugsystemen mit Hilfe der Simulationsbibliothek dargestellt und optimiert werden kann. Da es in der Praxis jedoch nicht nur Standard-, sondern auch Sonderfälle gibt, muss es Ziel der weiteren Forschung sein, auch diese Sonderfälle zu implementieren und die Simulationsbibliothek weiter zu verbessern.

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1. Introduction

The internal logistic in most of the production plants is still based on forklifts, which have proven themselves as flexible material supply system. The forklift transports the different kind of goods through the factory to its destination and can therefore easily adapt to the change of situations and environments. [BGL15]

In the recent years large automotive companies started to replace their forklift fleet by tugger trains. With this replacement the number of vehicles is reduced significantly and due to this change the dictum of “forklift-free plant” was introduced. Fig. 1 shows an example of a typical tugger train consisting of a tractor with trailers coupled to it. Efficiency is the major driver for this shift, because the capacity of a tugger train is two to four times higher compared to a forklift.[SMS16]

The common delivery strategy for a tugger train system is the milk run logistic system. A milk-run system uses a derived concept from the delivery method used in the dairy industry. In this industry the tankers collect milk from several farmers or provide the milk to different households. On the route of the milk supplier there are two activities involved, delivering the full bottles and collecting empty bottles. A big advantage of the milk-run system is to minimize the total distance travelled and to maximize the utilization. With these advantages the transport is done more efficiently and the overall costs are reduced.[KIP18]



Figure 1.: Example of a tugger train [SIC18]

Recent studies show that tugging train systems are a central element in the material supply strategy nowadays. All major automotive OEM's and also many other industries is the tugging train to supply their production areas.[KHF18]

An increasing spread of the tugging train as means of transport for the internal logistic can be observed. This is shown in a study of Lieb et al. and happened in many different industries not only in the automotive industry. As already mentioned is one of the reasons for this increase the efficient transport of different load carriers which can be done at a high frequency by the tugging train. [LKG17] To make this trend more visible the increasing use of tugging train systems which was found in this study is shown in Fig. 2. It is shown that over the last years the number of implemented tugging train systems is steadily increasing.

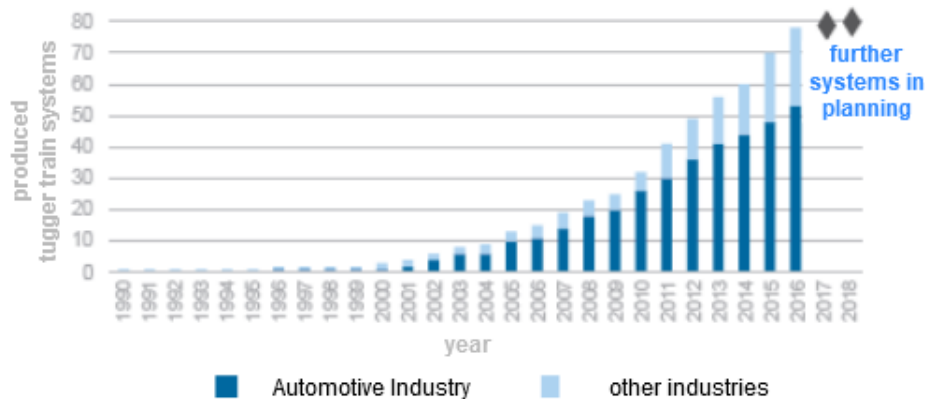


Figure 2.: Trend of the use of tugging trains in industry [LKG17]

With the increasing use of the tugging train the correct planning of them also became of great importance. The experience of the planner is the main factor that influences the quality of the planning results.[RaD09] In addition, there many different methods for the planning of tugging train systems can be found in the literature. The methods differ a lot because most of them have the focus on a special part of the planning process. Some focus solely on the dimensioning with exact algorithms or dynamic programming, others have small parts of the dimensioning included but give a lot of design alternatives to choose the right tugging train. There are also methods that include the use of simulations in the planning process as well as some that are only based on existing knowledge. With this variety of planning methods, it becomes visible that with less know-how available, then it is more likely to just follow design recommendations.[FGP13] However not all the technical literature on planning methods for tugging train systems is publicly available, which poses a problem for the planner to choose the right method for his planning process.[GGK12b]

This is the reason why participants expressed the need for guidelines and software support during a tugging train study which was made by Günthner et al.[GGK12a] In this master thesis the main focus is on this software support especially on the use of Simulation to support the planning of tugging train systems. Plant Simulation is a simulation software which is used to perform various simulations including material flow simulations. In the course of this master thesis it is shown in an analysis that there are currently only elementary elements for the simulation of tugging train systems included. With these elements it is possible to simulate a tugging train system, but the requirements of the planning process cannot be sufficiently represented which is made possible by the simulation library. There are already additional libraries for Plant Simulation, which contain to some extent methods and elements for the simulation of tugging train systems. However, these are not publicly available and commercial.[SIM20]

This is reflected in the literature, where the incorporation of tugging train simulations is done by developing special simulation models with other software. In their article "Simulation as a Tool for Planning a Material Delivery System to Manufacturing Lines" Costa et al. describe the development of a simulation model for a use case, which serves to optimize the tugging train system but only for certain criteria.[CDO08] The planning methods of Wiegel et al. and Raposo et al. ([WIK13][RaD09]), which are described in more detail in chapter 3, show the integration of a special simulation model into the planning process, but these are also only applicable for the respective methods and are limited to part problems such as routing problems or number of vehicles, etc.

This reveals the research gap, which is reflected as the lack of an accessible simulation approach for tugging train systems in Plant Simulation, which is applicable for different planning methodologies and is not limited to one or to only a part problem of the planning process.

Therefore, the goal of this master thesis is to find a simple way to simulate and evaluate different tugging train systems in Plant Simulation. It should be possible to represent different configurations and design alternatives, which are described in the presented planning methods. The goal is to create a simulation library which makes this possible. The planner should be able to use Plant Simulation to simulate tugging train systems and also implement them into their existing simulation models of their facility, without having to rely on other software to simulate parts of the facility, such as the tugging train system.

To show how this goal is achieved and the research question answered this master thesis is organised as follows. In chapter 2 the theoretical basics of tugging train systems and Plant Simulation are presented which are needed for the following chapters.

Chapter 3 starts with introducing different methods for the planning of tugging train systems which are also compared and discussed to show similarities as well as advantages and disadvantages. Additional aspects of the planning process such as fluctuations in demand and technical criteria are also shown in this chapter. A catalog of requirements for the simulation library is created as well as an analysis of Plant Simulation regarding its possibilities to simulate tugging trains. The chapter ends with a hierarchical model, and a discussion of different approaches for the development, of the simulation library.

In chapter 4 the process of the development of the library is shown and the different components are described in detail. A basic procedure of how the simulation library is used to simulate a tugging train is presented. The library is also applied to create five different practical examples to show the coverage and also serve as an evaluation. The examples are each evaluated and at the end an evaluation of the whole simulation library is done.

Chapter 5 covers a Summary of the thesis which includes the results as well as further steps that should be done.

2. Theory

In this chapter, the theoretical basics and terms of tugging train systems will be presented and explained. This also includes a description of the elements and parameters a tugging train consists of as well as the operational criteria and some boundary conditions, which will be further explained in chapter 3. Another topic which is presented in this chapter is the determination of the transport requirement and at the end, a short introduction to Plant simulation and its basic elements are presented.

2.1. Tugger Train Systems

This chapter will show the principle of a typical tugging train system and the main elements and parameters will be presented. A tugging train system typically uses the milk run principle as a delivery strategy. The milk-run principle is derived from the dairy industry, where tankers collect milk from several farmers and deliver it to different households.[KIP18] Applied to a plant this means the tugging train drives a defined route and is transporting goods from a storage area to different stations as shown in Fig. 3.

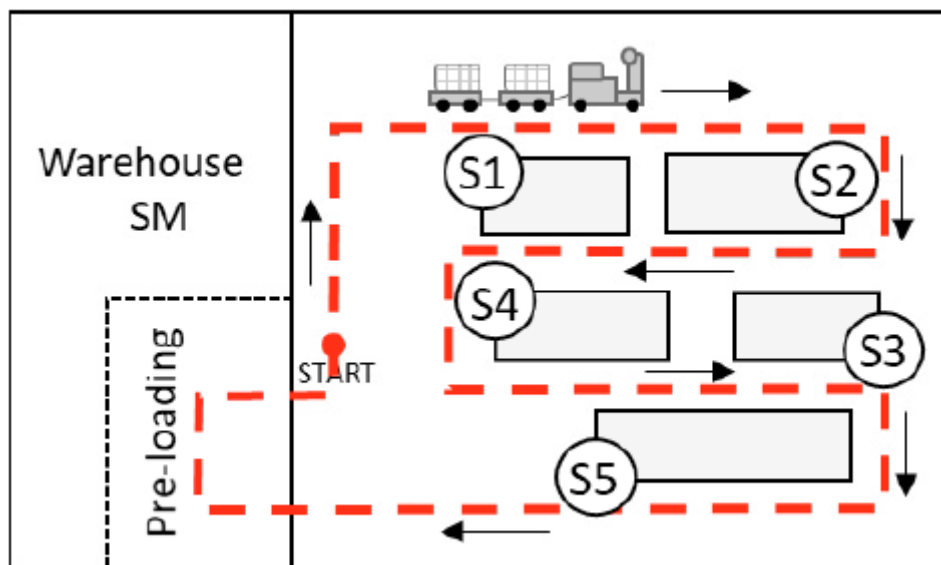


Figure 3.: Tugger train system layout (example) [UBE18]

According to Bozer and Ciernoczołowski this system is a cyclic material handling system in which parts, mostly in containers, are transported from a storage area to different stops along an assembly line.[BoC13] As shown in Fig. 3 the start of the tour of a tugger train is at the storage area.

There are different possibilities as to how the storage area is designed. It can be a centralized storage area of the company, for example, the warehouse where the goods and parts of the company are stored, or a supermarket.

Supermarkets are decentralized storage areas and are in direct vicinity to the assembly line or stations which are supplied. Larger industrial trucks are replenishing the supermarkets from a remote store with parts which are stored there till a part demand of an assembly station is made. Then the bins, according to the demand, are generated and prepared for the tugger train. Bigger containers are loaded with a forklift, or it is also possible that already pre-loaded trailers are delivered to the supermarket which are afterwards just coupled to the towing vehicle of the tugger train. These goods then are delivered to the assigned stations.[EmB12]

According to a study it was observed that at multiple German OEMs these supermarkets have usually between 20 and 30 stations assigned and are located close to the stations. Multiple tugger trains start their assigned tour at the supermarket to supply these stations. The typical number of tugger trains per route is between three and five. The routes are planned so that the train tour length is as short as possible. In the plants, they use multiple supermarkets that are replenished with the goods for the assigned assembly stations.[EmB12]

2.1.1. Tugger Train

The tugger train consists of a towing vehicle or tractor to which a set of trailers is coupled. The typical number for such a set of trailers varies between 2 and 5 which are loaded with the Unit Load (UL). There are different kinds of unit loads (see chapter 2.2.2) and therefore also different types of trailer.[UBE18]

- **Tractor**

The towing vehicle of a tugger train is the tractor of which there are several types available on the market. Usually, they are distinguished into three- or four-wheel tractors. In chapter 3 more design alternatives are shown. The three-wheel version, also shown in Fig. 5 is compared to the four-wheel tractor (Fig. 4) more manoeuvrable. Therefore, it is mainly used for internal transport with narrow driving paths and limited space.[HoS10] Another important difference is that the three-wheel tractor can tow less overall load weight in comparison to the four-wheel tractor. The four-wheel tractors of STILL for example can tow load weights up to approx. 25 t which make them suitable for outdoor and heavyweight transports.[STI20]



Figure 4.: Four-wheel tractor [STI20]



Figure 5.: Three-wheel tractor [STI20]

- **Trailer**

As described in the beginning a tugger train not only consists of a tractor but also of a set of trailers coupled to it. There are different types of trailers available with different advantages and disadvantages. In Fig. 6 a U-Frame and in Fig. 7 a B-Frame are shown as an example. These are trailers that use the insertion concept. In this concept, the load carrier is on a trolley which is loaded and unloaded on the trailer. Further trailer designs are compared and described in chapter 3.3.2. The different trailer types can be, depending on the supplier, combined with each other. ([STI20][JUN20])



Figure 6.: U-Frame [JUN20]



Figure 7.: B-Frame [STI20]

2.1.2. Unit Load

The unit load is the transported goods that are loaded and unloaded onto the trailers. These goods are typically either transported in individual load carriers, in load carriers on a transport aid, or without any load carriers. An individual load carrier is for example a small load carrier (SLC). Load carriers on a transport aid are usually large load carrier (LLC) on a trolley.[VDI16a]

These two types of load carriers are further defined and described in the following.

- **Small load carriers (SLC)**

The small load carrier (SLC) are in most cases plastic crates in various sizes. They are typically used as an inner package and modularly adjusted to the base area of Euro pallets (800mm x 1200mm). The reason for this is that they are often assembled on packaging carriers to make transport easier and more efficient.([VDA16][GDK13])

- **Large load carriers (LLC)**

A large load carrier (LLC) is standardized with larger dimensions and often plastic boxes or lattice boxes with the base dimension of a Euro pallet (800mm x 1200mm). It can be used as a container to transport SLC's but also as an individual carrier for bigger goods.([GDK13][VDA16])

The choice of the used load carriers also influences the choice of the trailer types, since not all can transport both types but only one. The load carriers also influence the processes in the tugger train system because the loading time differs between SLC, LLC or if no load carrier is used. The base area can also be adapted to the ISO dimensions which is relevant for the selection of additional transport aids.

2.1.3. Route

The term route describes the defined driveway of a tugger train. The route is fixed in the plant layout and has multiple stopping points assigned to it. At these stopping points, the material is either loaded or unloaded. Typically, the stations are supplied with material and empty load carriers are loaded. There are different systems for this exchange and does not have to be 1:1. These systems are further explained in chapter 3 in the planning method of Günthner et al. There is also a special case in which material is loaded at the stations. It is possible that several tugger trains are driving the same route, therefore, supply the same stations along the route.[GGK12a]

2.1.4. Tour

The tour of a tugger train not only includes driving along the route but also all the activities carried out along the route. These are loading and unloading at stopping points as well as ancillary activities carried out there.[VDI16a] The term tour also describes exactly one specific run of a tugger train along the route.

2.1.5. Stopping point

A stopping point is a position along the route at which the tugger train stops and where the loading and/or unloading process is carried out.[VDI16a] Multiple delivery points can be assigned to one stopping point which is for example further described in chapter 3.1.7 as the two-buffer principle.

2.1.6. Tact time

The time of the regular cycle in which a tugger train starts is defined as the tact time. From the point of view of a stopping point, this means that the tact time is the fixed time interval at which a tugger train arrives there. Some tugger train systems start their tours permanently and have therefore no fixed tact time.[GGK12a]

2.1.7. Cycle Time

The cycle time of a tugger train is the overall time it needs to drive along the route and complete its activities. Several different times influence the cycle time. The first time to look at is the time needed for driving on the route and the time for stopping at the stopping points. Therefore, the length of the route and the amount of stations influences the cycle time. Other influencing times are the time needed for loading and unloading at stations, the time for handling containers and if included in the tugger train system, the time for unloading empties. In a real system, the cycle time can vary, depending on the number of containers delivered. Fluctuations in demand also an influencing factor and may let the cycle time vary, which can lead to delays. The planned cycle time should be less than the tact time of the tugger train and if more than one tugger train is driving on one route, the cycle time should be below the tact time multiplied by the number of trains. The reason for this is to avoid delays and to avoid that the system gets out of the given tact.[GGK12a]

2.2. Objectives and benefits of a tugger train system

The ongoing shift to the tugger train systems has several objectives and benefits which have to be individually justified and always depend on the specific case, since not every benefit may apply to every case. The “VDI 5586 Blatt 2” gives some objectives and benefits of the implementation of tugger train systems. To give an overview about possible reasons to use a tugger train some of these objectives are listed in the following.

- high-frequency supply and disposal of the production lines
- Stabilization of the material flow
- Reduction of stocks in the production area
- Reduction of the number of transports through transport bundling
- Increase in transport capacity
- Reduction of the transport routes (in total)
- Reduction of the number of empty runs
- Reduction of the number of means of transport and the volume of traffic
- Reduction of the risk of accidents

In some cases, the goods are needed at a higher frequency. This leads automatically to a higher transport cost, and therefore, the benefits may not be seen directly in the tugging train system. With deliveries at a higher frequency, there is less material stored at the assembly stations and therefore also less storage space needed there. This can lead to improvements and higher efficiency at the assembly stations, which would represent the benefit in this case. As shown there may be hidden benefits, but the overall benefits always have to be determined in comparison to other transport systems.[VDI16b]

2.3. Operational criteria

To ensure that the tugging train system works efficiently and as intended, several operational criteria must be met. In the following Tab 1 an overview of how suitable a tugging train system is depending on these operational criteria.

	Increasing suitability of tugging train systems	
Number of delivery points	low	high
Distance between delivery points	small	big
Fluctuation of the throughput per route	high	low
Variation of the required supply frequencies per route	high	low
Transport goods/ load carrier weight	high	low

Table 1.: Suitability of tugging train systems ([VDI16b] p. 4)

Tugging trains are usually not able to reverse therefore, the supply of goods to a delivery point positioned at a dead-end must be avoided. The operational criteria also include a restriction of horizontal transports. The tractor has a maximum towing load, therefore the individual load limit of the trailers as well as the overall load limit must not be exceeded.[VDI16b]

The production layout must meet certain criteria to ensure wide enough tracks and space to ensure sufficient access to the delivery points. They also have to be wide enough to ensure that other industrial trucks or tugging trains can overtake even if a tugging train is loading or unloading at a station. It is also important that all these criteria are done in compliance with the security guidelines.[GGK12a]

The right choice of tractors and trailers also influence how these criteria are met. The reason for this is that different types of trailers have different loads, curve radii, etc. and therefore, either the route might have to be adjusted or different trailers have to be chosen. An overview and comparison of the different trailers is given in chapter 3.3.2.

2.4. Boundary conditions

Most of the planning methods presented in chapter 3.1 have two major boundary conditions, which are the transport task and the determination of the transport requirement. The primary transport task of a tugger train system is typically one of the following three tasks.

- Supply task (supply of stations with the material)
- Disposal task (finished goods are transported to the warehouse)
- Mixed task of supply and disposal

Usually, if the transport task is a mix between supply and disposal the planning process and the control of the system gets more complex.[VDI16a]

The determination of the transport requirement is an important boundary condition and is also considered in most planning methods, which are presented in chapter 3.1. There is also shown that it influences different parameters of the tugger train system such as labour, equipment, etc. Therefore, in the following section, the determination of the transport requirement is explained in detail.

2.4.1. Determination of Transport requirement

In principle, the determination of transport requirements can be either demand-oriented or consumption-oriented. These two systems are explained in the following and types for signalling the transport requirement are also described.

In a demand-oriented system, the transport requirement is determined based on a plan. This plan is the production plan and is the basis for the calculation of the times at which the material is required at the station. The result of this calculation is the latest time at which the material must be available at the station to avoid delays and downtimes.

The signalling of the transport requirement is carried out automatically by a computer system if the system is demand-oriented. The system follows the production plan and gives a signal at the pre-defined times to start the delivery process. [VDI16a]

On the other hand, if the determination is consumption-oriented the transport requirement only arises in certain cases. This happens if due to actual material consumption either a minimum stock is reached, or a minimum amount of material is not available at the station any more. In a consumption-oriented system, the times at which a demand occurs are not known beforehand and therefore the planning is more difficult. To avoid possible material bottlenecks or delays, the material stock at the stations must be dimensioned big enough. It must be enough to supply the station until the tugger train delivers the next lot of material.

In a consumption-oriented system the tugger train driver, a logistician, or a technical aid carry out the task of sending the transport requirement. There are different systems for this process to happen. It can either be done analogue with for example a Kanban card, empty load carrier, or a Signal-Kanban, but also electronically in the form of an e-Kanban system. [VDI16a] The traditional and the electronic Kanban system are explained in the following.

- **Traditional Kanban System**

In a Kanban system, a signal is given to start the transport requirement. The signal contains the demand for either a specific product or raw elements and the quantities in which they have to be delivered to a specific station. The signal giver can be for example a Kanban-card or an empty load carrier. In the traditional Kanban system, the Kanban card is used for signalling the transport requirement. The cards have an inventory number and are attached to the parts. On them, all information and details required for each step are noted. Therefore, these cards contain all the information about the product from production to assembly.[HAA17]

- **Electronic Kanban System**

The traditional Kanban system has some disadvantages, which are that cards have limitations. They can be manipulated, have irregular movements due to not moving them when the consumption happen, or they can be lost or misplaced. These problems can be solved with a computerized system. The electronic Kanban or e-Kanban system is using the “Radio Frequency Identification” (RFID), barcodes, or other electronic messages instead of the Kanban cards. With this replacement, fewer errors occur and the triggering of the movement and tracing of the material within the manufacturing or assembly gets easier.[HAA17]

2.5. Simulation software Tecnomatix Plant Simulation

Plant Simulation from Tecnomatix is a simulation software used for the creation of digital models of production facilities and the logistic system within them. With these digital models, the characteristics of the system can be studied and allow to try our “what-if” scenarios to optimize its performance. This has the major advantage that the existing production and logistic system has not to be changed for these experiments and analysis. Therefore, in the planning stage, these models are very valuable, and detailed analysis can be carried out with the tools provided by Plant Simulation. There is an

analysis of throughput and utilization, different charts such as Sankey and Gantt, and also the graphical output to just name some of the many available analysis tools of Plant Simulation. In the following, some of the main capabilities of Plant Simulation are listed and in Fig. 8 an example of a 3D model is shown.[SIE20]

- A hierarchy of the objects in the model with inheritance
- Good interface support and open architecture
- A library with different pre-set objects and object management
- Optimization with genetic algorithms
- Analysis and optimization of energy consumption through simulation
- Simulation and mapping of the value stream
- Simulation results can be automatically analysed

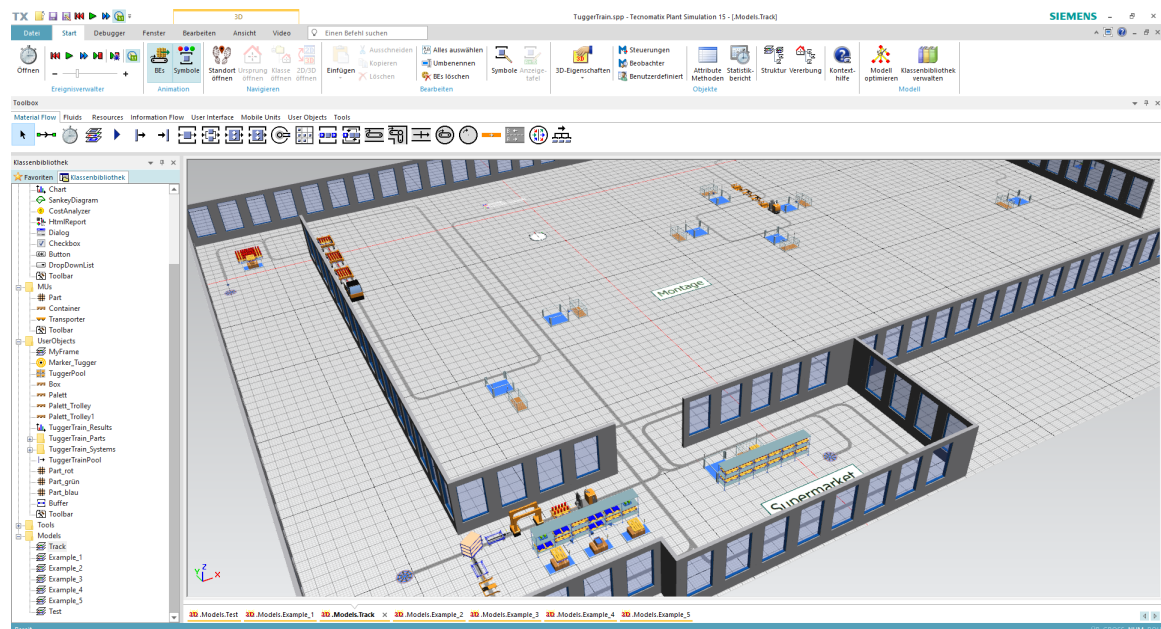


Figure 8.: Plant simulation 15

2.5.1. Basic elements

As already mentioned Plant Simulation has many different tools and elements implemented. Therefore, this chapter gives an overview of the basic elements which were used in chapter 4 for the creation of the simulation library for the planning of tigger train systems. There is also a short explanation for each of these elements included.

- **EventController**
With the "EventController" all the different processes during a simulation are coordinated. The different times at which an event (process) is carried out in the model are saved in a list inside the EventController. The EventController is also responsible for starting and stopping the simulation run as well as defining the duration of the simulation.[SIE19]
- **Methods**
Basic blocks call and start the "Methods", which consists of code lines that control parts of the simulation. The user can create and adjust these methods to simulate certain actions.[BAN11]
- **Variables and data types**
Two different variables are distinguished in Plant Simulation, namely the global and the local variables. A local variable is created in a method and is only usable within this method. Therefore, local variables are "unreachable" for other methods. On the other hand, global variables can be used in all methods of the model and can be read or changed by these methods.[BAN11]
The programming code SimTalk provides different data types to work with. There are acceleration, any, boolean, date, date-time, integer, length, list, money, object, queue, real, speed, stack, string, table, time, time sequence, and weight included.[BAN11]
- **Table**
The table element is a two-dimensional list in which data is stored. Methods can access and read or store data there but also other elements use them for example as storage of production plans, parametrization or to collect statistical information. [BAN11]
- **Mobile Units (MUs)**
The mobile units (MU) represent the transported goods within the model. They are used to simulate the material flow through the model of the facility. At the start or during the Simulation the MU's are created but can also be destroyed.[BAN11]
- **Source**
To create the described mobile units, the source element is needed. In the settings of the source the types and sequence of the created mobile units are defined. With methods, these sequences or types can be influenced and changed during the simulation, so that different cases within a company can be simulated.[BAN11]

- Drain

The material flow object that is responsible for the destruction of mobile units is the drain. The drain has a single workstation at which the MU is processed. The processing time can be adjusted so that for example packaging can be simulated but also set to 0 seconds to simulate a throwaway. There are different data automatically collected within the drain which are the number of destroyed parts, the processing time, etc.[BAN11]
- Store

The store element has a defined number of spaces organized in form of a matrix. If there is no input control the element will place the incoming MU at any free space within the matrix and as long as there are free spaces incoming MUs will be stored.[BAN11]
- Buffer

The Buffer has mainly two purposes within the simulation model. The first purpose is to temporarily store parts that wait to be used in the next process or for transport. Secondly, it prevents the production process from grinding to a halt by moving parts on if the following station is missing a component for the production simulation.[SIE19]
- Track

To model transport routes the passive element "track" is used. There is only the vehicle element that can move on the track.[BAN11]
- Vehicle

For the vehicle element, it is possible to model some material transport systems like the automated guided vehicle (AGV). The vehicle drives with a set speed along with the track element in the given direction and stops at the end of the track.[BAN11]

3. Tugger train systems

This chapter covers the necessary details and aspects which have to be taken into account while planning a tugger train system as well as the basis for the development of the simulation library. It starts with a detailed explanation of several different planning methods which are discussed and compared with each other. Afterwards, additional aspects are discussed like demand fluctuations and tugger train designs. Then the catalog of requirements for the simulation library is presented as well as a rough modelling of the elements for the library. At the end, a state-analysis of Plant Simulation is presented with two possible approaches for the creation of the library elements.

3.1. Methods for the planning of tugger train systems

In the literature, different methods are described which have been developed specifically for the planning of tugger train systems. In the following nine different planning approaches are presented. The various planning methods differ in the degree of detail and scope. They range from rough knowledge-based guidelines to detailed methods for planning the entire tugger train system, but also very complex methods for sub-problems of the planning process are included. At first, these methods are explained in detail, and afterwards, a comparison of the methods regarding different aspects is presented.

3.1.1. Approach according to Alnahhal 2015

The planning approach of Alnahhal is a very complex method, which deals with various optimization problems. It optimizes supermarket locations as well as other planning problems for demand-oriented systems. The approach solves simultaneously the route, tour, and loading problems by taking the capacitive restrictions into account. It uses exact algorithms and dynamic programming to achieve these optimization results.

The supermarket location problem is solved by making several assumptions and using different complex algorithms. The results are further used for the solving of several planning problems which are described in the following. On the left side of Fig. 9 the general procedures of the approach are shown and on the right side the objectives which are minimized. The balance in the right bottom corner should represent the weight of the objectives.

There are several assumptions made for this methodology. The first one is that the routing is the same for all tugger train cycles of the shift and that the cycle time is constant. The station cycle time is exactly the time interval between delivering bins to the station. The explanation of the methodology is done with an example where 20

stations are supplied by a tugger train with four different types of products. In the first step, the demand of products in bins per station is calculated. This is done by tracking the demand of parts per station and station cycles and then transferring the part amounts into the number of bins needed. It is also mentioned that it is useful to use three different types of buffers at the stations. The safety stock replenishes the station in case the bins are delivered too late. There can also be a time buffer that has the purpose of compensating for this delay so that the next station cycle is not affected by the delay, but it should not be too big so that the solution still stays feasible. The third buffer is an empty side-line buffer that takes deliveries that arrive too early.[Aln15]

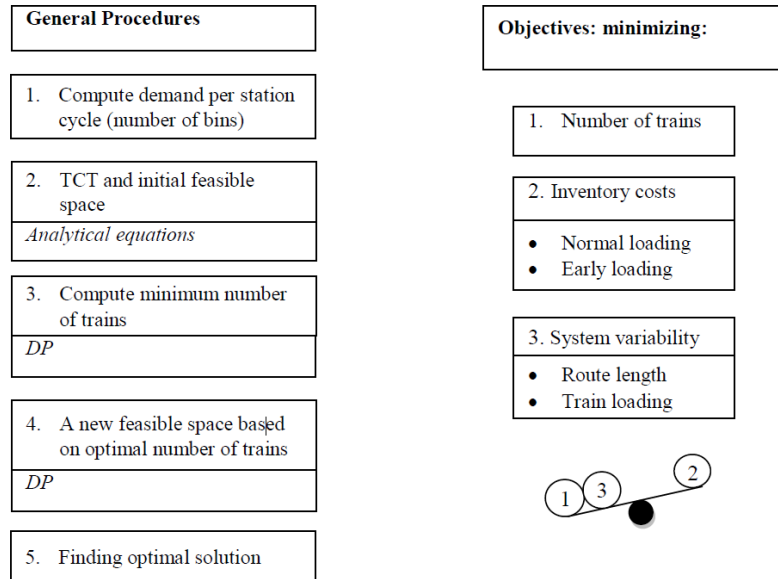


Figure 9.: Major steps and objectives of the planing method [Aln15]

The second step is the determination of the train cycle time (TCT). A necessary assumption for this step is that if a tugger train supplies a certain station in the first cycle, it will supply this station in all following cycles too with a constant train cycle time. This means that for example if a tugger train delivers every 60 min a bin to the station but is faster in a cycle, then it must wait a certain amount of time before starting the next tour so that the TCT stays constant. To ensure that the train cycle time is not too long the train capacity and side-line area work as a restriction. With this assumption and capacity restriction, the calculation of the TCT can be done. An analytical equation is used to calculate the minimum number of train cycles per shift. This number is used in another equation to calculate the feasible solution range of the train cycle time.[Aln15]

In the third and fourth steps, the minimum number of trains is calculated by using dynamic programming (DP). The routing problem is programmed with Matlab and therefore the DP is done there to find the minimum number of trains needed. Based

on this optimal number of trains the feasible solution space is calculated also by using DP. The last step is to find the optimal solution in which the number of tugger trains, the variability of loading, and the route length are minimized simultaneously by re-applying dynamic programming until the optimal solution is found. As shown in Fig. 9 it is possible to minimize the number of tugger trains, the inventory costs, and the system variability such as route length and train loading times with the use of this methodology.[Aln15]

3.1.2. Approach according to Günthner et al. 2013

The planning approach "Schlanke Logistikprozesse" of Günthner et al. focus on the design but also the dimensioning of a tugger train system. It is a very comprehensive method that includes technical and organizational criteria and has an entire tugger train system as a planning result.

While planning a tugger train system with the approach, multiple different steps are to be carried out, starting with the determination of limits and boundary conditions. In this step, many aspects of the system are considered, namely the logistical task, the load carriers, the layout, and the distances between stations. The typical logistic task used for this planning approach is the milk-run, which means as already mentioned the supply of different stations from a supermarket. The logistic task is carried out by loading the different materials at the supermarket and deliver them to the supply locations along the route. At the same time, the tugger train loads finished or semi-finished goods and transports them back to the warehouse. For these transport tasks, a distinction is made into 3 different possibilities. The three cases are 1:n which means a supply task of multiple stations with one supermarket. The second one is the disposal task(n:1), which collects finished goods and deliver them to a warehouse. The last one is the mixed (n:m), where both are done at the same time. The different cases are also shown in Fig. 10.[GDK13]

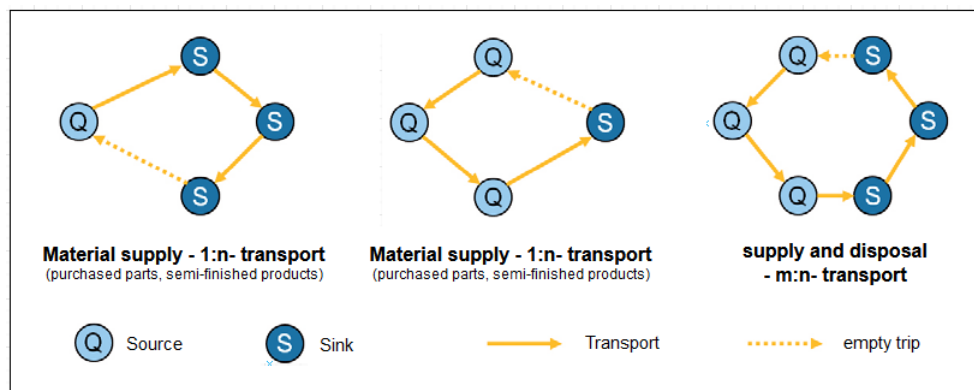


Figure 10.: Distinction between transport [GDK13]

Another thing to consider is the spectrum of the delivered goods. This is important in terms of fluctuation which could occur if the spectrum is too big. Therefore, a balance has to be found to enable stable operations. The load carriers are differentiated in SLC and LLC as also described in chapter 2.2.2. The layout of the production facility needs to be checked and may be adjusted so that the tracks are wide enough to enable safe loading and unloading. This also includes that dead ends are avoided because tugger trains usually can't reverse. Another thing regarding the route is to verify if the tugger train is feasible, which may not be the case if the distances are too short or the route is too complex.

The second step begins after the determination of the boundary conditions is finished. This step deals with defining the process design of the tugger train system. For tugger train systems, there are many design possibilities regarding the process, technology, and control systems. The route is the first thing to define in this step, which is done either as fixed, dynamically planned, or freely selectable routes. Fixed routes are easy to standardize and transparent, but less flexible compared to dynamically planned routes which are mainly used for high fluctuations in demand. The start of these routes is determined by the control system which starts the route either according to a timetable, load-oriented, or permanently. It is possible that the loading is included as an action during the route as well as the process of transporting empty load carriers back to the warehouse. An overview of the process design options is shown in Fig. 11.

As the next step, the design possibilities of the technology are determined. There are various solutions for tugger trains, which consists of a tractor unit towing multiple trailers, available at the market. The choice of the trailers is influenced by different aspects which are further discussed in chapter 3.2.3 and shown in Fig. 23. The planning approach of Günthner et al. provides some examples of overall concepts, to make the selection easier for the planner.[GDK13]

Route	fix	dynamically planned	freely selectable
Tugger Train Control	clocked / with timetable	workload-oriented	permanent
Loading strategy	sorted	fixed arrangement	unsorted
Integration Loading	Loading as part of the tour	Change train / trailer	
Integration of the empties process	1:1 exchange	Carriage on sight	separate empties process

Figure 11.: Design possibilities - Process [GDK13]

According to the method, the next step after the design determination is the dimensioning of the tugger train system. The parameters that are calculated during this step are the cycle time, number of employees, number of tugger trains, work in progress, utilization, etc. Within the scope of the dimensioning process, it is necessary to either

roughly define the route or the cycle time. The first strategy is to define the route based on the layout and to derivate the cycle times and tact times by adding up the transport quantities. In the second strategy, it is the other way around and a uniform tact time is defined for the system. With this tact time, it is possible to derivate the cycle time and the stations are distributed in a way that all of them have the same workload. Additionally, to these steps of the planning method, Günthner et al. also recommend a flexibility and fluctuation reserve at the stations to compensate for breakdowns, interruptions, etc. With the use of a case study this planning process is evaluated, and it is also shown how to include the fluctuation reserve. [GDK13]

3.1.3. Approach according to Gyulai et al. 2013

In the conference contribution of Gyulai et al., the authors put the focus on route and tour planning of tigger train systems. The goal is to minimize the number of required tigger trains and therefore the related costs. To achieve this the method uses a heuristic decision model and key figures as evaluation. It is mainly used for the optimization of already designed tigger train systems.

The planning approach is split into three steps starting with constraints of the shop floor and general requirements regarding the layout. The vehicle routing problem (VRP) is formalized in this step. To do that the layout of the shop-floor is considered as a directed graph with a set of nodes between the stations and edges are also represented as a node. With these nodes, the distance between stations can be seen. During this process there occur some direct and indirect routing constraints. An indirect constraint would be for example a narrow one-way corridor which is preventing the tigger train from reaching the station, while direct constraints are solved with additional equations during the construction phase of the graphs. To handle the constraints effectively a hierarchical layout is generated with defined classes. These classes are the route nodes, the route, and the stations as shown in Fig. 12. With these elements, the VRP model can be generated and solved by using the Dijkstra algorithm.[GPS13]

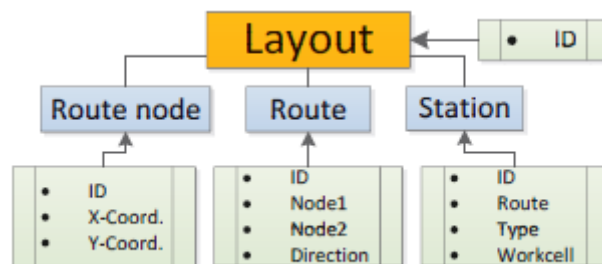


Figure 12.: Hierarchy of the layout representation [GPS13]

In order to calculate the shortest distance between two nodes, the Dijkstra algorithm is used. The calculation for the undirected graph happens with the length of the edges.

[DoD05] The heuristic values are improved by using this algorithm and repeating the process until a goal is found.

In the second step, an initial solution is generated with a so-called triplet solution. Triplet solution means that three main properties are used by the algorithm. These properties are the current position, the previous position, and the next position. This is done to avoid impossible movements of the vehicle and handle the route constraint efficiently. The algorithm prohibits the previous position for the vehicle and the next position, the shortest path is calculated. The triplet is only used by the algorithm and afterwards the implementation of a solution generation heuristic is done. Based on practical reasons the cluster generation defines the clusters which is the difference of the heuristic compared to the algorithm. The paths with the most visits are used for the initial solution which is used by the planning algorithm. In the last step, a neighbourhood function and local search are done. This function is used to improve the generated initial solution. For each combination of visits, the algorithm is applied and repeated. In these repeated runs the number of vehicles is adjusted in case that the total time is bigger than the given cycle time and therefore, the number of vehicles is optimized. The result is an approach with an initial solution generation heuristics method to solve the planning problem of a milk-run system.[GPS13]

3.1.4. Approach according to Kilic et al. 2012

In their article Kilic et al. classify tigger train systems depending on the assignment of tigger trains to routes. It has the goal to minimize the number of tigger trains and the travelled distances of already existing tigger train systems. The planning method consists of exact algorithms and includes planning recommendations.

The authors differentiate with either one or more routes per tigger train, but also if the tour starts are fixed or variable. The goal of the approach is to optimize the system by minimizing the number of vehicles. Two models are created with known time periods of the routes given by the assigned problem. On the other hand, the layout of the routes and the number of used vehicles is not known. The models only differ in the assigned number of routes per vehicle because one model is for one routed and the other for multiple routed vehicles. In order to solve the two models, further assumptions are made such as a constant speed of the vehicles, no traffic problems, and that no breakdowns occur. Another assumption is that the costs for each tour stay the same and that the vehicles are identical. They also used a pull-based system with a fixed layout as the basis for these models. The objectives of the approach are not only to minimize the number of vehicles but also time periods and traversed distance. These objects are the same for both models used. They used a real-life case and therefore additional variables and parameters were given and used. With these parameters, restrictions, and assumptions, the models can be solved by using the GAMS optimization system. [KDB12]

To solve non-linear large-scale optimization problems, the GAMS modelling system for mathematical optimization is used. It is a powerful algebraic modelling language used to solve these problems based on compact formulation.[MGG19]

The results of the article show that an optimum solution can be found in a short time amount but only for the model with the one routed vehicle. For the model of multiple routed vehicles, no optimum solution was found. This shows that one routed vehicles are easier to plan and manage in comparison with the multiple routed vehicles, which are mostly a special case.[KDB12]

3.1.5. Approach according to Krause et al. 2014

In their conference contribution, Krause et al. present a methodical approach to planning tugger train systems. The focus of the approach is on system design and has a completely planned tugger train system as result. The method is based on a heuristic decision model, which is applied to seven different planning fields and provides alternatives for actions taken.

The first field should enable standardized resource planning by adjusting the production control. The goal is to balance the quantities and the mix of the produced products. This not only standardizes the resource planning but also the used technology and the personnel. In the second step, the layout is adjusted to achieve driven distances that are as short as possible. To achieve this goal the routes, as well as route widths and other factors, are planned and designed with the needed delivery volume. The next step is to plan the transport equipment. It is recommended to use standardized load carriers. These should be chosen by taking the maximum weight and ergonomic aspects into account. Field four covers the transport technology. In this field, the goal is to optimize the utilization by using different technologies. A variance of used technology and flexible solution can increase the utilization of the capacity. The route bundling is done in the fifth step. This means that in the case that different products are loaded and delivered at the same time, the bundling of these different containers on one route can increase the efficiency. Low load change times of containers increase the efficiency of tugger trains significantly. This is considered in step 6. In the last step, the traffic control is optimized. This step is important because waiting times must be avoided and by doing that the efficiency is increased. Different existing technologies and control concepts are used to deal with traffic control and increase the internal material supply system. With better traffic control the traffic flow is automatically accelerated. In the end, the best solution is selected by evaluating the different fields regarding efficiency. This heuristic model created by Krause et al. is completely knowledge-based. [KMS14]

Krause et al. especially take up flexibility and mutability as evaluation criteria in two further published conference contributions. The determination of the optimal flexibility corridor and the organization of the adaptability is the result of the increased efficiency caused by the change of design elements. ([KMS15][KMS16]. Fig.13 shows that with a

tugger train in contrast to a forklift the flexibility level is reduced, but the efficiency is increased.

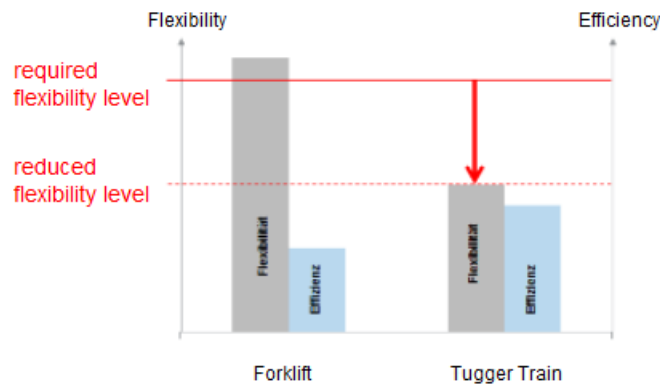


Figure 13.: Schematic comparison of flexibility and efficiency of forklift and route train [KMS14]

3.1.6. Approach according to Meinhardt, Schmidt 2012

The planning strategy for the tugger train systems of Meinhardt and Schmidt focuses on two basic topics. The first one deals with the evaluation and dimensioning of the tugger train system, but only for already given routes. Therefore, the locations of the stations which are supplied are also given and already combined to routes.

The other topic the authors focus on is the forming of the optimal route. This means the optimization of the existing routes by for example changing the allocation of the stations. Solutions for this are known as the vehicle routing problem (VRP), which is not further discussed in this planning strategy.

Regarding the dimensioning and evaluation, the planning strategy includes five questions, which must be asked and answered for every route individually. The first question is about the necessary interval in which the route must be driven with the tact time as result. For this question several parameters and aspects have to be taken into account, starting with the layout of the facility and the existing routes. Furthermore, the delivery quantity is considered by assigning load carriers to the stations and therefore monitored, which also includes loading times. For the loading process, additional time has to be included to compensate for braking and acceleration processes. Not only process-related aspects influence this question, but also technical parameters like the transport capacity which is limited by the trailers. Another influencing factor is the average speed of the tugger train. With the definition of all these components, the tact time can be calculated. The second question is, how long the route takes for the tugger train to finish its tour. This is answered by calculating the cycle time, which mainly depends on the load of the tugger train. The cycle time is generated with the maximum loading possible

with exactly one loading process per stop. For the further determination of means of transport, the cycle time is the decisive factor. There are four components that make up the cycle time, which are the travel time, the check-in time at stations and at the supermarket, as well as a safety margin to compensate for failures. The next objective to calculate is the amount of the necessary means of transport. According to Meinhardt and Schmidt, this is described by the rounded-up quotient of cycle time and tact time. [MeS12]

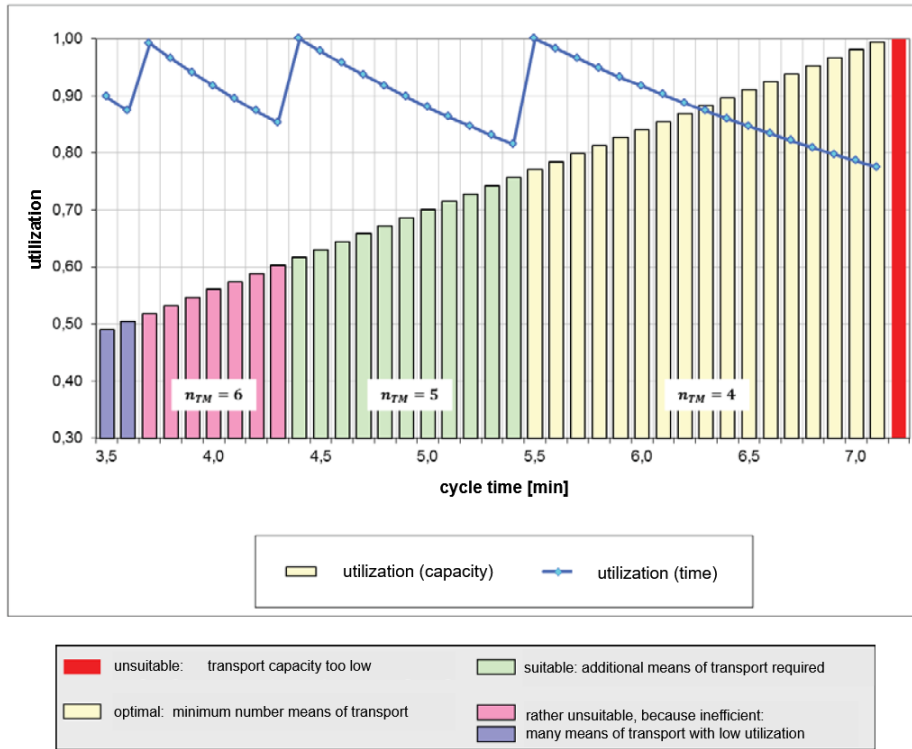


Figure 14.: Relation between cycle time, degrees of utilization and number of means of transport [MeS12]

In the planning approach, two different degrees of utilization are distinguished, which are the capacity and the time utilization. The capacity utilization describes the available transport offer as a ratio of average and maximum load (transport capacity). In contrast, time utilization is the ratio of the cycle time and the total time, which also includes the waiting times after a finished tour. These two degrees of utilization are the main results of the planning strategy, which are used for the evaluation. In Fig. 14 is shown that the capacity utilization grows proportionally to the cycle time, which has the reason that with a shorter cycle time the route frequency rises and therefore also increases the possible amount of transported goods. The time utilization on the other hand is indirectly proportional to the cycle time. The shown jump points result from

the necessary increase of the vehicles to keep the cycle time.[MeS12]

In the last question, the necessary buffer space is determined. According to the planning method, tigger train systems typically use a so-called two buffer principle. In this principle, every location has two buffers per type of delivered goods. One buffer for the full load carriers and the other for the empties. The capacity of the buffer must be big enough to bridge the time between the deliveries. On the other hand, the maximum size of the buffer is set to the capacity of the used tigger train. In the case that the reserves get very large and therefore delays in delivery occur, further buffer capacity is necessary.[MeS12]

3.1.7. Approach according to Raposo et al. 2009

The planning and simulation of a tigger train system of the Qimonda plant in Porto (Portugal) is described in the published article of Raposo et al. The planning method consists of different steps and has the optimization of waiting times, number of employees, and utilization as the goal. It has also a material flow and sensitivity analysis included to further enhance the tigger train system.

The first step is to use the available information and based on it to dimension the tigger train system. Therefore, to enable this step different types of information were collected. In this case, the supermarket management and transportation are performed by different resources which is also called decoupled route format. With the collected information the authors chose a trolley capacity of 10 packs and a Kanban system for the signalling of the transport requirement. The supermarket has one assigned worker and the route was driven by two tigger trains with a delivery route operator per tigger train. The tact time was defined as 12 min with an offset of 6 min. The authors observed that even if the system is not optimized but the rearranging of the route and tact times already brought advantages to the workers. One of these advantages was that the work in progress was reduced as well as downtimes. Important for the creation of the simulation model is that even small differences or variations of the real system can cause false results. Therefore, even if the information provided is reliable, it is important to know how a variation of parameters and inputs influence the results of the simulation model. For this reason, Raposo et al. propose a sensitivity analysis to get an understanding of which parameters and inputs influence the different results. [RaD09]

In Fig. 15 the simulation model they created is shown. It is used to evaluate different scenarios and has as goal to show if more human resources are necessary or not. This is done by varying different key factors and create new combinations with them to simulate different possible solutions. The key factors which were used in the simulation model are the route design, influenced by the location of the stations, and the human resources. The number of delivery route operators is an important factor since the goal is to optimize it and therefore lower the labour costs. Other factors that influence the model are loading and unloading times, tigger train capacity as well as the travelling speed of the tigger

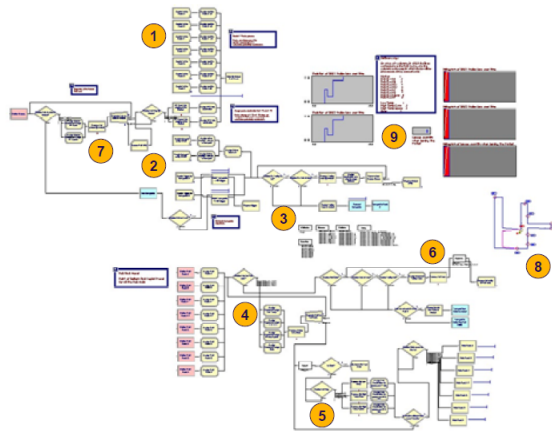


Figure 15.: Arena simulation model[RaD09]

train. The simulation has the purpose to reflect aspects of the real-world system and to evaluate them. The start of the route with a fixed tact time or permanent and also to the transportation of products either in lots or packs are these aspects. Seven different scenarios with different travelling speeds and tact times as well as a different number of tugger train operators were tested. The results of these simulations are that with the usage of simulation, transportation waste can be reduced. The optimized utilization of the human resources is the other interesting result of the planning of a tugger train system using a simulation model.[RaD09]

3.1.8. Approach according to VDI 5586

The planning approach according to VDI 5586 is a very comprehensive method that includes all aspects of the planning process for a tugger train system. It includes a detailed morphology with design alternatives as well as detailed instructions for the dimensioning. The result of this planning method is a completely designed tugger train system.

According to “VDI 5586 Batt 2”, the planning of a tugger train system, as shown in Fig.16, can be split into 4 Phases with possible iterations between the phases.

Before the planning of a tugger train system, the different boundary conditions and input variables must be identified. This includes the gathering of data about the transport goods, load carriers, layout, and delivery quantities. Furthermore, there are corporate guidelines that have to be considered, for example, the maximum number of trailers, maximum length, travel speed, etc. All these conditions have to be considered, but in principle, tugger train systems are differentiated according to their primary transport task. The transport task is either supply, disposal, or a mix, which are already described in chapter 2.5.[VDI16b]

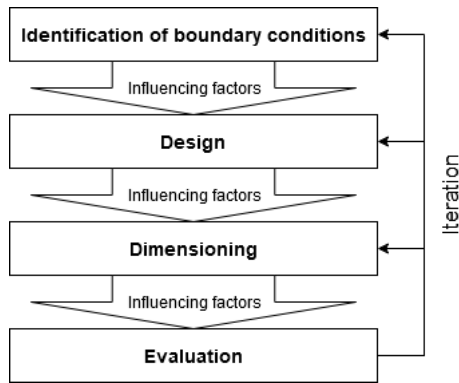


Figure 16.: Tugger Train planing phases ([VDI16b] p. 5)

In the second step, the technical and organisational design is defined. According to VDI 5586 the technical design alternatives define components of the tugger train, which means to choose the suitable tractor and trailers. In table 2 the morphology for the technical design alternatives of VDI 5586 is shown.[VDI16a]

Feature		Design alternative				
Tractor	Drive type	Electric drive	Combustion engine	LPG propulsion	Fuel cell drive	
	Design	Three wheel tractor		Four wheel tractor		
	Operation	manually		automatically		
Trailer		Standing version	Seated version			
	Load carriers	no load carrier	Standard small load carriers (modularly adjusted to the base areas 800 × 1200mm (Euro) and 1000 × 1200mm (ISO))	Standard large load carriers (base area 800 × 1200/ 600 × 800mm (Euro) or 1000 × 1200mm (ISO))	Special small load carrier (base area deviates from Euro or ISO dimensions)	Special large load carrier (base area deviates from Euro or ISO dimensions)
	Requires further technical aids to provide	no	permanently installed technology at the supply points (e.g. roller conveyors)		Use of an auxiliary means of provision (e.g. hand pallet truck)	
	Loading / unloading side	one-sided	both sides (loading side defined unloading side)		both sides (loading and unloading side independent)	
	Steering system	unsteered (single axle)	Turntable steering (1 axle)	Turntable steering (2 axles)	Ackerman steering (1 axle)	Ackerman steering (2 axes)
	Media supply for trailers	none	Hydraulics		Pneumatics	Electricity

Table 2.: Technical design alternatives for tugger train systems [VDI16a]

The tractors can basically be distinguished into three- and four-wheel tractors. A further distinction can be done according to their drive, design, and operation. The choice of the drive strongly depends on the application, for example, the exclusion of combustion drives within buildings, but also on the expected operating costs. The design has an influence on its manoeuvrability and towing capabilities but also defines if the tractor

drives manually or automatically. On the other hand, the trailers are basically distinguished by their suitability for the different types of load carriers. This means that the used load carriers, also see chapter 2.2.2, are a decisive factor for the selection of the trailer. In chapter 3.2.3, the selection of the trailers is further discussed. The comparison includes aspects like loading side, steering systems, media supply, turning cycle.[VDI16a]

As already mentioned, not only the technical design alternatives are relevant, but also the organisational design alternatives. These alternatives include several aspects like the assignment of tugger trains to routes or start points. An essential feature to define is the number of routes, which influences the complexity of the control system. If there is only one route, the control and assignment of stations is easier compared to the case that there are multiple routes per tugger train. A reason for this is that several delivery points can be assigned to a single stop, which reduces the number of stops on the one hand but may extend the routes on the other hand.

The tugger train drivers can be also assigned in the same way as the tugger trains. A tugger train driver can either be assigned to exactly one route (1:1), one driver for several routes (1:n). There is also the possibility to assign several drivers to one (m:1) or multiple routes (m:n).[VDI16a]

The start of a tour can be controlled in different ways. It can follow a fixed schedule in which the tours are always starting at the same times or in a fixed interval. This system is frequently used in practice because it leads to even and predictable throughput times of the transported goods. However, fluctuations in the transport quantities usually occur in this system which is further described in chapter 3.2. This problem is solved by the “load-oriented” system, which starts the tour if there are sufficient transport orders. This way the capacity utilization of a tugger train stays consistently high and fluctuations can be smoothed. In the third system, the tours start permanently, which means they start immediately after the previous tour has ended.

To achieve a high capacity utilization, it is important to calculate the necessary capacity first which is done with the number of different load carrier sizes and the respective share per size. The same principle applies to the number of tugger train trailer types.

A further distinguishing feature with a decisive influence on the handling times at the staging points is the order of the load on the tugger train. Order can be achieved, for example, by placing the load carriers on the trailers according to the unloading sequence.[VDI16a] In the dimensioning, there are several input variables considered, which are resulting from the boundary conditions and the design. These include the throughput requirements, the capacity restrictions based on the tugger train and buffer sizes, as well as the process times.[VDI16b]

The last step of the planning method is the evaluation of the planned tugger train system. For this process, some key indicators must be calculated first. These essential key indicators are the time and capacity utilization and the resulting overall utilization of the system. There are a few more key indicators like the average number of stops and loads per tour, as well as the cycle times. With these indicators, the system is evaluated and show which areas can be optimized.[VDI16a]

3.1.9. Approach according to Wiegel et al. 2013

Wiegel et al. observed that in many companies the implementation process of a tugger train system is not following a systematic approach but is done by trying out and based on intuition. Therefore, the authors developed a simulation model to plan and optimize tacted tugger train systems. The approach includes a sensitivity analysis as well as a material flow analysis and has the optimization of work in progress, number of vehicles, and other aspects as result.

The planning process starts with the determination of the transport requirement and the signalling of it. The focus lies on the control system and the designing and optimization of its parameters. The fluctuations in material and transport requirements are one of the big challenges in the planning process. They are caused by the high dynamics of production processes, which are not sufficient considered in a static design. A static design can for example be a system based on the average requirement. To aid the optimization of such a design the simulation model was created. The purpose of the simulation is to iteratively optimize different parameters and test them out, without changing the real system. The simulation model is split into two different models namely the consumption model and the actual model of the cyclical milk-run system. The reason for this is the high frequency in which the deliveries take place in their case. In the consumption model, the material demand of the production lines is represented with the flow production as a requirement. The model is based on material lists of an ERP system in which the number of components required is stored. By trying out different frequencies or higher transport capacities the milk run can be optimized in terms of capacity utilization.[WIK13]

The goal of simulation-based optimization is to achieve a system that works as efficiently as possible. An example of this would be a system with low transport capacity but high supply security. To achieve this result different configurations of the system are tried out and evaluated. These changes of the parameters are limited by boundary conditions such as process requirements but also technical limits. In the simulation model, the optimization is done by varying three different parameters. These parameters are the number of Kanban cards the tact time and the capacity of the tugger trains. To adjust the model of the milk-run system to the conditions and objectives of the company additional parameters such as the utilization of load carriers, the number of transports, and stock levels are tried out in different configurations and afterwards evaluated and compared. During the planning phase, it was proven that with the help of simulation the milk-run system can transport all material groups which were tested. In a real case, they showed that with the results of the simulation a fast implementation of the tugger train system is possible which is done step by step. The results of the researched case were that the transport was reduced by 75 percent in comparison with the original system.[WIK13]

3.1.10. Comparison of the approaches to the planning, evaluation, and optimization of tigger train systems

In this chapter a comparison of the introduced planning strategies is done, starting with the in Fig.17 shown differentiation by functions and procedures of the methods. The comparative analysis particularly highlights the divergent views and objectives of the authors in the respective areas.

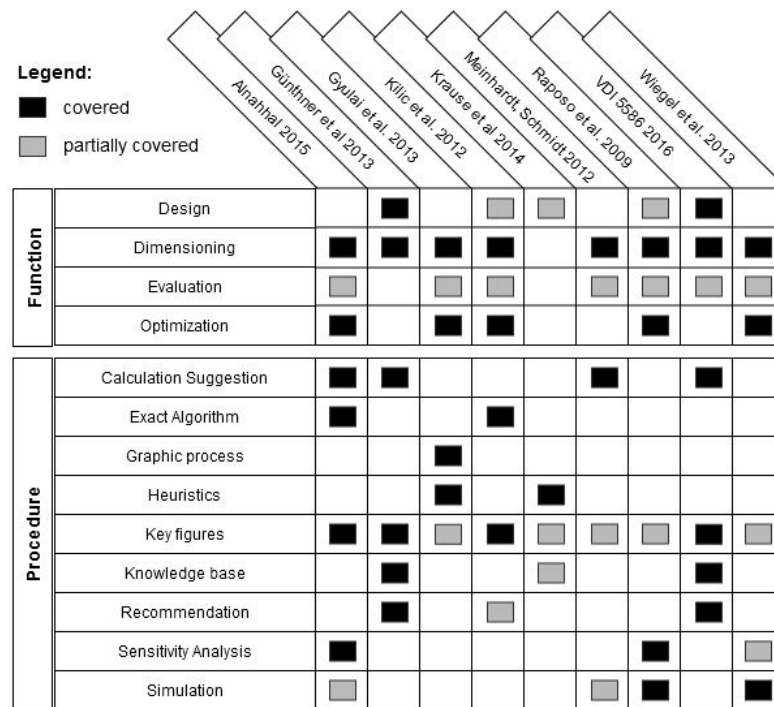


Figure 17.: Comparison of the approaches regarding function and procedure

Another aspect that becomes visible with this analysis is that the approaches can be divided into two categories. In the literature, these categories are the production technology and operations research.[MST14]. Planning approaches of the operations research category focus on the modelling and solving optimization problems and not on the implemented tigger train system. Therefore, they are mostly limited to a special sub-problem but still have the dimensioning as a focus. The goal of the operations research is the optimization of these sub-problems with the use of mathematical algorithms or simulations. The evaluation is done automatically as a side result of the optimization because the mathematical algorithms and heuristic models are used to find a good solution. These models also use different key figures for the evaluation, but design aspects of the tigger train system are not included in the planning methods. Of the introduced methods, the planning approach of Kilic et al., Alnahhal, Gyulai et al. and Wiegel et al. ([KDB12][Aln15][GPS13][WIK13]) are part of this category.

The rest of the presented planning approaches are part of the production technology category which has not only the dimensioning as the focus but also the design of the implemented tugger train system is a big part of the method. The only exception is the method of Krause et al. because their heuristic model is purely knowledge-based and doesn't include dimensioning tools. The design determination is often based on simple calculations and assumptions. In this planning approaches the optimum solution is pushed into the background at first because the main goal is the creation of a feasible system. Some of these methods also include criteria catalogs and sensitivity analyses as aids for the evaluation. If this is not the case then the evaluation of the approaches is limited to some key figures of the tugger train system, which vary and depend on the used method.

The methods can be also further compared regarding their suitability, results, and advantages and disadvantages. In Fig. 18, these differences are presented. With the comparison of the suitability, it becomes visible that the different methods are usually designed to solve a specific sub-problem. These can either be the optimization of routes or loading problems, the minimization of the number of vehicles and the costs, but also the overall optimization of an existing tugger train system. On the other hand, some methods are used to design and dimension the whole tugger train system. To achieve these goals, the planning approaches use different tools, like exact mathematical algorithms, simulations, heuristic models, or design catalogs. For the reason, that the methods have different goals, they also have different planning results. These results depend on the focused sub-problem and can vary from a complete overall system to the optimum solution for one aspect of the tugger train system. Common results are the number of necessary vehicles, number of employees, and the utilization because these results ultimately also minimize the costs of the system. Other results are the different times, especially the cycle and tact time but also waiting and loading times, which also influence the utilization.

The comparison also shows that the different methods have advantages as well as disadvantages. An advantage that is often visible, is that the methods provide a specific step-by-step procedure, which makes the usage easier for the planner. In many planning approaches, there are also case studies included, to show the correct procedure and to serve also as decision-making aids. Others have the advantage to focus on one special problem and therefore provide an optimum solution and procedure for that case. Unfortunately, the methods not only have advantages but also disadvantages. The lack of design alternatives is a big disadvantage of many planning approaches, but also the limited applicability resulting from special assumptions or used programs. Another disadvantage, mainly for planning approaches that are used for the implementation of a new tugger train system, is that they miss some aspects or don't cover them in necessary detail. These differences are further presented and clarified in Fig. 18. In summary, it can be stated that there is no standard method for the planning of tugger train systems because each method has a different focus and therefore should be selected accordingly.

	Suitability	Method	Evaluation Criteria	Planning Results	Advantages	Disadvantages
Alnahhal 2015 Efficient Material Flow in Mixed Model Assembly Lines	<ul style="list-style-type: none"> Optimization of tuggler train systems regarding routes and loading problems 	<ul style="list-style-type: none"> exact algorithm dynamic programming (DP) 	<ul style="list-style-type: none"> Number of tuggler trains Inventory costs System variability 	<ul style="list-style-type: none"> number of trains needed train cycle time (TCT) supermarket location 	<ul style="list-style-type: none"> Specific procedure for dimensioning optimal solution through repetition sensitivity analysis used 	<ul style="list-style-type: none"> only specific planning tasks covered no design alternatives
Günthner et al. 2013 Schlanke Logistikprozesse Handbuch für den Planer	<ul style="list-style-type: none"> given concept or at least either given layout or takt time low demand fluctuations 	<ul style="list-style-type: none"> use of mathematical algorithms Suitability Catalogue for design alternatives Decision-making aids 	<ul style="list-style-type: none"> Number of employees 	<ul style="list-style-type: none"> complete tuggler train system Cycle and route times Nr. of tuggler trains Nr. of employees 	<ul style="list-style-type: none"> Application in case studies Tuggler Train Concepts Design alternatives detailed description 	<ul style="list-style-type: none"> only certain planning tasks Differentiation based only on the loading process
Gyulai et al. 2013 Milkrun Vehicle Routing Approach for Shop-floor Logistics	<ul style="list-style-type: none"> Optimization of a already designed tuggler train systems 	<ul style="list-style-type: none"> solution generation heuristics graphic planning process for routes 	<ul style="list-style-type: none"> number of vehicles cycle times 	<ul style="list-style-type: none"> number of vehicles optimized routes cycle times 	<ul style="list-style-type: none"> efficient route planning with VRP optimal solution through repetition 	<ul style="list-style-type: none"> special program and still a prototype high effort to create the layout data
Kilitic et al. 2012 Classification and modeling for in-plant milk-run distribution systems	<ul style="list-style-type: none"> minimization of number of vehicles and traveled distance for existing tuggler train systems 	<ul style="list-style-type: none"> exact algorithm for dimensioning recommendation of key figures 	<ul style="list-style-type: none"> idle time number of vehicles costs 	<ul style="list-style-type: none"> optimized routes and tour times optimized number of vehicles 	<ul style="list-style-type: none"> a numerical example is given detailed description of constraints and parameters 	<ul style="list-style-type: none"> many assumptions limit the applicability only certain planning tasks
Krause et al. 2014 Methodischer Ansatz zur Ganzheitlichen Planung von Routenzugsystemen	<ul style="list-style-type: none"> integrated planning of a tuggler train system 	<ul style="list-style-type: none"> knowledge base heuristic model key figures 	<ul style="list-style-type: none"> Efficiency Flexibility 	<ul style="list-style-type: none"> complete overall system 	<ul style="list-style-type: none"> Specific step by step method recommendations regarding flexibility 	<ul style="list-style-type: none"> only knowledge based no design alternatives no dimensioning equations
Meinhardt, Schmidt 2012 Einsatzplanung für Routenzugsysteme	<ul style="list-style-type: none"> Dimensioning and optimization of already designed tuggler train systems 	<ul style="list-style-type: none"> static simulation of the buffer locations mathematical calculation of the means of transport 	<ul style="list-style-type: none"> reliability of supply Utilization Number of means of transport 	<ul style="list-style-type: none"> Capacity utilization and time utilization frequency of loading required means of transport 	<ul style="list-style-type: none"> Specific procedure for dimensioning 	<ul style="list-style-type: none"> no design alternatives specific assumptions limit the applicability
Raposo et al. 2009 Simulation of a Milk Run Material Transportation System in the Semiconductors Industry	<ul style="list-style-type: none"> planning of a Milk Run System with the use of a simulation model 	<ul style="list-style-type: none"> Material flow simulation sensitivity analysis 	<ul style="list-style-type: none"> operator utilization Trolley capacity utilization idle times 	<ul style="list-style-type: none"> waiting times of Products delivered trolleys Operator utilization number of employees 	<ul style="list-style-type: none"> method shown through a actual case use of a sensitivity analysis analysis through simulation 	<ul style="list-style-type: none"> high effort creating the simulation model related to the project and only partly applicable
VDI 5586 2016 Routenzugsysteme Grundlagen, Gestaltung und Praxisbeispiele	<ul style="list-style-type: none"> Design and dimensioning of tuggler train systems 	<ul style="list-style-type: none"> mathematical equations key figures and catalog for design alternatives 	<ul style="list-style-type: none"> limited evaluation through key figures 	<ul style="list-style-type: none"> complete tuggler train system utilization cycle time Nr. and design of the tuggler trains 	<ul style="list-style-type: none"> given practical examples concrete morphology for the design coverage of many planning tasks 	<ul style="list-style-type: none"> no route planning limited evaluation
Wiegel et al. 2013 Simulationsgestützte Optimierung innerbetrieblicher Milkruns	<ul style="list-style-type: none"> Optimization of already existing routing systems 	<ul style="list-style-type: none"> Material flow simulation sensitivity analysis 	<ul style="list-style-type: none"> Work in progress Number of transports Utilization 	<ul style="list-style-type: none"> optimized tuggler train system Number of transports amount of stocks 	<ul style="list-style-type: none"> use of a sensitivity analysis simultaneous optimization 	<ul style="list-style-type: none"> no design alternatives High effort for creating the simulation model no aid for the design

Figure 18.: Comparison of the approaches regarding different aspects

3.2. Further relevant aspects for the Simulation library

This chapter deals with two aspects that were either not detailed enough for the Simulation library or only mentioned as a recommendation in the introduced planning approaches. The first presented aspect is fluctuations in demand, which is an important topic and is mentioned in several planning approaches as an important factor to consider. The second aspect is the technical criteria for the selection of tugger train trailers. There are different components a tugger train consists of, starting with different tractors which are also mentioned in chapter 2.2.1, followed by a wide range of trailers. As the first step, the technical criteria for tugger train trailers are examined in more detail, and finally, a comparison of trailer designs is made as a summary

3.2.1. Fluctuations in demand

Since tugger train systems, as a component of the value creation networks, are subject to demand fluctuations, this chapter deals with the theoretical principles behind them. The demand fluctuations are mentioned in some of the presented planning approaches and are an important topic and therefore discussed in more detail. Fig. 19 shows the various fluctuations in demand and where they occur in the value chain. However, only the demand fluctuations of the tugger train system (inter-process fluctuations) are relevant for this master theses and therefore, the external and internal fluctuations are not further explained.

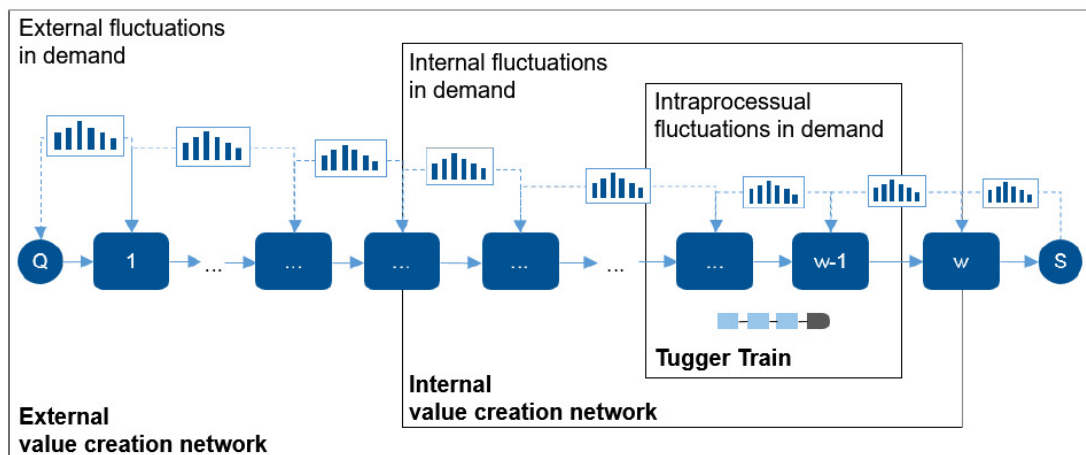


Figure 19.: External, internal and intraprocessual demand fluctuations in value creation networks [LHG18]

The demand Fluctuations in tugger train systems are created in the in Fig. 20 shown basic replenishment cycle in consumption-based or demand-based tugger train systems. It shows that along the replenishment cycle 5 different types of demand fluctuations can be identified, which are explained in more detail below.

First of all, a replenishment need must be created, either by reaching a minimum stock level of units or by the demand times determined in advance and the resulting production program. This can be influenced, for example, by production stops, maintenance, etc. The next type of possible demand fluctuations is based on the fluctuating time until the replenishment demand is perceived. Here, however, a distinction must be made between consumption-oriented and demand-oriented processes. In the consumption-oriented method, the replenishment demand must be perceived first to start the replenishment cycle. The fluctuation of the time depends on the technical and organisational design. On the other hand, the time for perception can be neglected in the demand-oriented process, since in this process the transport requirement is based on calculated consumption. The fluctuating time for demand depends on the selected transmission of demand. For example, it is significantly longer for analogue transmission than for digital transmission of demand, such as e-Kanban. The material is then removed from storage and made available at the source and transported to the sink. In both cases, disturbances and blockages affect the process times. Process and cycle times are also influenced by human working methods.[LHG18]

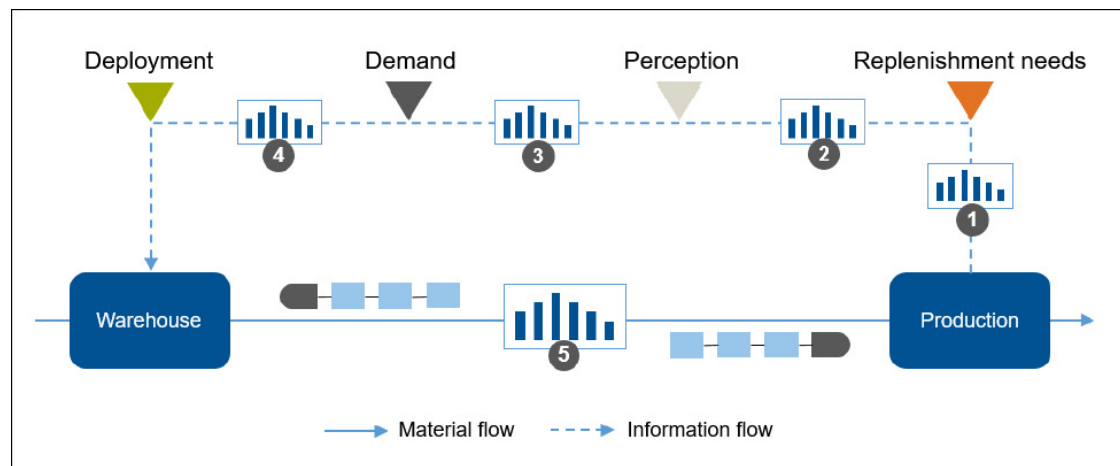


Figure 20.: Replenishment cycle in consumption- or demand-oriented tugger train systems [LHG18]

3.2.2. Technical criteria for the selection of tugger train trailers

As shown in chapter 3.1.9 the morphology of "VDI 5586" already gives a rough overview of the technical design of the tugger train trailers and tractors. The tractors are mainly differentiated into four- or three-wheel tractors with the main difference of the overall weight they can tow. The three-wheel tractors mainly use an electric drive and are used for indoor transport whereas the four-wheel tractors are used for outdoor and heavyweight transport.[STI20] On the other hand for trailers there are more differences and aspects to look at and therefore, this chapter takes a closer look at the technical criteria for the selection of tugger train trailers. As an introduction, Fig. 21 gives a good

overview of the technical criteria.

Flexibility	Driving characteristics	Operational requirements
<ul style="list-style-type: none"> • Loading and unloading flexibility (direction, sequence) • Variation with regard to load carriers and trolley sizes • Complexity of route planning 	<ul style="list-style-type: none"> • Turning circle • Tracking accuracy • Noise generation 	<ul style="list-style-type: none"> • Media supply necessary • Maintenance expenditure • Auxiliary equipment necessary (forklift, trolley) • Coupling and uncoupling of trailers
General conditions		<ul style="list-style-type: none"> • Required load capacity • Weight limits for pushing the trolleys/trailers • Allowed number of trailers per train

Figure 21.: Technical criteria for the selection of tugger train trailers [GGK12a]

In the following, these criteria are examined separately and described in detail, starting with the general conditions followed by flexibility, driving characteristics, and finally operational requirements.

- **General conditions**

Several general conditions have to be defined at first, in order to make a feasible trailer selection. Many different company guidelines, factory layouts, and published articles about internal transport were researched and the general conditions shown in Fig. 21 are the results of this research. It is visible that different trailer designs might be not suitable for the tugger train system, right from the beginning. The reason for this is the maximum load capacity of the trailers which varies between 500 to 1000 kg and therefore some containers can't be transported. In addition to this restriction, many companies also limit the weight for pushing load carriers because of ergonomic aspects. If the weight limits for pushing load carriers are exceeded the advantage of trolley-based solutions can't be used, since a loading aid, for example, a forklift is necessary. The third mentioned general condition is the allowed number of trailers per train. This condition is often dependent on the towing power of the tractor. The available space may also limit the tugger train length. [GGK12a]

- **Flexibility**

Another essential technical criterion in the selection of tugging train trailers is flexibility. The flexibility criterion covers multiple aspects such as loading and unloading, load carriers but also aspects of the route planning. The load carrier size must be considered because some trailers use the insertion principle with trolleys pushed onto the trailer and other trailer designs vary in the types of load carriers which can be transported. Another aspect regarding flexibility that has to be discussed are loading and unloading properties. Some trailer design only allows to load and unload into one direction such as the E-frame others like the B-frame can be loaded from both sides. Regarding the order of loading, there is no restriction for trailers that are loaded from the side. For platform wagons, it is advisable to implement a loading and unloading sequence for ergonomic reasons. The choice of trailers which can only be loaded from one side usually results in longer walking distances for the tugging train driver. The reason for this is that it is not always possible to plan the stopping points in a way, that the unloading area is on the side coincides with the unloading side of the trailer. Therefore, sophisticated route planning is advisable to ensure that as many stopping points coincide with the unloading side of the trailer. On the other hand, route planning often gets more complex in these cases.[GGK12a]

- **Driving characteristics**

The driving characteristics of the individual trailer also influence the choice of which technology is used. In particular, the axle and steering system of the trailer as shown in Fig. 22 are important for the choice. With these systems, it is also possible to implement tugging trains in compact factory layouts with narrow roads, since tight curve radius and high directional stability are achievable. To understand how the different axle and steering systems influence the choice of trailers, they are explained in more detail.

The first described axle system is the single-axle trailer. This type of trailer uses a rigid drawbar that connects two trailers with each other. The drawbar lengths of the trailers are matched to each other and connect the two trailers with only one coupling point. This allowed the single-axle trailer to achieve minimum curve radii and ideal tracking behaviour which makes them very suitable for narrow tracks. However, the single-axle trailer also has disadvantages which are that a single trailer is not pitch-stable and therefore needs additional support if it is necessary for it to be stable while uncoupled.

On the other hand, the two-axle designs need a suitable steering system to achieve good handling. A typical steering system used for these two-axle designs is the so-called turntable steering system. A turntable steering system is characterised by a robust and relatively simple design but has a high load capacity. The driving characteristics are whereas just moderately good since the entire wheel axle is rotatably connected to the trailer platform. This influences the stability and turning radius of the trailer.

The third presented steering concept is the all-wheel Ackermann steering system. In this system compared to the turntable steering, not the entire axle is rotated but each wheel is steered individually. A handlebar system and drawbars are transmitting this steering movement to the individual wheels. The big advantage of this steering system is that it guarantees a high load capacity due to the reason that the trailer remains stable even with a high steering angle. The steering of the wheels individually also enables ideal tracking behaviour and allows that very tight curves can be driven. The downside of this steering system is the high maintenance requirements and the complexity of the whole steering construction.[GGK12a]

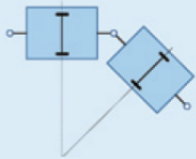
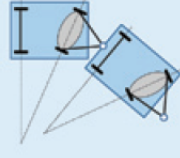
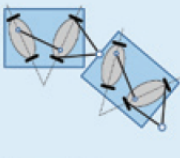
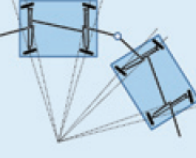
			Track Running	Turning radius	Properties
Single axle trailer	unsteered		yes (for rigid drawbar)	small	<ul style="list-style-type: none"> • Very simple construction • Limited load capacity • Uncoupled not stable
	Turntable steering (1 axles)		no	medium	<ul style="list-style-type: none"> • High load capacity • Simple construction • Risk of tipping over with large turning angle
Two axle trailer	Turntable steering (2 axles)		no	yes (for rigid drawbar)	<ul style="list-style-type: none"> • High load capacity • Tilt and pitch resistant • Uncoupled not stable
	All wheel Ackermann steering		yes	small	<ul style="list-style-type: none"> • Highest load capacity • Tilt and pitch resistant • Complex steering construction

Figure 22.: Axle and steering systems for tugger train trailers [GGK12a]

- **Operational requirements**

The operational requirements are differentiated mainly into three parts which are the maintenance effort, the need for handling aids, and the requirements for the tractor. The maintenance requirement often is directly linked to the required media support. This is shown with all free-lifting trailers, which need a media supply from the tractor. This can be either pneumatic, hydraulic or electromotive support which is used for lifting devices. There are also innovative solutions for these lifting devices which work autonomously and recover the energy needed for the lifting process during the tour. However, as mentioned is depending on the

lifting device the additional maintenance requirement not negligible. If frequent coupling and uncoupling of trailers are involved in the tugger train system, then it is not recommended to use trailers that use a pneumatic system. The couplings of these connections are not designed for the frequent coupling and therefore, a lot of malfunctions occur.









Regarding the need for handling aids, the trailer designs are divided into two groups. The first group uses the insertion principle in which a trolley is used as an aid and loaded into the trailer. The second group consists of trailers that are loaded directly with load carriers by a forklift truck for example. In general, it is important to not underestimate the handling of the full trolleys as well as the empty trolleys. This must be controlled within the delivery process of the tugger train system.[GGK12a]

3.2.3. Comparison of the different trailer designs

In the previous chapter, the technical criteria of tugger train trailers were presented. No trailer fits every needed criterion and therefore, the different trailer designs available on the market are discussed in this chapter. During the selection of a tugger train trailer, multiple different properties influence the decision. There are several different manufacturers, therefore differences in the properties of the design can occur, nevertheless is the following comparison based on general properties of the trailers which are also shown in Fig. 23.

For this comparison, the trailer designs are split into two categories, the concepts for picking up and the transport trolley. The trailer designs with which the load carriers are mounted are the most common designs. As already mentioned in previous chapters, this design uses the insertion principle which means that the load carriers are pushed into the frames. The load carriers are on trolleys and the process happens at ground level. In the comparison, it is shown that some trailer designs like the E- or C-frame are only able to be loaded from one side. As others like the B- and U-frame enable the loading from both sides. This directly influences the complexity of the route planning which is shown in Fig. 23 that trailers with only one loading side have a higher route planning complexity compared to others. The loading and unloading sequence can be chosen freely for all frames, except for the platform trailer, because of ergonomic reasons. For most frames, it is possible to load different sizes of trolleys or load carriers. Only the taxicabs use a uniform load carrier. The direct loading with a forklift is only necessary for the platform trailer due to the reason that the load carrier has to be put on top of the platform, which is for certain weights not possible without a forklift. The big difference between the two mentioned categories is that for the trailers, using the insertion principle, a trolley is necessary which depending on the manufacturer runs along and produces noise. The transport trolleys on the other hand can be either used as a trolley for the first category or can also be coupled to the tractor as an individual trailer. The trailer designs use the different steering systems which are already explained in chapter 3.2.1. Depending on which steering system is used the turning circle of the trailers changes. Some of

the trailer designs also need media support of the tractor like pneumatic, hydraulic, or electricity. Depending on the manufacturer the necessary media support can differ. This media support is necessary for the trailers to automatically lower at the loading and unloading points. This process is done so that the trolleys can be pushed in at ground level and therefore, make the loading or unloading process easier for the tugger train driver. Empty load carriers on trolleys are loaded just as easily. As soon as the loading process is finished the trailer is lifted and the tugger train can continue its tour. An important factor to consider during these lowering and lifting processes are the safety aspects. During the automatic process, different errors can occur like crushing or shearing points as well as other emergencies. Therefore, the trailers must have an emergency stop device implemented, to prevent these emergencies.[DGU18]

	Concept for picking up					Transport trolley		
	E-Frame	C-Frame	U-Frame	B-Frame	Taxicabs	Platform-trailer	Shelf-trailer	Pallet-trailers
								
Loading and unloading (side)	on one side	on one side	on both sides	on both sides	on both sides	on both sides	on both sides	on both sides
Loading and unloading (sequence)	freely	freely	freely	freely	freely	consecutively 1)	freely	freely
Flexibility trailer/ trolley/ load carrier	different sizes	different sizes	different sizes/ uniform 2)	different sizes	uniform	different trailers	different sizes	different sizes
Complexity of route planning	high	high	low	low	low	high	average	average
Direct loading with forklift necessary	no	no	no	no	no	yes	no	no
Trolley necessary	yes	yes	yes	yes	yes	no	no	no
turning circle	~ 4m	~ 7m	~ 7m	~ 4m		~ 4m	~ 4m	~ 4m
trolley runs along (noise)	yes / no 2)	no	yes / no 2)	no	no	-	yes	yes
required support for trailers	Pneumatics Hydraulics Electricity none 3)	Pneumatics Hydraulics Electricity 3)	Pneumatics Hydraulics Electricity 3)	Pneumatics Hydraulics Electricity 3)	none	none	none	none
Maintenance expenditure 4)	average / low	average / low	average / low	average / low	low	low	low	low

1) Uncoupling of the last trailer possible - Trailer from the centre of the composite only possible to uncouple if the load carriers have low weights
2) Depending on supplier
3) Depending on supplier and design
4) Depending on required support, mechanics and power unit, wheels; systems that require support or have special installations -medium,otherwise low

Figure 23.: Comparison of the different trailer designs [DGU18]

3.3. Catalog of requirements for the simulation library

To understand the dynamics in most production systems a simulation model is commonly used. With this simulation model, different analyses are carried out during projects or studies and therefore serve as an evaluation tool.[KIP18] In order to achieve reliable results, the simulation library must be able to simulate different situations and use cases.

Therefore, the catalog of requirements for the simulation library which is presented in this chapter includes the important factors of the introduced planning methods. The main focus lies on the design alternatives since the dimensioning is in most cases done beforehand and the simulation model evaluates the results.[KIP18]

As shown in previous chapters the planning approaches cover and involve different kinds of requirements and criteria of the tigger train system. Overall, they can be differentiated into three categories. These categories are the boundary conditions, the organisational design, and the technical design. In the following, these 3 categories are further described.

The first category of the catalog is the boundary conditions. All the introduced planning methods consider these boundary conditions during the planning process. The tigger train systems are differentiated to their transport task, if it is a supply task, a disposal task, or a combination of both. The planning methods are also either developed for demand or consumption-oriented systems and some are applicable for both. Therefore, the simulation library must include both possible systems. The ways of signalling the transport demand vary in the methods and always depend on the transport requirement system. Three of the planning methods only use the Kanban or e-Kanban system, one method is purely for demand-oriented systems and uses therefore a production plan. Of the other introduced planning methods, three are applicable for both, and two are mainly for the routing problem and don't consider the transport signalisation. These boundary conditions are summarized and shown in Tab. 3.

Boundary Conditions	
Transport task:	Include control methods for supply task, disposal task and a combination of both.
Transport requirement:	The possibility to simulate demand-oriented and consumption-oriented tigger train systems.
Signalisation of the transport requirement:	The library must include the ways of transport requirement signalisation by either Kanban (cards or empty load carrier), e-Kanban or electronically according to a production plan.

Table 3.: Catalog of requirements: Boundary conditions

The second category is the organisational design, which is an important part of the introduced planning methods. Three of the methods provide methodologies to define routes regarding the number of routes, the assignment of tigger trains per route, the

tour start control of routes, the delivered load carriers, and the assignment of delivery points to stopping points on the routes. Furthermore, these methodologies include the trailer types per tugger train as well as the connection of the trailers to the tractors. The integration of the loading process into the tour and the integration of the transport of empty load carriers is also part of these planning approaches. The other six methods use already defined routes and optimise them regarding one or several of the mentioned factors and two of them especially cover the assignment of buffers at the stopping points. The demand fluctuation is also considered in two methods and in another one, it is recommended to include it into the planning process. All the mentioned design criteria are required by several of the introduced planning methods and therefore must be included in the simulation library. In Tab. 4 the organisational design criteria are summarized.

Organisational design	
Number of Routes:	It must be possible to create not only simulation models with one but also with multiple routes.
Assignment Trains per Route:	The number of tugger trains per route must be variable, so that either one or multiple tugger trains can drive on one route, but also that one tugger train can drive on multiple routes.
Tour start control:	The control of the tour start can either be according to a fixed timetable (tact time) or permanent.
Trailer types per tugger train:	One tugger train can have multiple different types of trailers.
Connection of Tractor and Trailers:	The connection of the trailers and tractor can be either fixed or allows the uncoupling of empty trailers and the coupling of full trailers.
Load carrier types per route:	The stations on a route must be able to be supplied with multiple different load carriers and not with just one type.
Empties integration:	The possibility to include the empties transport must be part of the simulation library. It can either be 1:1, on sight or a separate tugger train to transport the empties.
Loading integration:	The loading of parts at the storage area is either part of the tour or not.
Assignment delivery points to stopping points:	At a stopping point the tugger train must be able to supply more delivery points at once. This is also the two-buffer system, which is described in chapter 3.1.6.
Demand fluctuations:	A possibility to simulate demand fluctuations must be included.

Table 4.: Catalog of requirements: Organisational design

The technical design is also relevant for the simulation model and therefore must be included in the simulation library. Three of the introduced planning approaches include recommendations for the selection of the tugger train components and in another four it is mentioned that the selection is an important part of the planning process. For the reason, that the methods only provide recommendations for the selection of the tugger train components, the technical criteria are explained in detail in chapter 3.3.1. Not all these criteria are relevant in a simulation model, for example, the engine or the steering of the tractor. For the catalog of requirements the relevant criteria, which are considered in the planning approaches are selected. These are the different types of tractors and trailers with their parameters, which are speed, maximum trailers, turning circle, capacity, loading time, load carriers, and loading side. Additionally, the inclusion of 3D models of the tugger train elements is also part of the catalog of requirements. In Tab. 5 The technical design requirements are summarized and presented.

Technical design	
Tractor	
Types:	Different models for the three- and four-wheeled tractor must be included.
Maximum trailers:	The tractors must have an adjustable limitation on how many trailers can be attached.
Speed:	A predefined speed, which can be adjusted in case that the tractor is from a different supplier.
Turning circle:	The maximum turning circle must be limited according to the data sheet of the tractor.
Trailers	
Types:	The most common trailer designs on the market must be included (B-, C-, E-, F-, U-, Pallet-Trailer, Shelf-Trailer)
Capacity:	The capacity of the trailers is limited according to their data sheets.
Loading time:	The loading time must be adjustable in case that additional technical aids are necessary for the loading and unloading process.
Load carriers:	A limitation of the loadable load carriers must be included, so that a trailer can't load carriers that are not possible to be transported.
Loading side:	The possible loading side of the trailers must be considered by the simulation library.
3D visualisation:	A 3D visualisation of the different tractor and trailer types must be included.

Table 5.: Catalog of requirements: Technical design

The simulation model is used as a verification and evaluation tool. For this reason, the simulation library must be able to present key factors as a result. As shown in chapter 3.1.10 the different methods have different results for the evaluation. For the simulation library, the most used evaluation criteria were selected as requirements. These criteria are:

- number of tugger trains
- tour times and max. tour time
- the driven distance
- the utilization
- delivered goods and transported empties

To sum up, the catalog of requirements consists of 3 parts the boundary conditions which provide a frame for the tugger train system. The technical design regarding the tugger train and its components as well as the organisational design of the process. The simulation model also has to provide results so that an actual evaluation can be done.

3.4. State-analysis of Plant Simulation

In order to develop a simulation library, which fulfills the in chapter 3.3 presented requirements, a throughout analysis of Plant Simulation is necessary. This analysis is described in the following and shows the possibilities of Plant Simulation regarding material flow simulations.

Plant Simulation provides an existing library with different models and functions to ensure the successful creation of these models and simulations. In the following different material handling systems are shown and to what degree it is possible to simulate these systems with Plant Simulation. The need for the creation of the simulation library for tugging train systems will also be shown and visualized.

Typically, a manufacturing facility has two different systems included. The material handling system of the logistic system and the production system. The logistic system is responsible for the transport of the manufactured units from one cell to another. The cells can be either a machine or station but also a collection of stations or even a complete facility. All these cells form the production system.[LaN11]

Lasrado, Nazzal describe in their article the use of conveyors as the material handling system. The conveyors are used in high volume manufacturing facilities as closed-loop conveyors to supply several machines with the required materials.[LaN11]. The existing library of Plant Simulation provides enough different elements to create and simulate these kinds of material handling systems.

On the other hand, Filz et al are presenting the matrix structured manufacturing system consisting of workstations connected by a flexible transportations system. The authors focus on the flexible material transport between the supermarket and workstation which results in three supply strategy also shown in Fig. 24.

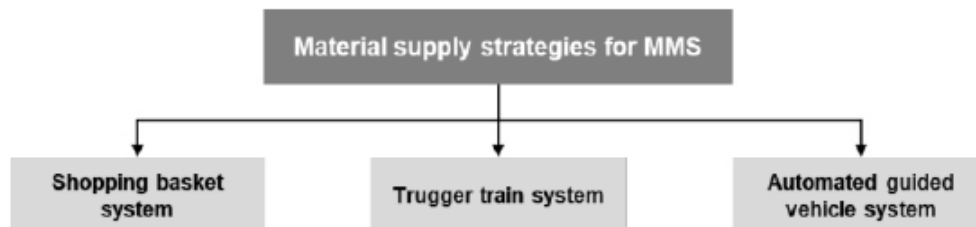


Figure 24.: Material supply strategies for MMS [FGH19]

A frequently used material supply strategy in the automotive industry is the shopping basket system. Depending on its capacity the shopping basket can supply either one or multiple workstations with parts that are stored inside the basket according to their assembly order. Automated guided vehicles (AGV) are responsible to transport these shopping baskets through the facility.[FGH19]

Another supply strategy is to use AGV's but without shopping baskets. Since no shopping baskets are used the AGV is not restricted to a specific product but can transport almost the entire material spectrum. Depending on the material which has to be transported, the vehicle type is selected. Because of the reason that the AGV's can operate autonomously within the network, the logistic system gets highly complex.[FGH19] Plant simulation provides the possibility to create and simulate these 2 supply systems with the existing library. In Fig. 25 a simple example of these automated guided vehicles in Plant Simulation is shown.

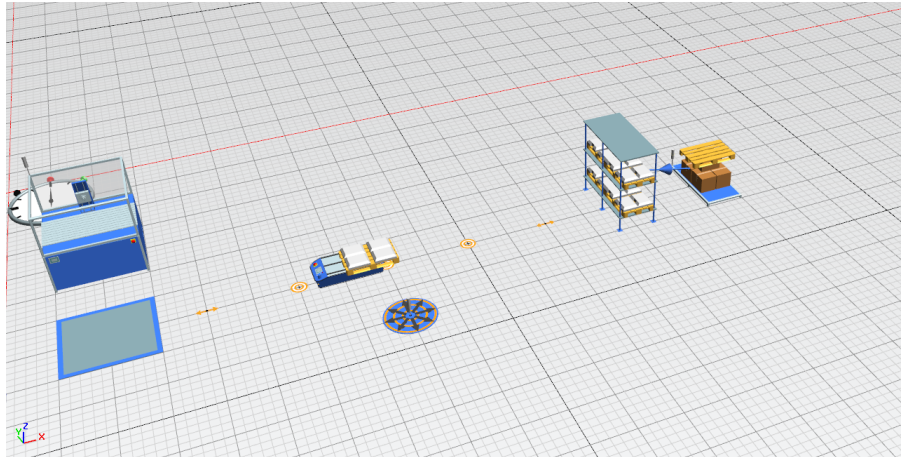


Figure 25.: Plant Simulation example using an AGV for material supply

The third supply strategy is the tugger train system. For this system, it is important to make a sophisticated layout design, because the efficiency strongly depends on the layout and the placement of the supermarket. The supermarket is the source of the materials and should therefore be placed in the vicinity of the supplied manufacturing system. There can be multiple routes that increase flexibility. Regarding transported materials, there is almost no restriction for the part size.[FGH19] Filz et al. also made a detailed comparison of the supply strategies. It is shown that the output of tugger trains is lower, and the lead time higher compared to the automated guided vehicle system. On the other hand, regarding the utilization of the logistic system, the result of the tugger train is significantly higher than the AGV system.[FGH19]

This study shows that the tugger train system is a viable and also important material supply strategy in today's companies. Plant Simulation provides only basic elements for the creation and simulation of tugger trains. It provides the "hitchMethod" which couples two vehicles together but no predefined control system or tugger train elements like different tractors and trailers. With the additional simulation library presented in this master thesis, the planer cannot only simulate conveyor systems or AGV systems but also has an easy way to simulate tugger train systems and therefore all of the presented flexible material supply strategies.

3.5. Modeling of elements for the simulation library

In order to fulfill the catalog of requirements which was specified in chapter 3.3 and to provide a comprehensible structure of the library, a hierarchical model formation offers itself as shown in Fig 26.

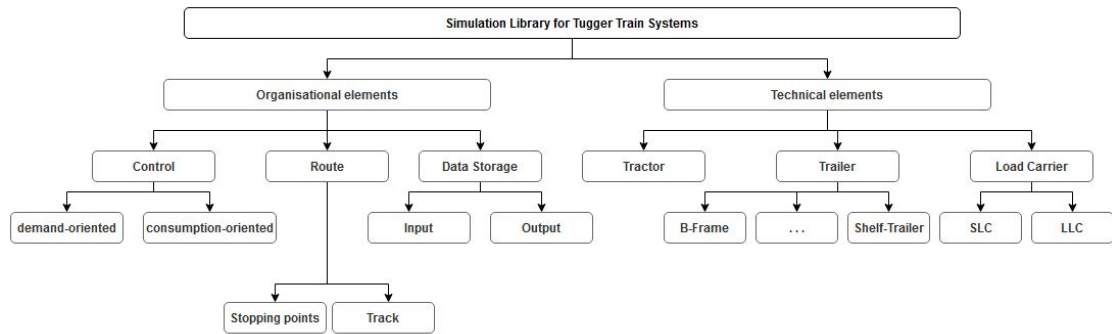


Figure 26.: Hierarchical model of the Simulation library

A hierarchical model is built by dividing the system into multiple sub-systems. Through this division, it gets possible to represent the sub-levels individually, which leads to the advantage of being able to represent and describe a complex system in different modules.[Dür01]

The catalog of requirements which is presented in chapter 3.3 includes 3 categories, the boundary conditions, the organisational, and the technical design. Therefore, the hierarchical model is divided into organisational elements, which also fulfill the boundary conditions and technical elements.

The organisational elements are a control element which includes the methods for demand- and consumption-oriented systems, as well as all other methods which are required to control the tugger train and its actions along the route. The second element is the route which consists of the stopping points with the required buffers and the track on which the tugger train drives. For the evaluation, there must be an element that stores all the data of the simulation. This element stores not only the input data but also the key figures, which are provided in an output file at the end of the simulation.

The technical elements are mainly the tugger train itself as presented in chapter 3.3. The first element of this category is the tractor with its parameters for example speed, maximum trailers, etc. Another technical element is the trailer, which is split into the most commonly used types (B-, E-, C-, U-Frame, Pallet-Trailer, Shelf-Trailer). Another technical element is the used load carrier because it influences the selection of trailers.

This chapter provides just a rough overview of the modelling of the simulation library which is further described and executed in chapter 4. There it is shown how the different elements and processes are designed as well as how they are linked to enable the simulation of a tugger train system.

3.6. Possible approaches for developing the Simulation Library

With the current version of Plant Simulation, two possible approaches can be used to develop a simulation library for tugging train systems. The first one uses the “marker” element to set the route and the other approach uses the “track” element. In the following, these two methods are explained and in the discussion is shown which one was later used for the creation of the simulation library.

3.6.1. Approach with “Marker” as routing element

Plant Simulation has already elements implemented to control “AGVs” (automated guided vehicles). You can use the resource objects “AGVPool” and “Marker” to model AGV systems. The “AGVPool” element is responsible for the controlling and creation of the automated guided vehicles. The “Marker” element are points in the model which define the route of the AGV. A marker can be a turning point, a stopping point, or just a point to further define the route. The AGV is not bound to a permanently installed route network but drives freely within the area of the installation and orients at the “Marker” elements.[SIE19] It is possible to set routes through the usage of Tables and lists in which the different “Marker” along the route are inserted. Afterwards, a method is necessary to navigate the AGV through the set route. An example for this is shown in Fig. 27.

3.6.2. Approach with “Track” routing element.

In this approach, the passive object “Track” is used to define the route. A passive object can’t directly be connect to stations but needs an available transporter on the “Track” and the connection to a station is done with a sensor. This transporter is loaded and unloaded at the different stations. The sensor can be located at any point on the length-oriented object “Track”. If a transporter passes the sensor, then Plant Simulation calls the control method of the sensor. A Sensor is defined by its Sensor-ID, its Position, its length unit, and the Method object triggering it. [SIE19] In Fig. 28 it is shown how such a model may look like.

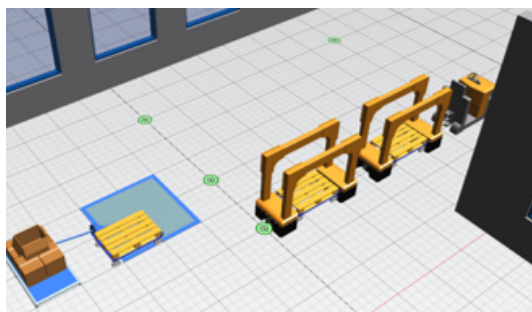


Figure 27.: Model of the approach with the “Marker” element

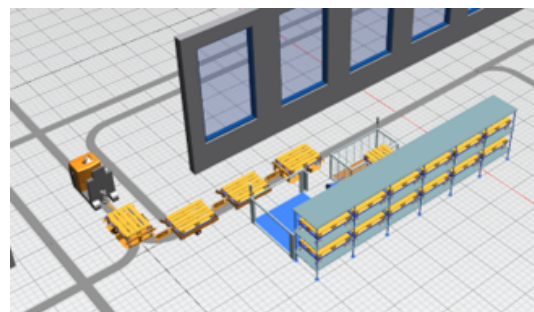


Figure 28.: Model of the approach with the “Track” element

3.6.3. Discussion of the Approaches

Both approaches have multiple advantages and disadvantages. At first, the Marker approach will be discussed. One of the main advantages of this approach is that the AGV, which is modified to work as a tugger train, moves freely through the model and searches the quickest route to the target with the given marker. Therefore, it is easy to set the route by placing "Markers" at stopping points and turning points. Unfortunately, the necessary definition of the route in the tables, so that the tugger train can be navigated through the route, is complex. The major disadvantage is that with this approach it is only possible to control one AGV element, which means that it is not easy to adjust the trailers since pre-set tugger trains are used. There is also no possibility to set a collision control between different tugger trains.

For the approach with the "track" element, the route definition is done with one continuous track element through the model. The "track" element is defined by the length and turning circles. The disadvantage with this route setting is that changes in a later planning stage are harder to implement. The remedy for this is to split the track element into several shorter parts, as it is then easier to change the route later on. The first advantage is that the setting of the route for the control methods is easier compared to the "Marker" approach since this is done with sensors on the track which work as stopping points. The major advantage is that the designer can freely adjust the parts of the tugger train. For example, in the first simulation 3 E-Frames, and in the next simulation run 5 B-Frames are used.

Through the identification of these major advantages and disadvantages, the approach with the "marker" was discarded since it must be possible to easily and freely adjust the tugger train parts. Therefore, the approach with the "track" element is further pursued and is used for the development of the simulation library which is presented in chapter 4.

4. Simulation Library

In this chapter, all the necessary information about the simulation library will be presented and explained. Starting with an introduction of the simulation library to give an overview of it, which also includes a diagram of the information flow between the elements of the library. In the next section the elements of the library as well as the control methods, parameters, and settings are described. Subsequently the basic procedure of how the simulation library is used to create a functional simulation model. At the end of this chapter, there are five practical examples presented, which were modelled with the simulation library and therefore used as an evaluation for it.

4.1. Introduction to the simulation library

As described in the previous chapters, the typical tugger train system is designed as a milk-run system. This also means that it consists of several different components, which must be included in the simulation library, to enable the creation of a feasible simulation model. The hierarchical model presented in chapter 3.5 represents the different elements of a tugger train system and their functions. This is just the overview that had to be realized with the possible means of Plant Simulation. In Fig. 29 a simulation model of a tugger train system, created with the finished simulation library is shown.

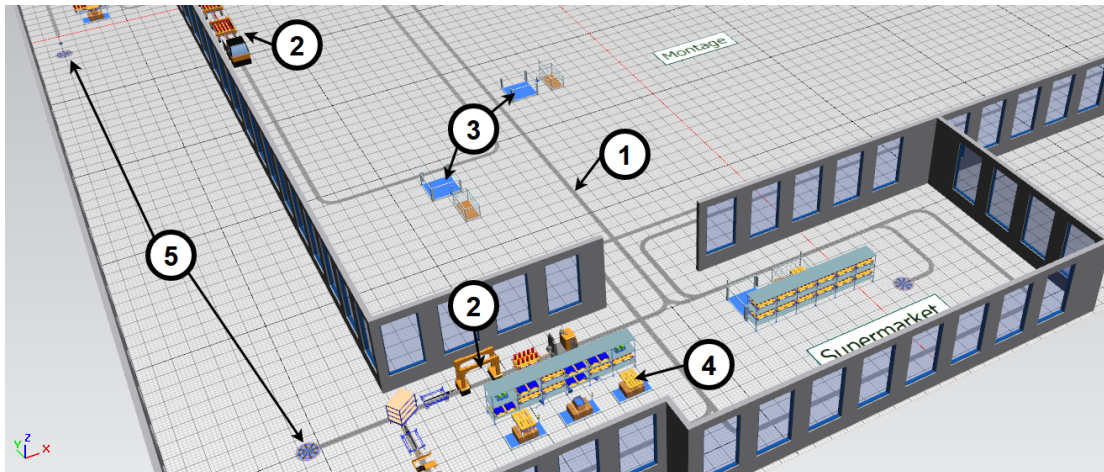


Figure 29.: Example of a simulation model of a tugger train system

The components of the simulation library are created as already defined in the hierarchical model. The first element is the route, which is simulated with the track element (1 in Fig. 29). With it, all other elements are connected and the route of the tugger train through the facility is defined. The second parts of the hierarchical model are the other elements, which are part of the tugger train system and included in every route. The first and most obvious components are the tractor and the trailer (2 in Fig. 29), of which every tugger train consists of. The tugger train drives along the route and carries out several processes such as the driving, loading, and unloading but also the coupling of the trailers to the tractor is a necessary process. Along the route, there are the different stations and the supermarket which are represented in the simulation library with the buffer element (3 in Fig. 29). At these stations, the loading and unloading processes are carried out and the transport orders are sent to the control system. Another part of the library are the load carriers (4 in Fig. 29) with which the different stations are supplied or which are collected and transported back to a warehouse. The last and most complex element of the simulation library is the control system. The different possible control methods of the tugger train are stored in the TuggerTrainGarage (5 in Fig. 29) element. These methods are used by all other elements to simulate the whole tugger train system. There are additional elements included in the simulation library, which are used for the input of parameters and the output of the results. All of these elements and methods are further described and presented in the following chapters. The diagram shown in Fig. 30 presents the flow of data between the different elements of the simulation library. It starts with the input of certain parameters, which are used by the elements during the simulation to create the resulting key figures. These results are then exported and presented in an output file (Excel file).

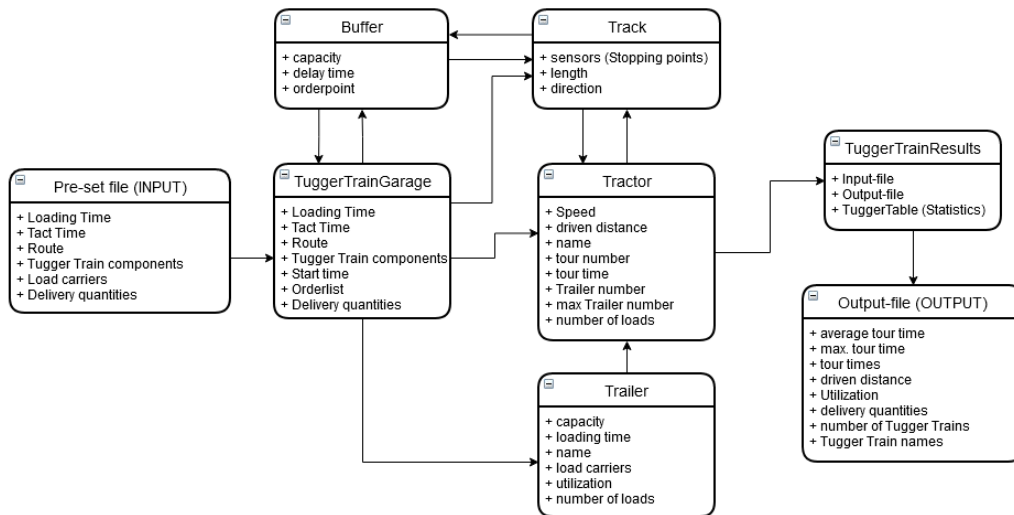


Figure 30.: data-flow diagram of the simulation library

4.2. Elements of the Simulation Library

This chapter contains the elements of the simulation library which are used to design and simulate a tugger train system with PlantSimulation. In the following, all the elements are examined in more detail and the parameters, options, and key areas of the elements are described.

There are 3 elements that are not separated explained below, because each has only one task which is nonetheless essential for the simulation model. The first is the "EventController" of the library which is similar to the basic element of PlantSimulation with the only difference that it uses the second element "SimStart" as the InitCtrl method. The InitCtrl method is the first thing that is opened after the start of the simulation. The "SimStart" method opens two message boxes and asks the user to select the pre-set and output file on the computer. The third element is the "EndSim" method which is the last thing that is opened by the simulation run. This method exports the data of the "Tugger Train Results" element to the output file.

4.2.1. Tugger Train Garage

The "TuggerTrainGarage" is the heart of the simulation library because most of the parameters and methods which are used are saved in this element. There are multiple methods available which are listed below with a short description since they are described in detail later in chapter 4.3. In Fig. 32 it is shown where the different methods and attributes are saved inside the TuggerTrainGarage. Per route, there is always at least one "TuggerTrainGarage" which manages the tugger train on that route.

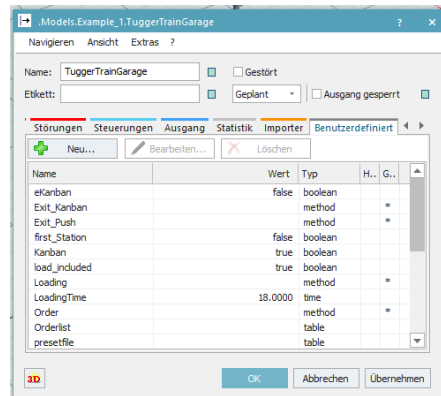
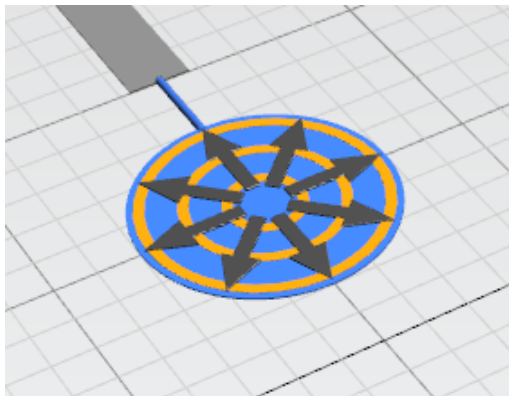


Figure 31.: 3D model TuggerTrainGarage Figure 32.: Attributes and methods of TuggerTrainGarage

- **Supermarket-Push:** This method is used by sensors at the location of the Supermarket or Storage. It is used in the case that the transport demand is created by a production plan or demand-oriented system. The method is responsible to

load the goods which are ordered by stations onto the tigger train and set the first delivery point as the next destination of the tigger train and recording the cycle time.

- **StationCtrl-Push:** Since the tigger train system does not only consist out of the supermarket but also stations this method is required to control the tigger train at the station. It is responsible for the unloading of the ordered goods and also giving the next target of the route.
- **Supermarket-Kanban:** As already described in chapter 3.1 there is not only the demand-oriented transport requirement but also the consumption-oriented. This method is responsible to control the tigger train at the supermarket in case the system is consumption-oriented. It checks the orderlist and loads the order goods onto the tigger train as well as record cycle time and define the next destination of the tigger train.
- **StationCtrl-Kanban:** In case the system is consumption-oriented the Stations also need a method that controls the tigger train there. This method does this and unloads the ordered goods.
- **Loading:** The method "Loading" is used to load any available goods at the station onto the tigger train as long as there is enough space and available goods.
- **Unloading:** This method is used to unload the whole tigger train, which means after the method is used the tigger train is completely empty.
- **Exit-Push:** The "Exit-Push" method is used as exit control of the "TiggerTrain-Garage" to give the tigger train its first destination as well as first orders. It also notes the first start time of the tigger train.
- **Exit-Kanban:** It works similar to the "Exit-Push" method with the only difference that it writes the first orders into the orderlist and doesn't give the tigger train the fixed amount of the production plan as ordered.
- **Order:** This method is used in a consumption-oriented system to create transport demand. It either gives right after a part leaves the buffer the order for a new one or at the moment if for example an empty LLC is unloaded at the Supermarket (Kanban card).
- **Settings:** The "Settings" method is not used for the control of the tigger train but is very essential for the simulation model. It uses all the data of the "pre-set file" to adjust the parameters and data in the different lists and tables of the library according to the settings chosen by the designer.

These are the methods that are used to control the tugger train and guide its actions during its tour. But there are also multiple parameters and booleans required for the methods to work. Therefore in the following at first the booleans and then the parameters are listed and described, they are also mentioned in chapter 4.4.2 since they are set with the pre-set file.

- **eKanban:** This boolean just works as a check for the designer that the transport demand is created by an e-Kanban system.
- **Kanban:** The "Kanban" boolean is used in case the transport demand is created by Kanban cards or with goods (see. example 5). The boolean is used in the "Unload" method so that the order is only given if an empty load carrier or kanban card is unloaded.
- **first-Station:** This boolean is set to true by the "Unloading" method in case it is a kanban card system. The moment it is set to true the orders are made if empty boxes are unloaded, and later at the supermarket set to false by the "supermarket-Kanban" method. As long as it is set to false the orders are delayed till it is set to true again.
- **load-included:** As later shown in the practical example in some systems the loading of the goods for the next tour is already included in the previous tour. This boolean is used by the methods to determine if that is the case or not.
- **tact-time:** The cycle time also described in chapter 2.2.7 defines the tact in which the tugger train starts its tours, therefore it is the fixed interval in which the tugger train passes a stopping point.
- **LoadingTime:** This time defines how long it takes the tugger train to load or unload a load carrier. In the simulation, it is a static time which represents the average time needed of the actual tugger train.
- **Start-time:** This parameter represents the start time of the tugger train and is used by the supermarket methods to calculate the cycle times and waiting times in case there is a given tact.

Since the methods and parameters are described the last part of the "TuggerTrain-Garage" are the used tables and lists, which are essential for the route finding and delivery of the orders. These lists and tables are adjusted by the "pre-set file" which is presented in chapter 4.4.2.

- **Orderlist:** The "Orderlist" consists of a list of the stations on the route which are supplied by the tugger train and also of the types and amount of the goods that are delivered. An example of this list is shown in Fig. 34.
- **Stations:** This is a list that contains all the stations on the route and is used by the methods to guide the tugger train through the route in the correct order.

- **TuggerTrain:** In this table, it is noted out of which parts the tugger train consists of. During the adjustment of the pre-set file, you choose which tractor and the amount and type of trailers you want to use. It is also possible to adjust some of the parameters, for example, the speed, of these parts in this table. The "TuggerTrainGarage" uses this list to create the tugger train. This TuggerTrain list can look for example as shown in Fig. 33.
- **presetfile:** This table is a copy of the Excel file with the settings which was imported into PlantSimulation. It stores all the data necessary for the "TuggerTrainGarage" to control the tugger train. The "Settings" method uses the data of this table to adjust the parameters and settings of the "TuggerTrainGarage".

object	integer	string	table
1	2	3	4
TuggerTrainPart	Number	Name	Attributes
1	*UserObjects.TuggerTrain_Parts.Tractor_small	TuggerTrain_AKT	x
2	*UserObjects.TuggerTrain_Parts.Shelltrailer	TuggerTrain_AKT	x
3	*UserObjects.TuggerTrain_Parts.B_Frame	TuggerTrain_AKT	x
4	*UserObjects.TuggerTrain_Parts.Tractor_small	TuggerTrain_AKT1	x
5	*UserObjects.TuggerTrain_Parts.Shelltrailer	TuggerTrain_AKT1	x
6	*UserObjects.TuggerTrain_Parts.B_Frame	TuggerTrain_AKT1	x
7	*UserObjects.TuggerTrain_Parts.Tractor_small	TuggerTrain_AKT2	x
8	*UserObjects.TuggerTrain_Parts.Shelltrailer	TuggerTrain_AKT2	x
9	*UserObjects.TuggerTrain_Parts.B_Frame	TuggerTrain_AKT2	x
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			
24			
25			

Figure 33.: Example of a TuggerTrain list

object	table	integer	integer
1	2	3	4
Station	Load		
1	Vof1		
2	Vof2		
3	Vof3		
4	Vof4		
5	Vof5		
6	Vof6		
7	Vof7		
8	Vof8		
9	Vof9		
10	Vof10		
11	Vof11		
12	Vof12		
13	Vof13		
14	Vof14		
15	Vof15		
16	Vof16		
17	Vof17		
18	Vof18		
19	Vof19		
20	Vof20		
21	Vof21		
22	Vof22		
23	Vof23		
24	Vof24		
25	Vof25		

Figure 34.: Example of an orderlist

4.2.2. Buffer

The buffer is used in the simulation model as the stations which are either supplied with goods or store goods waiting for disposal. The buffers have 4 parameters, which are mainly used by the "Order" method of the "TuggerTrainGarage" to ensure the orders are made correctly. In the following, these parameters are described and shown what their purpose is. In Fig. 35 the typical use of the buffer according to the two-buffer principle is shown, in which one is used for full load carriers and one for the empty carriers.

- **DelayTime:** This time is used to simulate the demand fluctuations in the tugger train systems, also described in chapter 3.2 It is used by the "Order" method to delay the time at which the order is made. In this time the times of the 5 different types of demand fluctuations are combined.
- **upperbarrier/lowerbarrier:** The two times upper- and lowerbarrier are used by the "Order" method to calculate the "DelayTime". This calculation needs an upper and lowerbarrier since the delaytime is based on a discrete uniform distribution.[LHG18]

- **orderpoint:** With the "orderpoint" you can appoint a different buffer to get the order, which means that if the load carrier leaves the buffer with the "Order" method order for the buffer assigned as "orderpoint" is made.

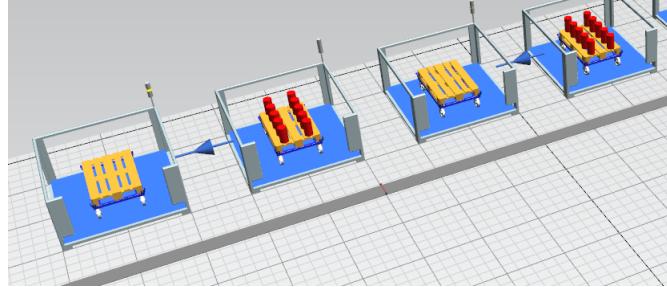


Figure 35.: Example of two-buffer principle

4.2.3. Track

This element represents the route of the tigger train in the simulation model. It is advisable to split it into multiple parts therefore changes in later stages of the simulation are easier done. In the control tab of the track element, you can configure sensors that are essential for the route, since they stop the tigger train if it has the destination of the sensor's target. In the options of the sensor the target is set to the buffer or station which belongs to the stopping point, and the control is the appropriate method as described in chapter 4.3. An example for the simulation of a route with the track (grey lines) is shown in Fig. 36.

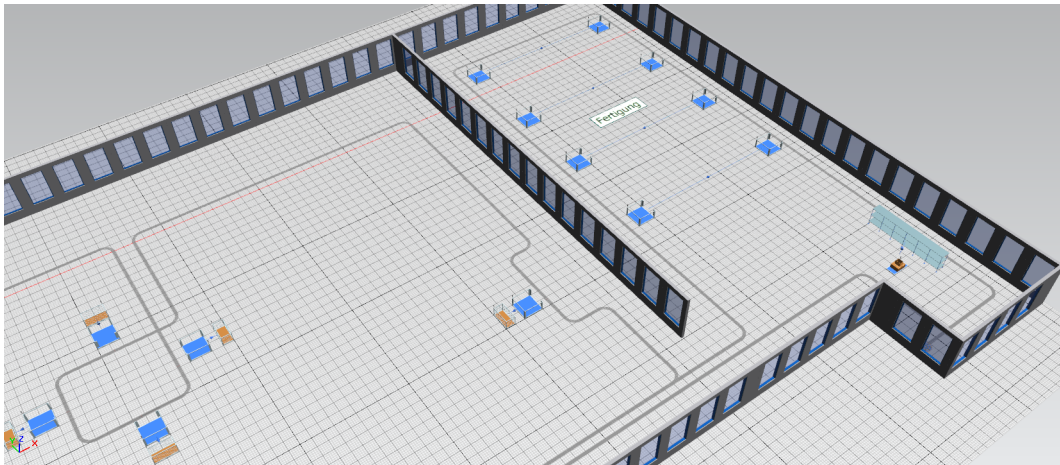


Figure 36.: Example of a route simulated with the track element

4.2.4. Tractor

The Tractor is a main component of the tugging train as also shown in chapter 2.2.1. In the simulation model, the tractor defines the speed at which the tugging train drives along the route. There are two different models included in the simulation library which are the "Tractor-small" and the "Tractor-big". These are a three-wheeled and a four-wheeled tractor. These elements have several parameters which purposes are described in the following and a separate 3D model included. These models of the three and four-wheeled tractors are shown in Fig. 37 and Fig. 38.

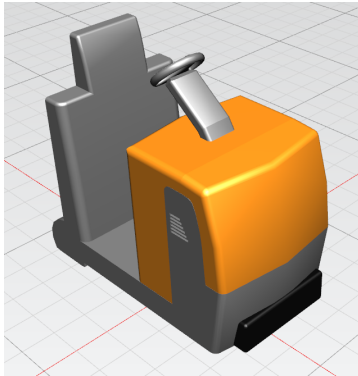


Figure 37.: 3D model of three-wheeled tractor

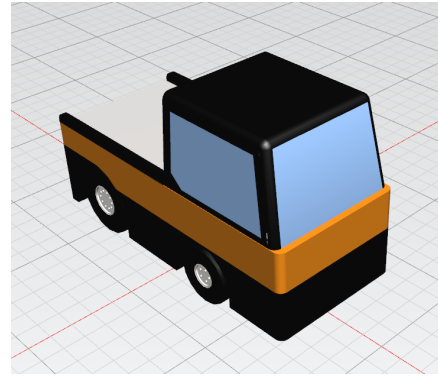


Figure 38.: 3D model of four-wheeled tractor

- **EndSim:** Each Tractor of the simulation model has the "EndSim" which is used at the end of the simulation time. This method is responsible for the calculation of several statistics which are also exported into the outputfile(see chapter 4.4.1).
- **route-times:** In this table, the Tractor saves the cycle time of every tour he drives. At the end of the simulation, this table is also exported by the "EndSim" into the outputfile.
- **Parameters:** The Tractor has several parameters that are used to calculate statistics for the outputfile. The first of these parameters is "max-route-time" which saves the maximal route time, the "ordercount" is used to determine at which order or station the tugging train is at the moment. This parameter is used by the Station control methods to check if the tugging train is at the right station and delivers the right order. Another parameter is the "output-order" which is the number of orders or goods delivered. "route-nr", "route-times" and "starttime" are the parameters to calculate how many tours the tugging train did and how long the cycle time of these tours was. Another route related parameter is "Station", this parameter just notes at which station of the route the tugging train is at the moment and is used by the station controls to determine the next destination. The last parameters of the Tractor are "TrailerNU" and "TrailerNUmax" which saves

how many trailers are attached to the tractor and the maximum of trailers that the tractor is allowed to pull.

4.2.5. Trailer

The trailers are, as already in chapter 3 explained responsible for the transportation of the load carriers. In the simulation library, there are several models included which are the B-Frame, C-Frame, E-Frame, E-Frame, U-Frame, Trailer, and shelf-trailer. Each of these models has a 3D model included in PlantSimulation which represents the actual design of the trailer. Each of these models has a list named "carriers" and a method "hitchMethod" included. In the "carriers" list the different load carriers are noted which are allowed to be loaded onto the trailer. This list is checked by the different station and supermarket methods. The "hitchMethod" is a feature of PlantSimulation to allow to attach the trailer to the tractor or trailer in front of it.

The 3D models which were implemented into PlantSimulation were designed according to the datasheets of the models presented in chapter 3.2.3. In Fig. 39 some of the models are shown which are already attached to a tractor model.

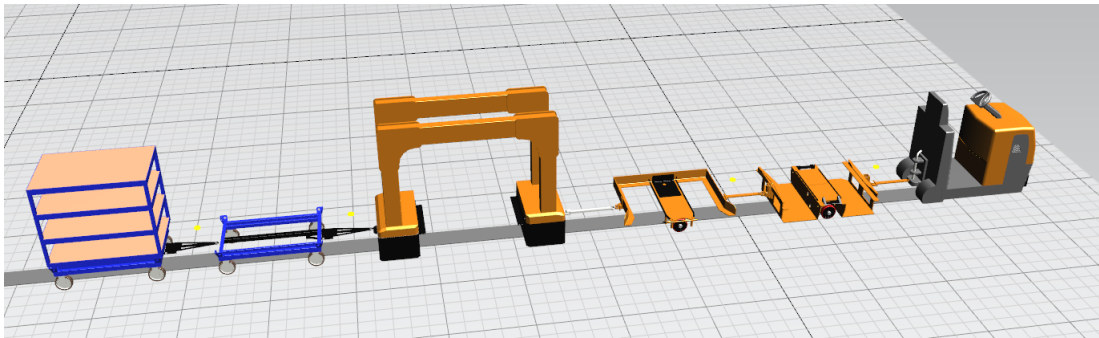


Figure 39.: Example of a tugger train model

4.2.6. Tugger Train Results

The "TuggerTrainResults" element is mainly responsible to save the data of the simulation model which will be exported and the storage location of the pre-set file and output file. Part of the element is the "Tugger-table" in which all the data of all the tugger trains of the simulation model is saved at the end of the simulation. The two strings "outputfile" and "presetfile" are the storage locations of the excel tables on the PC.

4.3. Control methods for the tugger train system

This section covers the in chapter 4.2.1 described methods for the control of the stations and supermarket in detail. In the beginning, the methods controlling the supermarket are explained and afterwards the methods for the stations.

4.3.1. Control of supermarket

There are two methods available to control the actions at the supermarket. The main difference between these two methods is that at the moment it checks which amount of goods has to be delivered they get the number from a different column of the "Orderlist". A.1 shows the code of the method "Supermarket-Kanban".

The first "for" loop sets the local boolean to true in the case that the tugger train that activated the method is a tugger train on the route managed by the corresponding "TuggerTrainGarage". This is important because the supermarket can be part of multiple routes, as shown later in the practical examples, and each route is managed by a separate "TuggerTrainGarage".

In case the "Tugger" boolean is set to true and it is a tractor that starts the method, the first condition is met and the tugger train stops. The typical start of the route is at the supermarket. Therefore, the next thing which is checked by the method is if the loading for the next tour is included or not. If not then the method increases the route number or the tractor by one. The next two if conditions are responsible for the calculation of the cycle time. This calculation is always done the moment the tugger train ends its tour and comes back to the supermarket to start the next one. Therefore at the beginning of the simulation and the first time reaching the supermarket these two conditions will be ignored. They also check if the tugger train has a tact time and if it does the method let it wait until the starttime for the next tour is reached.

The next if condition calculates the capacity of the tugger train and how many trailers are attached to the tractor. In the case that there are more trailers attached than the trailer is allowed to pull the method will give out a message and stops the simulation. The next big for loop is responsible for the loading of the goods that are to be delivered. The first five for loops are going through the whole "orderlist" and also through the storage of the supermarket. Then it is differentiated into 3 cases:

- **Full load carrier:** The first case is that the good stored in the supermarket is a load carrier for example an SLC that has parts loaded. If this is true then it is checked if it is the ordered good and if the tugger train still needs to load more. Afterwards, the trailers are checked if they have space and if they are allowed to carry this type of load carrier. If everything is right then the good is loaded and the method waits for the given loading time, after this time it is noted that one more good is loaded and the next loop begins again.
- **Empty load carrier:** In this case, the load carrier for example an LLC is empty. If this is true then it is checked if the ordered good is an empty LLC and if the

tugger train still needs to load more. Afterwards, the trailers are checked if they have space and if they are allowed to carry this type of load carrier. If everything is right then the good is loaded and the method waits for the given loading time, after this time it is noted that one more good is loaded and the next loop begins again.

- **Load carrier loaded on a load carrier:** The last case is a combination of the first 2. For example, an LLC loaded with full SLC's. If this is true then it is checked if the ordered good is the load of the SLC and if the tugger train still needs to load more. Afterwards, the trailers are checked if they have space and if they are allowed to carry this type of load carrier. If everything is right then the good is loaded and the method waits for the given loading time, after this time it is noted that one more good is loaded and the next loop begins again.

After the loading process is done there is again the check if the loading for the next tour is included in the cycle time. Now if this is the case the cycle time is not at the beginning of the method calculated but at this moment. And the tugger train waits after the loading for the start time of its next tour.

The last if condition checks at which station the tugger train is and sets its next destination. Afterwards, the ordercount is set to 1 which means that he now starts the first order. The first-Station boolean is used in case the system uses Kanban cards which is already described in Chapter 4.1.1.

But as already mentioned there are two methods not only "Supermarket-Kanban" but also "Supermarket-Push". The difference between these two methods is that an "if" conditions in the loading part of the Kanban version checks if there are orders and load them. The push method just loads the given amounts in the "min. amount" column of the orderlist, which therefore works as the delivery plan.

4.3.2. Control of the buffer

Because in a simulation model of a tugger train system there is not only the supermarket but also the stations which are either supplied or store goods waiting for disposal, this chapter explains the methods which control these stations.

StationCtrl-Knaban / StationCtrl-Push

These two methods are used to unload the order of the station. In A.2 the code of "Supermarket-Kanban" is shown. The method starts with the check if the tugger train is part of the route which is controlled by the corresponding "TuggerTrainGarage". If that is the case the first "if" condition is fulfilled and the tugger train is stopped.

Afterwards, a for loop begins which goes through the orderlist and checks if there are any orders and if the tugger train is at the right destination of the order. The next step is to check the trailers for the goods which are ordered. Here it is differentiated between the shelf-trailer and the other types of trailers. The reason for this is that the contentlist of the shelf-trailer is different because of the multiple storage rows. If the trailer is a

shelf-trailer, the next step is to check one storage place after the other and search for the ordered goods. During this step, it is checked if the loaded good is an empty SLC or a full SLC. If the order is either of these two and the trailer has some of the ordered goods loaded the unloading starts. The part gets moved to the buffer and the method waits for the loading time afterwards before it continues. After the unloading, the method notes in the "orderlist" that one less good is loaded and also decreases the amount of the order by one. The code for the unloading is similar for the empty and full SLC.

In the case that the trailer is not a shelf-trailer but any other type of the library, for example, a B-Frame the first "if" condition is not fulfilled and the method jumps to the "else". There the content of the trailer is checked again if it is either an empty LLC, an LLC loaded with parts or an LLC loaded with SLC's. If the loaded good is either of these then it is also checked if it is ordered and if the loaded good is part of the order. In the case that all conditions are fulfilled the load carrier is unloaded and it is noted in the "orderlist" that one less part is loaded and the amount of the order is also decreased by one. Then method waits till the loading time is over and goes on with the next step. The last "if" condition of the method is responsible to check where the tugger train is and to set the next destination using the "Stations" list. Afterwards, the ordercount of the Tractor is increased by one which means that it starts with the next order and the tugger train is not stopped anymore.

Since there are two different methods, one for demand-oriented and one for consumption-oriented systems there has to be a difference. This difference is that the "StationCtrl" method only notes that one part less is loaded after the unloading process. Furthermore, it doesn't check if anything is ordered it just checks if the load is the right type according to the orderlist and if anything of that order is loaded on the tugger train.

Loading

The "Loading" method is used in the case that there are empty load carriers in the buffer which has to be disposed of. A.3 shows the code of the method. The method starts with a check if the tugger train at the station is managed by the corresponding "TuggerTrainGarage" and if yes it stops the tugger train. Afterwards, the method checks the buffer if there are any load carriers available and if the trailer the tugger train is allowed to transport this type of carrier. In case these conditions are met and that there is space on the trailer the method loads the carrier and waits for the given loading time. The if condition at the end of the method is used for the pathfinding, which means it looks where on the route the tugger train is and set the next destination according to the "Stations" list.

Unloading

This method is mainly used at the buffer which is destined for the empty load carriers which are picked up by the tugger train during its tour. The code of the method is shown in A.4. The main purpose of the "Unloading" method is as the name already says to unload the complete tugger train. This happens after the method has checked if the tugger train is part of the route managed by the "TuggerTrainGarage" and has stopped. Now the method differentiates between shelf-trailers and the other type of trailers since the contentslist of the shelf-trailer differs. After the check which trailer is

used the method unloads all load carriers of all the trailers. At the end of the method, there is also the if condition to check the momentary position of the tugger train and set the next destination. If the system uses Kanban cards then this method also sets the "first-station" boolean to true which means that at this moment the orders of the stations are made.

4.4. Input and Output tools

In this chapter, the Input and Output files are described. These files are necessary to ease the adjustment of the settings for the tugger train system and for the representation of the results.

4.4.1. Output file

The output file shows the results which are exported from the simulation model. The file consists of multiple tables that contain the data regarding the tugger trains. Each tugger train has a separate table listing all its cycle times also shown in a graph which is included in the table. This can be seen in Fig. 41. The other table which is shown in Fig. 40 presents the results of the whole simulation model. In this table for each tugger train of the model, the average cycle time is shown as well as the maximum cycle time which was driven. There is also the driven distance of the tugger trains noted. Interesting data are the 2 following parameters which are the Relative Occupation and the Empty run. The Empty run represents the percentage of which the tugger train drove without any good loaded, this includes waiting times for the next start time of the next tour. The relative occupancy is determined by the sum of the retention times of all goods on the tugger train during the simulation time divided by the capacity and the total simulation time. This also represents the utilization of the tugger train. The next two columns show how many load carriers were loaded and unloaded. These numbers include the ordered carriers as well as the picked up empties. The last column only shows how many ordered carriers were delivered.

Tugger Train Name	Tour Time [s]	max. Tour Time [s]	driven distance [m]	RelativeOccupation [%]	Empty run [%]	Inputs [st]	Outputs [st]	Outputs order [st]
TuggerTrain_KLT_1	2120,785904	2239,958826	2786,381062	0,504824044	0,330864633	987	940	517
TuggerTrain_KLT_2	1744,387783	1821,779225	2593,738659	0,390592232	0,460001325	987	985	517
TuggerTrain_KLT_3	1938,483031	2117,783778	3008,230469	0,405597436	0,40313474	928	909	529
TuggerTrain_KLT_4	1953,638258	2222,114242	2571,597066	0,463385544	0,393763039	1008	1001	528
TuggerTrain_KLT_5	2508,220601	2508,220601	2793,330926	0,557746371	0,262521701	975	928	905
TuggerTrain_KLT_6	2508,220601	2508,220601	3002,464874	0,426822953	0,398766636	978	931	508
TuggerTrain_KLT_7	2526,220601	2526,220601	2584,230777	0,467011536	0,389316129	950	939	516
Total:			18739,98273			6883	6633	3630

Figure 40.: Outputfile data of the simulation model

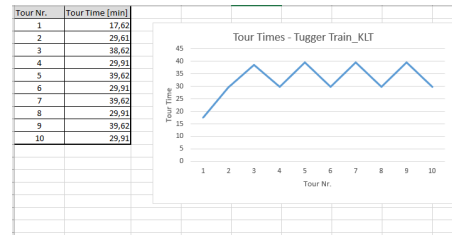


Figure 41.: Outputfile data of a Tugger Train

4.4.2. Pre-Set file

The "Pre-Set file" is the main tool to import settings and data into the simulation model. As shown in Fig. 42 the file contains the data necessary for the "TuggerTrainGarage" to control the tugger train. At first, the parameters are set according to the system of the simulation model. There are the 3 booleans (see chapter 4.2.1) of the "TuggerTrainGarage" to be set according to the system description as well as the tact time of the tugger train, at which it starts its tours. The last parameter to adjust is the Simulation-time which defines the duration of the simulation run.

With the rest of the file the route, parts of the tugger train, and the orderlist are defined. In column "C" the route is defined by inserting the names of the stations, which the tugger train supplies, in the right order. The next two columns define the components of which the tugger train consists. In the example of Fig. 42, the tugger train consists of one three-wheeled tractor and four shelf trailers. In the next column, you give the tugger train its name. The trailers which are attached to the tractor must have the same name since it is checked by some control methods during the simulation. It is also a necessary feature for the calculation of the statistics. The column "G" is a list of the stations that are supplied by the tugger train with goods. The type and amount of these goods are defined in the next columns. In the example, it is a red part, which means the tugger train loads the given amount of load carriers with red parts and delivers it to the defined station.

A	B	C	D	E	F	G	H	I
		Stations	TuggerTrain			Orderlist		
		Station	TuggerTrain Part	Amount	Name	Station	Load	min. amount
eKanban	false	Voll_ein3	.UserObjects.TuggerTrain_Parts.T tractor_small	1	TuggerTrain_KLT_6	Voll119	.UserObjects.Part_rot	2
Kanban	false	Leer119	.UserObjects.TuggerTrain_Parts.Shelftrailer	4	TuggerTrain_KLT_6	Voll126	.UserObjects.Part_rot	2
load_included	false	Voll119				Voll136	.UserObjects.Part_rot	2
LoadingTime	0:09	Leer26				Voll146	.UserObjects.Part_rot	2
Tact_time	0:45:00	Voll26				Voll156	.UserObjects.Part_rot	3
Simulationtime	8:00:00	Leer36				Voll166	.UserObjects.Part_rot	3
		Voll36				Voll176	.UserObjects.Part_rot	3
		Leer46				Voll186	.UserObjects.Part_rot	3
		Voll46				Voll196	.UserObjects.Part_rot	3
		Leer56				Voll106	.UserObjects.Part_rot	3
		Voll56				Voll118	.UserObjects.Part_rot	3
		Leer66				Voll126	.UserObjects.Part_rot	3
		Voll66				Voll136	.UserObjects.Part_rot	3
		Leer76				Voll146	.UserObjects.Part_rot	3
		Voll76				Voll156	.UserObjects.Part_rot	3
		Leer86				Voll166	.UserObjects.Part_rot	3
		Voll86				Voll176	.UserObjects.Part_rot	3
		Leer96						
		Voll96						
		Leer106						
		Voll106						
		Leer118						
		Voll118						
		Leer126						
		Voll126						
		Leer136						
		Voll136						
		Leer146						
		Voll146						
		Leer156						
		Voll156						
		Leer166						
		Voll166						
		Leer176						
		Voll176						

Figure 42.: Example of a Pre-Set file

4.5. Basic procedure for the simulation of tugger train systems

The basic procedure for the simulation of tugger train systems is divided into 3 steps which are explained in this chapter. The practical examples which are presented in the following chapters are simulated according to this procedure.

Step 1: Creating the simulation model

As the first step, an actual simulation model has to be created. This means that all the necessary elements for the simulation are created starting with the Eventcontroller, the "SimStart" and "EndSim" methods. Also to record the statistics of the tugger train system a "TuggerTrainResults" element is placed in the model. The next thing is placing the buffers at the location of the supermarket as well as where the stopping points of your route are or as in the real facility. In the case that the transport task is either supply or disposal only one buffer is placed, but if it is both then the two-buffer principle is used, and therefore, two buffers are required since in this case one for the supply and one for the disposal task is needed. After the placement of the stopping points in the model, they have to be connected by the track element. To facilitate changes, which are done at a later date, it is recommended to not create a continuous track element but short sections that are connected to each other. At the end of this step, a "TuggerTrainGarage" element is placed, preferable at the start of the tour or where the tugger train is parked, and connect it to the route with the track element.

Step 2: Adjusting sensors and methods

This step covers setting up the sensors and methods that control and guide the tugger train through the route. The sensors are created at the track element in the control section. It is created at the chosen distance from the start of the track element. That is also a reason why it is recommended to make shorter track section and not one continuous one. The sensors also have a defined target which is the corresponding buffer that is supplied. The tugger train systems are typically designed with the two-buffer principle (see chapter 3.1.6), therefore there are two buffers and also two sensors on the track, one for each buffer. The distance between these two sensors should be 0.01m to count as one stopping point. After the target, the control method is defined. As shown in chapter 4.2.1 there are different methods available that are chosen depending on the parameters of the system you simulate. The important thing is to choose the method of the "TuggerTrainGarage" that is responsible for that route. If the station is part of more than one route then for each route a sensor is needed and each has the method of the corresponding "TuggerTrainGarage" assigned.

Step 3: Run the Simulation

The last step is to run the Simulation of the model, but before that the "presetfile" has to be filled with data. In chapter 4.4.2 it is explained which parameters are defined in that file and also how to define the route, tugger train components, and orderlist. The next thing is to choose an "outputfile" which is an excel file chosen by the planners in which the results are exported. Now the start button of the simulation can be pressed and the simulation model asks the planner to choose the storage location of the "presetfile" and "outputfile". After these are chosen the settings are imported and the simulation runs for the defined duration time. At the end of the simulation run, the results are exported.

4.6. Practical examples

This chapter deals with practical examples that were modelled and simulated with the simulation library. Each example consists of a system description with a table of parameters, a description of the simulation model, and a short evaluation of the simulation. The examples are real use cases of which the description and system parameters are presented in the VDI 5586.[VDI16a]

4.6.1. Example 1: Supply with SLC from a supermarket

System Description

The first example is about a household appliance manufacturer, with a total of 20 different workstations which are supplied with small load carriers from a supermarket. The average throughput is 250 SLC's per shift. One tugger train drives a fixed route with a tact time of one hour. The stopping points are all located on this route and stopped at according to a fixed schedule. Each SLC contains a Kanban card on which material and destination are noted. The driver places the full SLC at the assigned delivery point and picks up empty SLC's, in the case that any are available. In each tour between 30 and 40 SLC's are delivered. The transport demand for the next tour is created with the Kanban cards. The tugger train driver drives through the supermarket and loads the SLC's for the next tour according to the kanban cards. After loading the SLC's for the next tour the tugger train waits at the supermarket until the start time of the tour.[VDI16a]

Number of supply points for loading	not specified
Number of delivery points for unloading (full goods)	20
Number of routes	1
Number of tugger trains per route	1
Load carriers	Small load carriers
Average throughput per shift (only full goods)	250 SLC
Determination of transport requirement	consumption-oriented
Type of demand signal	physical (Kanban-card)
Tour start	fixed schedule (timed)
Tact time of the route	60 min
Cycle time	40 min to 55 min
Empties management	integrated

Table 6.: Key figures of Example 1: Supply with SLC from a supermarket

Simulation setup

The simulation model is created according to the requirements of the example and is also shown in Fig. 44. B.1 shows the pre-set file of the model with some of the main settings, further described in chapter 4.4.1. According to the parameters, there is one route, which is simulated with the track element, through the model. To simulate the 20 workstations there were 40 buffers used, since always 2 represents one workstation. One

of the buffers is for the pick-up of the empty boxes, which includes the Kanban card. These buffers have the “Order” method as their exit control. To simulate the transport demand with Kanban cards, the “Kanban” Boolean of the “TuggerTrainGarage” is set to true, that way the order for a new box is made the moment the tugger train unloads the empties at the designated buffer. The other buffer of the stopping point is used for the delivery of the full SLC’s. To ensure that these 2 buffers are one stopping point there are also 2 sensors on the Track, with a distance of 0.01m between them. The first sensor has the method “Loading” as a control to pick-up empties and the second sensor has the “StationCtrl-Kanban” as a controlling method, responsible for the unloading of the delivered load carriers. At the end of the route, there is a buffer designated for the empties, at which also the orders for the next tour are given. At the position of this buffer, there is also a sensor on the track with the “Unloading” method controlling it. The next station is again the supermarket, where the tour also starts, with again a sensor using the “Supermarket-Kanban” method on the Track. With the adjustment of the speed of the tugger train and also the loading time of the goods, the requirement of the cycle time is met. The tact time is set at the “TuggerTrainGarage” to 60 min and the whole simulation duration is 8h (one shift). B.2, which is the outputfile of the model, the results are shown.

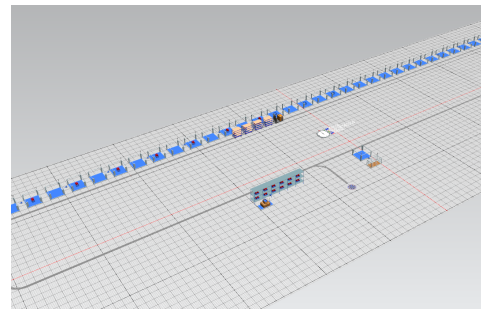
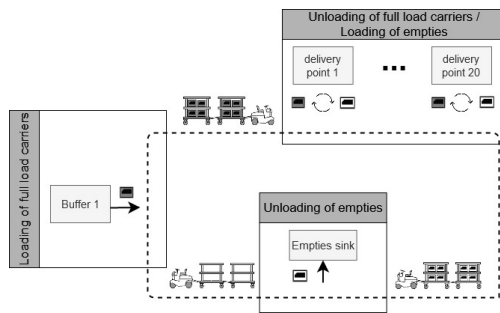


Figure 43.: Schematic diagram of example 1 Figure 44.: PlantSim model of Example 1

Evaluation of the Simulation model

This example shows how to simulate a system that uses Kanban cards to create the transport demand. The “Kanban” boolean in the “TuggerTrainGarage” makes this possible since it ensures that the order is only given if the empty box is unloaded at a certain station or supermarket. In this example, the buffer for the pickup of empties must have the “Order” method as exit control, since the Kanban card in the empty box creates the transport demand. Overall, it is a small example, which shows well how to simulate a tugger train system consisting of one supermarket supplying goods with one tugger train to multiple stations. There are no parameters for the distances between the workstations given, therefore the cycle times are met with adjusting loading time and speed of the tugger train. As shown in B.2 all the given parameters were met with the simulation and therefore, the case is successfully simulated.

4.6.2. Example 2: Supply with SLC from an MLS

System Description

In this example, a supplier to the automotive industry, which has 120 different supply locations along an assembly line, is presented. These locations are supplied with an average of 3600 small load carriers per shift. There are seven different routes defined on which every 45 minutes a tugger train starts its tour. There are four so-called "retrieval stations" (supply locations) in front of a small parts warehouse, where the tugger trains collect the load carriers, which are to be delivered. At the start of a tour, the tugger train drives to the supply location and gets automatically loaded with the SLC's for his tour. In this case, the tugger train has goods loaded for the station or if there are empties available, the tugger train stops and loads or unloads the SLC's. This way there are between 40 and 60 load carriers delivered per tour. At the end of the tour, the driver removes the empty SLC's and waits at the supply location until the start time of the next tour. The transport demand is determined by an It-system and follows a production plan.[VDI16a]

Number of supply points for loading	4
Number of delivery points for unloading (full goods)	120
Number of routes	7
Number of tugger trains per route	1
Load carriers	Small load carriers
Average throughput per shift (only full goods)	3600 SLC
Determination of transport requirement	demand-oriented
Type of demand signal	electronically (production program)
Tour start	fixed schedule (timed)
Tact time of the route	45 min
Cycle time	38 min
Empties management	integrated

Table 7.: Key figures of Example 2: Supply with SLC from an MLS

Simulation setup

The simulation model for example 2 consists of 120 buffers of which one half is assigned for delivery of full SLC's and the other half is the waiting area for empty SLC. The system description does not define how the routes are designed or how many tugger trains share a loading area at the supermarket. Therefore, the model is designed in a way that always 2 tugger trains share one loading area and the seventh tugger train has a loading area for itself. At the loading areas which are shared by two tugger trains, there are two sensors on the track, one for each tugger train, and these sensors have the "Supermarket-Push" method as control. Each of the seven tugger trains drives on a separate route with 17 or 18 stopping points. These stopping points always consist of two buffers with two assigned sensors on the track. One of the sensors is controlled by

the “Loading” method and the other one by the “StationCtrl-Push” method. The distance between the sensors is again 0.01m so that they count as one stopping point. The buffers in this example have no order method since the transport demand is controlled by a production plan, which means that each tour the tugger train delivers the exact amount of goods given by the plan. This simulation also has two buffers at which the empty SLC’s of the stations are unloaded. At the position of these 2 buffers, there are sensors for the tugger trains, whose route passes by, and all the sensors have the “Unloading” method of the corresponding “TuggerTrainGarage”. Fig. 46 shows the model in plant simulation and that the routes are connected and where the tugger trains share a loading area. According to the specifications of the example, the tugger trains have a tact time of 45 min which is saved in the different “TuggerTrainGarage” elements and set with other settings like the tugger train parts, routes, etc. as shown in the pre-set file in B.3.

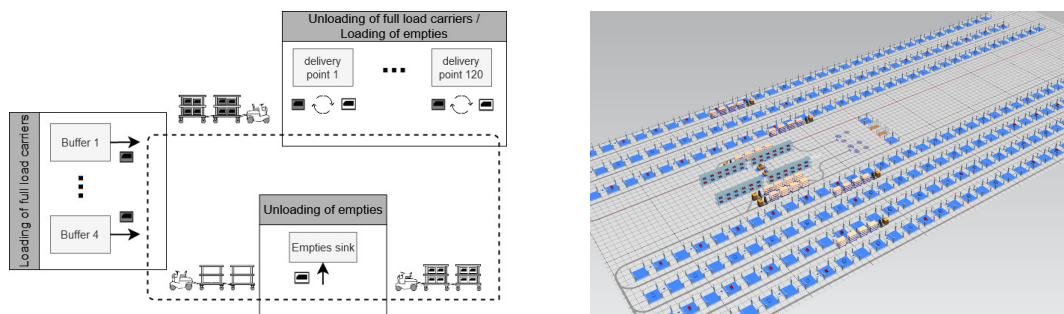


Figure 45.: Schematic diagram of example 2 Figure 46.: PlantSim model of Example 2

Evaluation of the Simulation model

In this example, it is visible how a tugger train system, in which multiple tugger trains share one loading area but have different routes, is simulated. In the model, the tugger trains sometimes have to wait till the one in front of him is done with loading the goods but this is the case since the system description only provides the average throughput and tact times but no distances between the stations or a layout of the routes, as well as no loading times, are provided. But the example shows that it is no problem if more than one tugger train shares parts of the route with another tugger train since in this example four tugger trains are doing this. According to B.4, the key figures of the example are met, of which the cycle time was reached by adjusting the loading time of the tugger trains in the pre-set file.

4.6.3. Example 3: Supply with LLC from a shelf storage with pre-loaded trolleys

System Description

This example is about the supply of 40 different production cells with large load carriers from a shelf-storage. The parameters of the example are shown in Tab. 8. The transport requirement is demand-oriented and is signalled by an e-Kanban (see chap 2.5.1) system. Four routes are defined for supplying the production cells, which are each traveled by 2 tugger trains. The average throughput per shift is 500 LLC's, which are loaded in the buffer area. There are 4 different supply stations (supermarket) and each of them is assigned to one route. The tour starts with the loading of the LLC's, which have no fixed arrangement on the tugger train. Per tour, a maximum of four LLC's will be delivered, and empties are picked up at the stopping points, if available. These empties are unloaded at the end of the tour at an assigned area for empty load carriers. The cycle time of a tour is approx. 20 minutes, without having a fixed tact. The tugger train consists of a four-wheel tractor combined with one type of trailer. [VDI16a]

Number of supply points for loading	4
Number of delivery points for unloading (full goods)	40
Number of routes	4
Number of tugger trains per route	2
Load carriers	Large load carriers
Average throughput per shift (only full goods)	500 LLC
Determination of transport requirement	consumption-oriented
Type of demand signal	electronically (e-Kanban)
Tour start	permanently
Tact time of the route	no tact time
Cycle time	20 min
Empties management	integrated

Table 8.: Key figures of Example 3: Supply with LLC from a shelf storage with pre-loaded trolleys [VDI16a]

Simulation setup

The simulation model, also shown in Fig.48, is created according to the key figures and description of the example. For the loading area, there are 4 buffers (one per route) used, which are constantly supplied with LLC's by a source. At the end of each route is one Buffer used as an area for empty load carriers. Every route consists of 20 buffers with an assigned stopping point which always consists of 2 buffers, one for the delivery of full LLC's and one for the pick-up of empty LLC's. At the moment a load carrier leaves the buffer and goes into the production line the "Order" control starts and checks if the min. amount of LLC's is still available, if not it gives an order through the orderlist to the tugger train so that in the next tour a full LLC is delivered. Since the production is designed as a black box, the buffers for the empty LLC's have a short entrance method

which is triggered the moment a full LLC enters the buffer. This method deletes the content of the LLC so that an empty pallet remains.

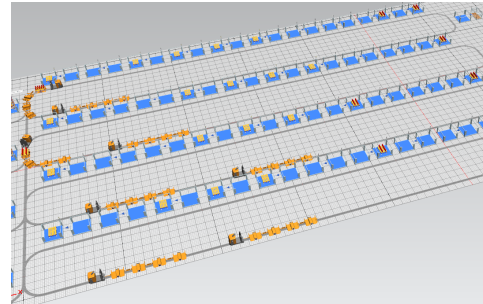
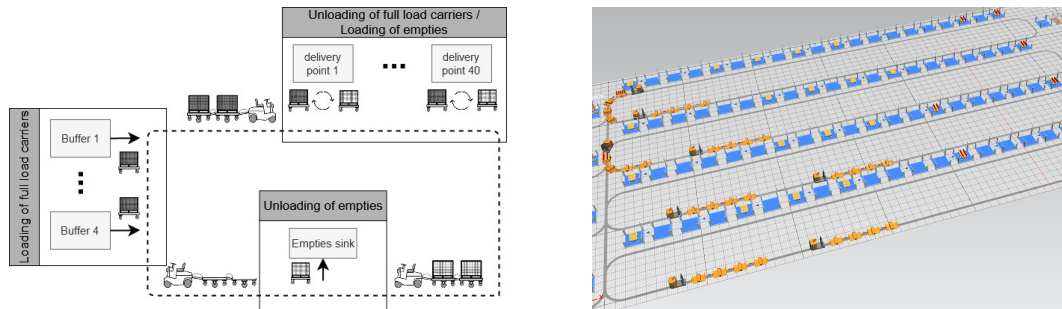


Figure 47.: Schematic diagram of example 3 Figure 48.: PlantSim model of Example 3

The route is designed with the Track on which the sensors are set at the stopping points. At the buffer representing the supermarket is the start of the tour, here is a sensor on the track with the "Supermarket-Kanban" method as control. Since the transport demand is signalled by an e-Kanban system the "kanban" boolean is "false" and the "ekanban" boolean is set to "true". Along the route, there are always 2 sensors at a stopping point with a distance of 0.01 m. The first sensor is for the check if there are empty LLC's at the stopping point and has the method "Loading" as control. "StationCtrl-Kanban" is the control of the second sensor, which is responsible to check if the tigger train has any ordered goods loaded and also unload them. At the end of the tour, there is another buffer for the unloading of the empty LLCs. The sensor at that stop uses the "Unloading" method as control. For every route, there is one "Tigger Train Garage" which creates the tigger trains and contains the methods for the simulation. B.5 shows the pre-set file of one "Tigger Train Garage" and shows how to configure the file that 2 tigger trains are created from one garage. Because the example description doesn't provide distances between the stations but only the average throughput, the speed of the tigger trains are adjusted to meet this requirement. At the end of the Simulation "Tigger Train Results" produce the outputfile, which is shown in B.6 for one tigger train.

Evaluation of the Simulation model

This Example shows well how to simulate Tigger train systems with multiple tigger trains per route. Although in this example the tigger trains consist of the same number and type of trailers it is possible to adjust them to the needs of the planner. The sensors on the route differentiate between the tigger trains through the different names. With the adjusted speed, it was possible to compensate for the lack of the distances in the parameters. As the outputfile shows in B.6 the results of the simulation meet the requirements of the average throughput and cycle time. Therefore, it is possible to simulate this case study successfully with the use of the simulation library.

4.6.4. Example 4: Supply with different load carriers, which were brought together in a buffer

System Description

In this example of an automotive manufacturer, different stations along an assembly line are supplied. The stations are supplied with SLC, LLC, and Set-LLC (assembly sets in set containers with LLC basic dimensions) from a supermarket and are loaded on the same tugger train. The supermarket consists of five buffer areas at which the load carriers are provided by the logistic staff. The logistic staff is picking up the needed load carrier of the corresponding storage and delivers them to the supermarket. Each of these five buffer areas is permanently assigned to one of five routes. The 300 stations along the assembly line are split and assigned to the five different routes. On each route, there are driving three tugger trains, which start their tour according to a fixed schedule. The average tour duration is 40min and the tact time is 60min. The driver stops at the displayed stopping points and provides SLC, LLC, and Set-LLC. He also collects empties (empty SLC, empty LLC, empty Set-LLC on a trolley). At the end of the tour, the driver drives back to the buffer area and unloads the empties at the empties buffer area. The driver then starts loading for the next tour. If there are more load carriers and trolleys for his route at the station than the tugger train can accommodate, he first loads those with the earliest destination provision times. The driver decides for himself on the arrangement on the train that makes sense for him. He confirms the loading of the train by scanning the labels of all load carriers on the tugger train. After loading, the driver waits until the start time of the next tour. Transport requirements are determined by the IT system according to a production plan.[VDI16a]

Number of supply points for loading	5
Number of delivery points for unloading (full goods)	300
Number of routes	5
Number of tugger trains per route	3
Load carriers	Large load carriers / small load carriers
Average throughput per shift (only full goods)	500 SLC/460 LLC/160 Set-GLT
Determination of transport requirement	demand-oriented
Type of demand signal	electronically (production plan)
Tour start	fixed schedule
Tact time of the route	60 min
Cycle time	40 min
Empties management	integrated

Table 9.: Key figures of Example 4: Supply with different load carriers, which were brought together in a buffer

Simulation setup

The simulation model is shown in Fig. 50. The original system consists of 300 stations

which are split up into 5 routes with 3 tugger trains per route. Due to the high number of stations, the simulation model was simplified. Therefore, the model consists of one route with 3 tugger trains and 60 stopping points, which are designed according to the two-buffer principle. This means that each stopping point consists of two buffers, one for full load carriers with the "StationCtrl-Push" method as control and the other is for empties with the "Loading" method controlling it. These methods are used at the allocated sensors of the buffers on the track. The supermarket was modelled with a storage element and a sensor on the track has the "Supermarket-Push" method as control. Fig. 66 shows the "pre-set" file for the model. As shown there the "Kanban" and "eKanban" boolean are set to false because the system is demand-oriented and follows a production plan. The "load-included" boolean is set to true since the tugger train driver loads the goods for the next tour and waits afterwards for the starting time of the tour. The orders of the stations were adjusted to the given throughput. At the end of the route, there is a buffer placed with the "Unloading" method controlling the sensor, which is used as the buffer area for empties. The "TuggerTrainGarage" element creates the three tugger trains which drive the route starting at the supermarket and ending at the buffer area for empties.

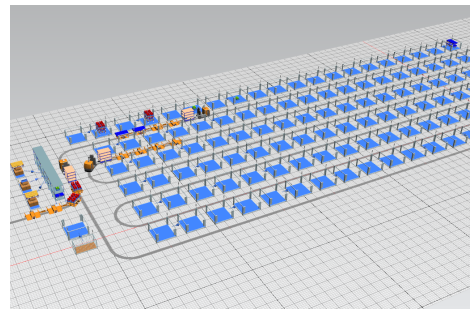
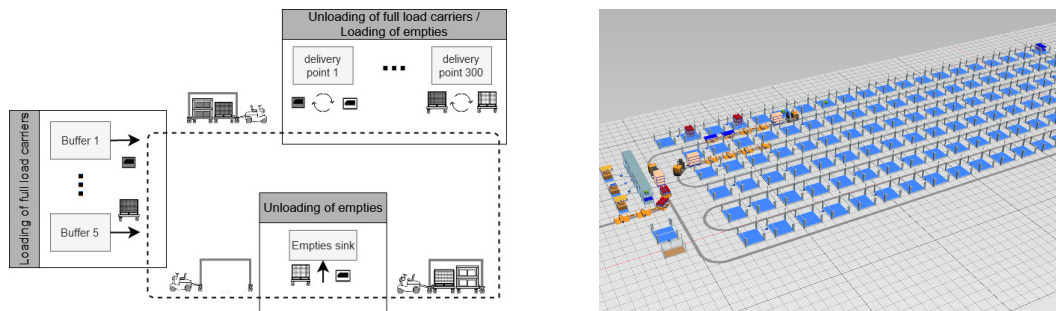


Figure 49.: Schematic diagram of example 4 Figure 50.: PlantSim model of Example 4

Evaluation of the Simulation model

This example shows multiple functions of the simulation library. The first thing is how to control multiple tugger trains on one route. The tugger trains all have the same stations and share one supermarket and the same empties area. This is done as shown in B.7 by adding 3 different tugger trains into the column "D" to "F" and giving them 3 different names. The other thing this example shows pretty well is how different load carriers are delivered by one tugger train. This is shown by loading SLC's, LLC's and Set-LLC'S (here LLC's with SLC's loaded) onto the tugger train. Therefore, the function to deliver different kinds of load carriers with one tugger train is given. B.8 shows the output file of the simulation and as shown there the throughput and cycle times are reached. For the reason that this tugger train system is demand-oriented and follows a production plan, the number of delivered load carriers is not split into several types, since the quantities were predefined and the number only serves as another check.

4.6.5. Example 5: Disposal of finished goods in LLC from production cells

System Description

This example is about a mechanical engineering company in which finished goods are collected from 30 different production cells. These goods are stored in LLC's and transported to the shipping area. Each of the 30 production cells is assigned to one of five routes and one tugger train is driving on each route. Along the routes, there is a stopping point at each production cell and if there are full load carriers available at the station, then these goods are loaded onto the tugger train. In case an LLC is loaded the driver provides an empty load carrier to the production cell at the same time. During a tour the tugger train collects a maximum of four load carriers and the whole tugger train system collects 360 finished good load carriers during an average shift. It also supplies the production cells with the same number of empty LLC's. The signalisation of the transport requirement is done by a Kanban system, in which the load carriers serve as Kanban cards. This means that for every delivered full LLC, an empty LLC is loaded and transported to the production cell. A tour of a tugger train lasts 20 minutes on average and are started permanently, which means that the next tour starts immediately after the previous one.[VDI16a]

Number of supply points for loading	30
Number of delivery points for unloading (full goods)	1
Number of routes	5
Number of tugger trains per route	1
Load carriers	Large load carriers
Average throughput per shift (only full goods)	360 LLC
Determination of transport requirement	consumption-oriented
Type of demand signal	physical (load carrier)
Tour start	permanently
Tact time of the route	none
Cycle time	20 min
Empties management	integrated

Table 10.: Key figures of Example 5: Disposal of finished goods in LLC from production cells [VDI16a]

Simulation setup

The simulation model for this example is designed as shown in Fig. 52. Because no distances between the stations and no details of the route were given in the system description, all buffers were lined up in one row. The route is designed in a rectangle form with the track element. According to the parameters, there are 5 different routes with one tugger train each. Therefore, the buffers are assigned to different routes with 12 each route. The reason for 12 buffers per route is that the two-buffer principle of Meinhardt and Schmidt is applied. This means that at every stopping point there are two buffers, one for the delivery of empty LLCs and the other for the pickup of the

full load carriers. To simulate this principle there are two sensors on the track at each stopping point, with a distance of 0.01m between them. The first one is controlled with the “Loading” method to pick up full LLC’s and the second one has the “StationCtrl-Kanban” method as a control for the delivery of empty load carriers. The buffer which is assigned as the pickup area for the full LLC’s has the “Order” method as exit control. The shipping area is designed as a buffer connected to a drain with a sensor per tugger train on the track with the “Unloading” method as control. The start of the route is at the supermarket, where a sensor with the “Supermarket-Kanban” method is placed on the track. Further configurations are that the “Kanban” Boolean is set to true since the full LLC’s are used as Kanban cards and that the tugger trains are designed with 4 trailers due to the maximum of 4 delivered load carriers per tour. The configuration of the tugger train system, as well as the settings of the route, are also shown in B.9 which is the pre-set file of this model.

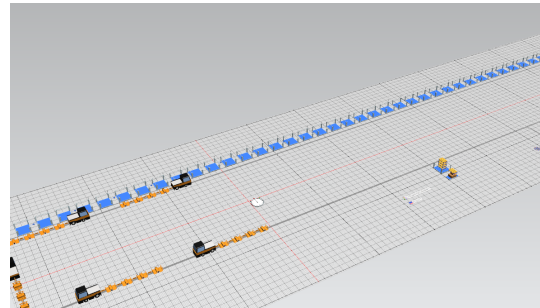
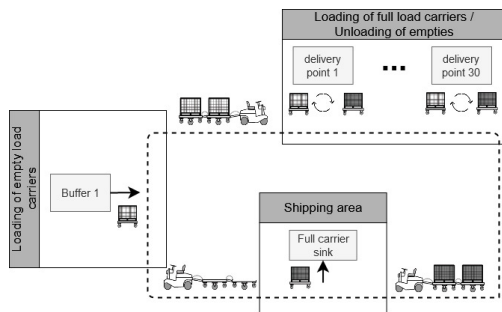


Figure 51.: Schematic diagram of example 5 Figure 52.: PlantSim model of Example 5

Evaluation of the Simulation model

This example shows how a tugger trains system with a mixed transport task of supply and disposal is simulated. In the simulation model, the buffer used for the full load carriers is making the order for an empty LLC, which is delivered to the other buffer at the stopping point. This means that this example shows how to simulate the case that one loading area makes an order for a different one. In the simulation model, it is also visible that multiple tugger trains drive on the same track, but have different routes. This feature can be useful to simulate cases where only one track goes through the facility. The given parameters, namely the average throughput and the cycle times are met by the adjustment of the loading times. This was necessary because the system description doesn’t provide any distances between the stations. The results are also shown in B.10.

5. Evaluation of the Simulation Library

The practical examples which are presented in the previous chapter are created with the use of the simulation library. Each of the examples includes a small evaluation of the respective simulation model, in which the main features are discussed and highlighted. In this chapter, an overall evaluation of the simulation library is done. The simulation library has to include several functions that are defined in the catalog of requirements (see chapter 3.3). These different functions will now be looked at separately and it is shown to which degree the catalog is fulfilled.

The first part of the catalog is the boundary conditions which start with the primary transport task. In the practical examples, it is demonstrated that the 3 different transport tasks can be simulated. In example 5 the disposal task is shown, and the 4 others are either a supply task or the combination of supply and disposal. The possibility to transport different load carriers is shown in example 4, where stations are supplied with several different load carriers at once. In terms of the determination of the transport requirement, the simulation library enables the creation of demand-oriented systems by providing the necessary control methods ("Supermarket-Push", "StationCtrl-Push"). There are not only the demand-oriented systems included but also the consumption-oriented systems, which are differentiated by the used methods ("Supermarket-Kanban", "StationCtrl-Kanban"). With the simulation library, it is not possible to use different triggers for the transport demand. The demand is always automatically triggered by either reaching a certain stock level or by a production plan. On the other hand, the library has the function included to differentiate between a traditional Kanban system with Kanban cards or an e-Kanban system. This is shown in example 5, in which the load carriers serve as Kanban cards compared to the e-Kanban system in example 3.

The second section of the catalog considers the technical criteria of the tugger train system. As shown in Fig. 39 the different trailers, as well as the different tractors (Fig. 37 and Fig. 38), are represented as 3D models in the simulation library. These models are matched with the results of the literature research and the comparison of the models available on the market. To regulate the allowed number of trailers per tugger train, a restriction is implemented within the tractor element. This restriction can be adjusted by the planner to allow different numbers of towed trailers. The trailers also have restrictions implemented, which define the capacity and also the types of transported load carriers. In the pre-set file the loading and unloading time for the tugger train can be adjusted, to simulate if for example additional equipment is needed or not. The turning cycle of the tugger train, as well as the needed width of the track, are not considered by the simulation library. It is not possible to include restrictions for these two parameters

in Plan Simulation. Therefore, the planner has to keep the necessary track width and turning cycles of the tugger train in mind, while creating the simulation model. Another thing that the designer must consider is the Loading and Unloading side since it was not possible to implement any restrictions for this in the simulation model. This must be done during the route defining step.

The last thing to evaluate is if the simulation library fulfills the organisational criteria. As shown in the examples it is possible to simulate multiple routes in one model and to assign more delivery points to one stopping point. In the examples, this is done by setting the distance between two sensors to 0.01m. The drivers per route are not able to be simulated, and therefore have to be considered by the designer separately. For the assignment of the tugger trains to the routes, the examples showed that it is possible to assign one or multiple tugger trains to one route. On the other hand, it is only possible to assign multiple routes to a single tugger train, if the routes are in an ordered sequence. This means the tugger train is not able to change the given route during the simulation run. There also can be multiple different types of trailers, attached to one tractor. The criteria regarding who loads the tugger train trailers and if additional support is needed, are not specially considered but can be simulated by changing the loading time needed. The different tour starts can be defined by either defining the tact time if there is a fixed timetable or setting the tact time to 0 so that the tugger train drives permanently. The capacity utilization oriented is not implemented, since the tact time for a certain utilization is dimensioned before the simulation. Another aspect that is not implemented is the changing of trailers during the simulation. But as shown in the examples, it is possible to include the transportation of empties and therefore, include the empties process into the tugger train system. It is also possible to define a delay time at the stations which are calculated as a discrete uniform distribution. This delay time represents the demand fluctuations. The time includes all 5 types of fluctuations and must be defined for each station. Therefore, it is not the most accurate simulation of demand fluctuations, but it brings the aspect of the demand fluctuations into the simulation model.

Additionally, there are several key figures, which the simulation library must present as results. As shown in the output files of the examples, the number of tugger trains, average and maximum tour times, driven distance, and the utilization, as well as the delivered goods and transported empties are presented. Therefore, this part of the catalog was fulfilled completely.

As shown with this evaluation, the simulation library includes most of the functions defined by the catalog of requirements, which is based on the literature research. It is also shown that the ideal simulation library is not completely reached because some special cases are not included. This means that the implemented functions enable the designer to create a wide range of practice-relevant tugger train systems, however, there is still further research necessary to expand the simulation library and include the special cases, as a next step.

6. Summary

The increasing number of implemented tugger train systems in the automotive industry, but also in other industries, lead to the development of several different planning approaches. These planning methods were presented and compared in this master thesis and it was shown that some already include the simulation or at least mention it as an important tool for the planning process. Therefore, the importance of the simulation of tugger train systems is also increasing. This was also shown during the study by Günthner et al. in which the participants expressed the need for software support.[GGK12a] All this led to the creation of this master thesis with the goal to simulate and evaluate tugger train systems in the software “Plant Simulation”. This goal was achieved by creating a simulation library inside of Plant Simulation to enable the planner to create a tugger train system within his existing model of the facility.

The first step of this creation was an extensive literature research on the topic of tugger train systems and their planning strategies. Various literature sources were used for this purpose, which was discussed and presented in chapter 3. Based on this literature research a catalog of requirements for the simulation library was created, which includes all the necessary functions that had to be implemented. In the next step, Plant Simulation was analysed to show which functions are already available and to find a way to create the simulation library with the available tools of the software. With this knowledge, the methods for controlling the tugger train as well as the necessary parameters and lists were created. These were then integrated into the library elements. It was also important to ensure that the components of the library work together and that all necessary functions are covered. After the controls and elements of the database were functional, visual adjustments were made. This means the creation of 3D models for the tugger train elements. Models for both the tractors and the trailers were created and integrated into Plant Simulation. These models include all the mentioned components of tugger trains, which were found during the literature research.

As the last step, the created simulation database was evaluated and checked if all functions, which were selected based on the literature research, are included. This was carried out by the simulation of five practical examples. Within this evaluation, it became visible that the simulation library includes most of the functions defined in the catalog of requirements.

Therefore, the created simulation library in this master thesis provides the mentioned simulation software support for the planning of tugging train systems. It enables the planner to simulate a wide range of practice-relevant tugging train systems and implement them into the simulation model of his facility. This also provides the possibility to optimize and evaluate the planned and dimensioned tugging train system. With that, it is now possible to simulate the most commonly used material supply strategies, including the tugging train, with Plant Simulation. The evaluation also showed that it was not possible to include all functions into the simulation library and therefore, that further research is necessary. This means that the next step must be the further expansion of the simulation library. So that it is not only possible to create simulation models of the standard and typically used tugging train systems, but also the special cases. The implementation of further restrictions and possibilities, for example, the assignment of multiple routes to one tugging train can be one step of the further research and expansion. The inclusion of route optimization, cost optimization, and other part-problems of the planning process can be another step of future research. This is an important research area because the simulation of transport systems will get more and more important in the future.

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7. Appendix

A. Control methods of the simulation library

A.1. Control method Supermarket Kanban

```
var Tugger:boolean := false
for var x := 1 to self.~.TuggerTrain.yDim
  if @.name = self.~.TuggerTrain[3,x] then
    Tugger := true
  end
end
next

if @.isTractor = true and Tugger = true then
  @.stopped:=true

  var pause:time
  var Tractor:object := @
  var Trailer:object := @.rearMU
  var TrainCapacity:integer := 0

  if self.~.load_included = false then
    if Tractor.destination = self.~.Stations[1]
      Tractor.route_nr := Tractor.route_nr + 1
    end

    if Tractor.route_nr > 0 and self.~.Tact_time = 0 then
      Tractor.route_time := eventController.simTime - Tractor.starttime
      Tractor.starttime := eventController.simtime
      Tractor.route_time := Tractor.route_time / 60
      Tractor.route_times.writeRow(1,Tractor.route_times.yDim+1,Tractor.route_nr,Tractor.route_time)

      if Tractor.max_route_time < Tractor.route_time then
        Tractor.max_route_time := Tractor.route_time
      end
    elseif Tractor.route_nr = 0 then
      self.~.Start_time := eventController.simtime
    end

    if self.~.Tact_time > 0 and Tractor.route_nr > 0 then
      pause := (self.~.Tact_time * Tractor.route_nr) + self.~.Start_time - eventController.simTime
      if pause < 0 then
        Tractor.route_time := self.~.Tact_time - pause
        pause := 0
      else
        Tractor.route_time := self.~.Tact_time - pause
      end
      Tractor.route_time := Tractor.route_time / 60
      Tractor.route_times.writeRow(1,Tractor.route_times.yDim+1,Tractor.route_nr,Tractor.route_time)

      if Tractor.max_route_time < Tractor.route_time then
        Tractor.max_route_time := Tractor.route_time
      end
      wait pause
    end
  end

  if Tractor.destination = self.~.Stations[1] then
    Tractor.TrailerNU := 0
    for var k := 1 to self.~.TuggerTrain.yDim
      if self.~.TuggerTrain[3,k] = Tractor.name then
        TrainCapacity := TrainCapacity + (self.~.TuggerTrain[1,k].capacity * self.~.TuggerTrain[2,k])
        Tractor.TrailerNU := Tractor.TrailerNU + self.~.TuggerTrain[2,k]
      end
    end
  next
end
```

Figure 53.: Supermarket Kanban method part one

```

Tractor.TrailerNU := Tractor.TrailerNU - 1
if Tractor.TrailerNU > Tractor.TrailerNUmax then
    messagebox("There are too many trailers attached to the tractor.", 1, 2);
end
root.Ersignisverwalter.stop
end

for var i := 1 to self.orderList.yDim
    for var p := 1 to self.orderList[2,i].yDim
        for var j := 1 to self.orderList[2,i][3,p]
            for var l := 1 to Tractor.destination.contentsList.yDim
                for var m := 1 to Tractor.destination.contentsList.yDim
                    if Tractor.destination.contentsList[l,m] /= void and Tractor.destination.contentsList[l,m].cont /= void and
                    if Tractor.destination.contentsList[l,m].cont.inherentclassname = "Place" then
                        for var n := 1 to Tractor.TrailerNU
                            for var o := 1 to Tractor.TrailerNU
                                if Tractor.destination.contentsList[l,m].class = Trailer.carriers[o] and Trailer.full = false then
                                    Tractor.destination.contentsList[l,m].move(Trailer)
                                    wait self.loadingTime
                                    self.orderList[2,i].writeRow(4,p,self.orderList[2,i][4,p] + 1)
                                    n := Tractor.TrailerNU
                                    o := Trailer.carriers.Dim
                                end
                            end
                        next
                    if Trailer.rearNU /= void and Trailer.rearNU.isTractor = false then
                        Trailer := Trailer.rearNU
                    end
                end
            end
        end
    end
elseif Tractor.destination.contentsList[l,m] /= void and Tractor.destination.contentsList[l,m].cont = void then
    if Tractor.destination.contentsList[l,m].class = self.orderList[2,i][1,p] and self.orderList[2,i][4,p] < self.orderList[2,i][3,p] then
        for var n := 1 to Tractor.TrailerNU
            for var o := 1 to Trailer.carriers.Dim
                if Tractor.destination.contentsList[l,m].class = Trailer.carriers[o] and Trailer.full = false then
                    wait self.loadingTime
                    self.orderList[2,i].writeRow(4,p,self.orderList[2,i][4,p] + 1)
                    n := Tractor.TrailerNU
                    o := Trailer.carriers.Dim
                end
            end
        next
    if Trailer.rearNU /= void and Trailer.rearNU.isTractor = false then
        Trailer := Trailer.rearNU
    end
end
next
end

Tractor.destination.contentsList[l,m].cont.inherentclassname = "Goods" then
    if Tractor.destination.contentsList[l,m].cont.class = self.orderList[2,i][1,p] and self.orderList[2,i][4,p] < self.orderList[2,i][3,p] then
        for var n := 1 to Tractor.TrailerNU
            for var o := 1 to Trailer.carriers.Dim
                if Tractor.destination.contentsList[l,m].class = Trailer.carriers[o] and Trailer.full = false then
                    wait self.loadingTime
                    self.orderList[2,i].writeRow(4,p,self.orderList[2,i][4,p] + 1)
                    n := Tractor.TrailerNU
                    o := Trailer.carriers.Dim
                end
            end
        next
    end
elseif Tractor.destination.contentsList[l,m] /= void and Tractor.destination.contentsList[l,m].cont /= void and
    if Tractor.destination.contentsList[l,m].cont.inherentclassname = "Goods" then
        for var n := 1 to Tractor.TrailerNU
            for var o := 1 to Trailer.carriers.Dim
                if Tractor.destination.contentsList[l,m].class = Trailer.carriers[o] and Trailer.full = false then
                    wait self.loadingTime
                    self.orderList[2,i].writeRow(4,p,self.orderList[2,i][4,p] + 1)
                    n := Tractor.TrailerNU
                    o := Trailer.carriers.Dim
                end
            end
        next
    end
end

```

Figure 54.: Supermarket Kanban method part two

A.2. Control method Station Kanban

```

var Tugger:boolean := false
for var x := 1 to self^.TuggerTrain.yDim
  if @.name = self^.TuggerTrain[x] then
    Tugger := true
  end
next
if @.isTractor = true and Tugger = true then
  @.stopped:=true
  var Tractor:object := @
  var Trailer:object := @.rearMU
  Tractor.Station := Tractor.Station + 1
  for var p := 1 to self^.OrderList[2,Tractor.ordercount].yDim
    if self^.OrderList[2,Tractor.ordercount][4,p] > 0 and self^.OrderList[1,Tractor.ordercount] = Tractor.destination then
      for var i := 1 to self^.OrderList[2,Tractor.ordercount][4,p]
        for var j := 1 to Tractor.TrailerMU
          if Trailer.class = UserObject.TuggerTrain_Parts.ShelfTrailer then
            for var k := 1 to Trailer.contentList.xDim
              for var l := 1 to Trailer.contentList.yDim
                if Trailer.contentList[k,l][m] /= void and Trailer.contentList[k,l][m].cont /= void then
                  if Trailer.contentList[k,l][m].cont.class = self^.OrderList[2,Tractor.ordercount][4,p] and
                    Trailer.contentList[k,l][m].move(Tractor.destination)
                    self^.OrderList[2,Tractor.ordercount].writeShow(3,p,self^.OrderList[2,Tractor.ordercount][3,p] - 1)
                    self^.OrderList[2,Tractor.ordercount].writeShow(4,p,self^.OrderList[2,Tractor.ordercount][4,p] - 1)
                    Tractor.Output_order := Tractor.Output_order + 1
                    wait self^.LoadingTime
                  end
                elseif Trailer.contentList[k,l][m] /= void and Trailer.contentList[k,l][m].cont = void then
                  if Trailer.contentList[k,l][m].class = self^.OrderList[2,Tractor.ordercount][1,p] and
                    Trailer.contentList[k,l][m].move(Tractor.destination)
                    self^.OrderList[2,Tractor.ordercount].writeShow(3,p,self^.OrderList[2,Tractor.ordercount][3,p] - 1)
                    self^.OrderList[2,Tractor.ordercount].writeShow(4,p,self^.OrderList[2,Tractor.ordercount][4,p] - 1)
                    Tractor.Output_order := Tractor.Output_order + 1
                    wait self^.LoadingTime
                  end
                end
              end
            end
          end
        end
      end
    end
  end
  for var k := 1 to Trailer.contentList.xDim
    for var l := 1 to Trailer.contentList.yDim

```

Figure 56.: StationCtrl Kanban method part one


```

    if Trailer.contentsList[k,l] /= void and Trailer.contentsList[k,l].cont /= void and
    Trailer.contentsList[k,l].cont.internalclassname = "Piece" then
        if Trailer.contentsList[k,l].cont.class = self.~.OrderList[2,Tractor.ordercount][1,p] and
        self.~.OrderList[2,Tractor.ordercount][4,p] > 0 then
            Trailer.contentsList[k,l].move(Tractor.destination)
            self.~.OrderList[2,Tractor.ordercount].writeRow(4,p,self.~.OrderList[2,Tractor.ordercount][3,p] - 1)
            self.~.OrderList[2,Tractor.ordercount].writeRow(4,p,self.~.OrderList[2,Tractor.ordercount][4,p] - 1)
            Tractor.Output_order := Tractor.Output_order + 1
            wait self.~.LoadingTime
        end
    elseif Trailer.contentsList[k,l] /= void and Trailer.contentsList[k,l].cont = void then
        if Trailer.contentsList[k,l].class = self.~.OrderList[2,Tractor.ordercount][1,p] and
        self.~.OrderList[2,Tractor.ordercount][4,p] > 0 then
            Trailer.contentsList[k,l].move(Tractor.destination)
            self.~.OrderList[2,Tractor.ordercount].writeRow(3,p,self.~.OrderList[2,Tractor.ordercount][3,p] - 1)
            self.~.OrderList[2,Tractor.ordercount].writeRow(4,p,self.~.OrderList[2,Tractor.ordercount][4,p] - 1)
            Tractor.Output_order := Tractor.Output_order + 1
            wait self.~.LoadingTime
        end
    elseif Trailer.contentsList[k,l] /= void and Trailer.contentsList[k,l].cont /= void and
    Trailer.contentsList[k,l].cont.internalclassname = "Goods" then
        if Trailer.contentsList[k,l].cont.class = self.~.OrderList[2,Tractor.ordercount][1,p] and
        self.~.OrderList[2,Tractor.ordercount][4,p] > 0 then
            Trailer.contentsList[k,l].move(Tractor.destination)
            self.~.OrderList[2,Tractor.ordercount].writeRow(3,p,self.~.OrderList[2,Tractor.ordercount][3,p] - 1)
            self.~.OrderList[2,Tractor.ordercount].writeRow(4,p,self.~.OrderList[2,Tractor.ordercount][4,p] - 1)
            Tractor.Output_order := Tractor.Output_order + 1
            wait self.~.LoadingTime
        end
    end
next
next
next
if Trailer.rearMU /= void and Trailer.rearMU.isTractor = false then
    Trailer := Trailer.rearMU
end
end
next
if Tractor.destination = self.~.Stations[self.~.Stations.Dim] then
    Tractor.destination := self.~.Stations[1]
else
    Tractor.destination := self.~.Stations[Tractor.Station + 1]
end
|
| Tractor.ordercount := Tractor.ordercount + 1
| Tractor.stopped := false
end
end

```

Figure 57.: StationCtrl Kanban method part two

A.3. Control method Loading

```
var Tugger:boolean := false
for var x := 1 to self.~.TuggerTrain.yDim
  if @.name = self.~.TuggerTrain[3,x] then
    Tugger := true
  end
next
if @.isTractor = true and Tugger = true then
  @.stopped:=true

  var Tractor:object := @
  var Trailer:object := @.rearMU

  Tractor.Station := Tractor.Station + 1

  for var l := 1 to Tractor.destination.contentsList.xDim
    for var m := 1 to Tractor.destination.contentsList.yDim
      for var i := 1 to Tractor.TrailerNU
        for var o := 1 to Trailer.carriers.Dim
          for var j := 1 to Trailer.capacity
            if Trailer.full = false and Tractor.destination.NumMu > 0 and
              Tractor.destination.contentsList[l,m].class = Trailer.carriers[o] then
              Tractor.destination.cont.move(Trailer)
              wait self.~.LoadingTime
            end
          next
        next
      next
      if Trailer.rearMU /= void and Trailer.rearMU.isTractor = false then
        Trailer := Trailer.rearMU
      end
    next
  next

  if Tractor.destination = self.~.Stations[self.~.Stations.Dim] then
    Tractor.destination := self.~.Stations[1]
  else
    Tractor.destination := self.~.Stations[Tractor.Station + 1]
  end
  Tractor.stopped := false
end
end
```

Figure 58.: Loading control method

A.4. Control method Unloading

```
var Tugger:boolean := false

for var x := 1 to self.~.TuggerTrain.yDim
  if @.name = self.~.TuggerTrain[3,x] then
    Tugger := true
  end
end
next

if @.isTractor = true and Tugger = true then
  @.stopped:=true

  var Tractor:object := @
  var Trailer:object := @.rearMU

  if self.~.Kanban = true then
    self.~.first_Station := true
  end

  Tractor.Station := Tractor.Station + 1

  for var i := 1 to Tractor.TrailerNU
    for var j := 1 to Trailer.capacity
      if Trailer.class = .UserObjects.TuggerTrain_Parts.Shelftrailer then
        for var k := 1 to Trailer.contentsList.xDim
          for var l := 1 to Trailer.contentsList.yDim
            for var m := 1 to Trailer.contentsList[k,l].Dim
              if Trailer.contentsList[k,l][m] /= void and Tractor.destination.full = false then
                Trailer.cont.move(Tractor.destination)
                wait self.~.LoadingTime
              end
            end
          next
        next
      end
      if Trailer.empty = true and Trailer.rearMU /= void and Trailer.rearMU.isTractor = false then
        Trailer := Trailer.rearMU
      end
    else
      for var k := 1 to Trailer.contentsList.xDim
        for var l := 1 to Trailer.contentsList.yDim
          if Trailer.contentsList[k,l] /= void and Tractor.destination.full = false then
            Trailer.cont.move(Tractor.destination)
            wait self.~.LoadingTime
          end
        next
      end
      if Trailer.empty = true and Trailer.rearMU /= void and Trailer.rearMU.isTractor = false then
        Trailer := Trailer.rearMU
      end
    end
  next
end

if Tractor.destination = self.~.Stations[self.~.Stations.Dim] then
  Tractor.destination := self.~.Stations[1]
else
  Tractor.destination := self.~.Stations[Tractor.Station + 1]
end
Tractor.stopped := false
end
```

Figure 59.: Unloading control method

B. Configuration and Results of the examples

B.1. Configuration of example 1

		Stations	TuggerTrain		Name	Orderlist	Load	min. amount
		Station	TuggerTrain Part	Amount		Station		
eKanban	false	Voll_ein	.UserObjects.TuggerTrain_Parts.Tractor_small	1	TuggerTrain_KLT	Voll1	.UserObjects.Part_rot	4
Kanban	true	Leer1	.UserObjects.TuggerTrain_Parts.Shelltrailer	4	TuggerTrain_KLT	Voll2	.UserObjects.Part_rot	4
load_included	true	Voll1				Voll3	.UserObjects.Part_rot	4
LoadingTime	0:18	Leer2				Voll4	.UserObjects.Part_rot	4
Tact_time	1:00:00	Voll2				Voll5	.UserObjects.Part_rot	4
Simulationtime	8:30:00	Leer3				Voll6	.UserObjects.Part_rot	4
		Voll3				Voll7	.UserObjects.Part_rot	4
		Leer4				Voll8	.UserObjects.Part_rot	4
		Voll4				Voll9	.UserObjects.Part_rot	4
		Leer5				Voll10	.UserObjects.Part_rot	4
		Voll5				Voll11	.UserObjects.Part_rot	2
		Leer6				Voll12	.UserObjects.Part_rot	2
		Voll6				Voll13	.UserObjects.Part_rot	2
		Leer7				Voll14	.UserObjects.Part_rot	2
		Voll7				Voll15	.UserObjects.Part_rot	2
		Leer8				Voll16	.UserObjects.Part_rot	2
		Voll8				Voll17	.UserObjects.Part_rot	2
		Leer9				Voll18	.UserObjects.Part_rot	2
		Voll9				Voll19	.UserObjects.Part_rot	2
		Leer10				Voll20	.UserObjects.Part_rot	2
		Voll10						
		Leer11						
		Voll11						
		Leer12						
		Voll12						
		Leer13						
		Voll13						
		Leer14						
		Voll14						
		Leer15						
		Voll15						
		Leer16						

Figure 60.: Example 1: pre-set file

B.2. Results of example 1

Tugger Train Name	Tour Time [min]	max. Tour Time [min]	driven distance [m]	RelativeOccupation [%]	Empty run [%]	Inputs [#]	Outputs [#]	Outputs order [#]
TuggerTrain_KLT	42,56	49,35	2270,98	0,40	0,36	508	471	254
Sum:			2270,98					254

Figure 61.: Example 1: model output file

B.3. Configuration of example 2

		Stations	TuggerTrain	Amount	Name	Orderlist	Load	min. amount
		Station	TuggerTrain Part			Station		
eKanban	false	Voll_ein3	.UserObjects.TuggerTrain_Parts.Tractor_small	1	TuggerTrain_KLT_6	Voll119	.UserObjects.Part_rot	2
Kanban	false	Leer119	.UserObjects.TuggerTrain_Parts.Shelltrailer	4	TuggerTrain_KLT_6	Voll126	.UserObjects.Part_rot	2
load_included	false	Voll119				Voll136	.UserObjects.Part_rot	2
LoadingTime	0:09	Leer26				Voll146	.UserObjects.Part_rot	2
Tact_time	0:45:00	Voll126				Voll156	.UserObjects.Part_rot	3
Simulationtime	8:00:00	Leer36				Voll166	.UserObjects.Part_rot	3
		Voll136				Voll176	.UserObjects.Part_rot	3
		Leer46				Voll186	.UserObjects.Part_rot	3
		Voll146				Voll196	.UserObjects.Part_rot	3
		Leer56				Voll106	.UserObjects.Part_rot	3
		Voll156				Voll118	.UserObjects.Part_rot	3
		Leer66				Voll126	.UserObjects.Part_rot	3
		Voll166				Voll136	.UserObjects.Part_rot	3
		Leer76				Voll146	.UserObjects.Part_rot	3
		Voll176				Voll156	.UserObjects.Part_rot	3
		Leer86				Voll166	.UserObjects.Part_rot	3
		Voll186				Voll176	.UserObjects.Part_rot	3
		Leer96						
		Voll196						
		Leer106						
		Voll106						
		Leer118						
		Voll118						
		Leer126						
		Voll126						

Figure 62.: Example 2: pre-set file

B.4. Results of example 2

Tugger Train Name	Tour Time [min]	max. Tour Time [min]	driven distance [m]	RelativeOccupation [%]	Empty run [%]	Inputs [#]	Outputs [#]	Outputs order [#]
TuggerTrain_KLT_4	35,35	37,33	2786,38	0,50	0,33	987	940	517
TuggerTrain_KLT_2	29,07	30,36	2593,74	0,40	0,47	987	985	517
TuggerTrain_KLT	32,14	38,63	2808,24	0,47	0,40	958	909	539
TuggerTrain_KLT_1	32,56	37,04	2571,60	0,46	0,39	1008	1001	528
TuggerTrain_KLT_6	41,80	41,80	2793,33	0,56	0,26	975	928	505
TuggerTrain_KLT_5	41,80	41,80	2602,47	0,45	0,40	978	931	508
TuggerTrain_KLT_3	42,10	42,10	2584,23	0,47	0,39	990	939	516
Sum:			18739,98					3630

Figure 63.: Example 2: model output file

B.5. Configuration of example 3

		Stations	TuggerTrain	Amount	Name	Orderlist	Load	min. amount
		Station	TuggerTrain Part			Station		
ieKanban	true	Voll_ein3	.UserObjects.TuggerTrain_Parts.Tractor_small	1	TuggerTrain_GLT_6	Voll13	.UserObjects.Part_rot	1
Kanban	false	Leer13	.UserObjects.TuggerTrain_Parts.B_Frame_first	1	TuggerTrain_GLT_6	Voll23	.UserObjects.Part_rot	1
load_included	false	Voll13	.UserObjects.TuggerTrain_Parts.B_Frame	2	TuggerTrain_GLT_6	Voll33	.UserObjects.Part_rot	1
LoadingTime	00:25	Leer23	.UserObjects.TuggerTrain_Parts.Tractor_small	1	TuggerTrain_GLT_7	Voll43	.UserObjects.Part_rot	1
Tact_time	00:00	Voll23	.UserObjects.TuggerTrain_Parts.B_Frame_first	1	TuggerTrain_GLT_7	Voll53	.UserObjects.Part_rot	1
Simulationtime	8:00:00	Leer33	.UserObjects.TuggerTrain_Parts.B_Frame	2	TuggerTrain_GLT_7	Voll63	.UserObjects.Part_rot	1
		Voll33				Voll73	.UserObjects.Part_rot	1
		Leer43				Voll83	.UserObjects.Part_rot	1
		Voll43				Voll93	.UserObjects.Part_rot	0
		Leer53				Voll103	.UserObjects.Part_rot	
		Voll53						
		Leer63						
		Voll63						
		Leer73						
		Voll73						
		Leer83						
		Voll83						
		Leer93						
		Voll93						
		Leer103						
		Voll103						
		Leer_aus3						

Figure 64.: Example 3: pre-set file

B.6. Results of example 3

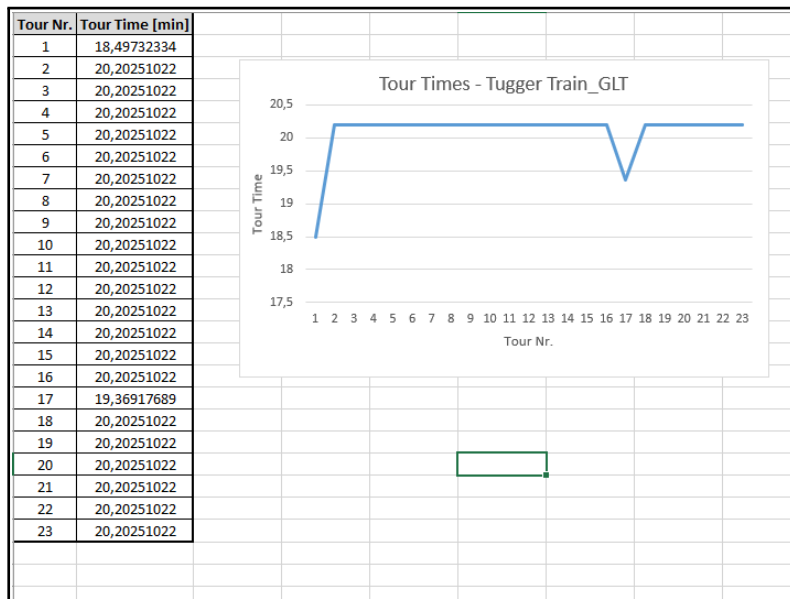


Figure 65.: Example 3: Tugger Train output file

B.7. Configuration of example 4

		Stations	TuggerTrain		Orderlist			
		Station	TuggerTrain Part	Amount	Name	Station	Load	min. amount
eKanban	false	Storage	.UserObjects.TuggerTrain_Parts.Tractor_small	1	TuggerTrain_KLT	Voll1	.Userobjects.Part_rot	1
Kanban	false	Leer1	.UserObjects.TuggerTrain_Parts.Shellfrailer	1	TuggerTrain_KLT		.Userobjects.Part_grün	
load_included	true	Voll1	.UserObjects.TuggerTrain_Parts.B_Frame	5	TuggerTrain_KLT	Voll2	.Userobjects.Part_rot	1
LoadingTime	1:05	Leer2	.UserObjects.TuggerTrain_Parts.Tractor_small	1	TuggerTrain_KLT1	Voll3	.Userobjects.Part_grün	1
Tact_time	00:00	Voll2	.UserObjects.TuggerTrain_Parts.Shellfrailer	1	TuggerTrain_KLT1	Voll4	.Userobjects.Part_grün	
Simulationtime	8:00:00	Leer3	.UserObjects.TuggerTrain_Parts.B_Frame	5	TuggerTrain_KLT1	Voll5	.Userobjects.Part_blaue	
		Voll3	.UserObjects.TuggerTrain_Parts.Tractor_small	1	TuggerTrain_KLT2	Voll6	.Userobjects.Part_blaue	
		Leer4	.UserObjects.TuggerTrain_Parts.Shellfrailer	1	TuggerTrain_KLT2	Voll7	.Userobjects.Part_blaue	1
		Voll4	.UserObjects.TuggerTrain_Parts.B_Frame	5	TuggerTrain_KLT2	Voll8	.Userobjects.Part_blaue	
		Leer5				Voll9	.Userobjects.Part_blaue	
		Voll5				Voll10	.Userobjects.Part_blaue	
		Leer6				Voll101	.Userobjects.Part_blaue	
		Voll6				Voll91	.Userobjects.Part_blaue	
		Leer7				Voll81	.Userobjects.Part_blaue	1
		Voll7				Voll71	.Userobjects.Part_blaue	
		Leer8				Voll61	.Userobjects.Part_blaue	
		Voll8				Voll51	.Userobjects.Part_blaue	
		Leer9				Voll41	.Userobjects.Part_blaue	
		Voll9				Voll31	.Userobjects.Part_blaue	
		Leer10				Voll21	.Userobjects.Part_blaue	
		Voll10				Voll11	.Userobjects.Part_blaue	
		Leer101				Voll12	.Userobjects.Part_blaue	
		Voll101				Voll22	.Userobjects.Part_blaue	
		Leer91				Voll32	.Userobjects.Part_blaue	
		Voll91				Voll42	.Userobjects.Part_blaue	

Figure 66.: Example 4: pre-set file

B.8. Results of example 4

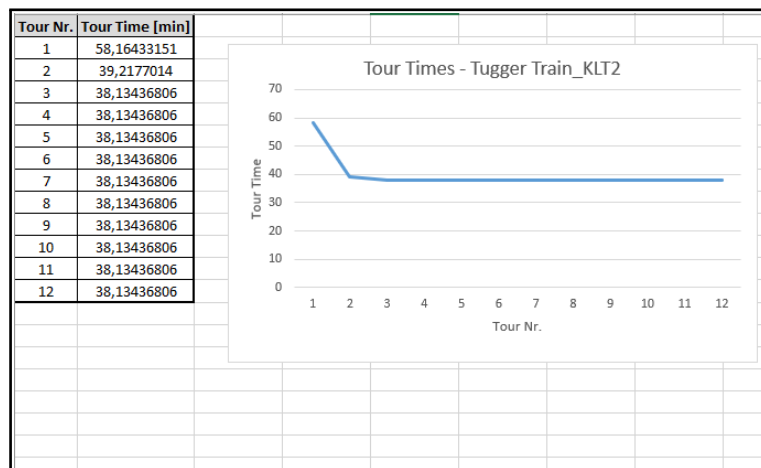


Figure 67.: Example 4: Tugger Train output file

B.9. Configuration of example 5

		Stations	TuggerTrain	Amount	Name	Orderlist	Load	min.amount
		Station	TuggerTrain Part			Station		
eKanban	false	Leer_ aus	.UserObjects.TuggerTrain_Parts.Tractor_big	1	TuggerTrain_1	Leer1	.UserObjects.Palett_Trolley	1
Kanban	true	Voll1	.UserObjects.TuggerTrain_Parts.B_Frame	4	TuggerTrain_1	Leer6	.UserObjects.Palett_Trolley	1
load_included	false	Leer1				Leer11	.UserObjects.Palett_Trolley	1
LoadingTime	1:10	Voll6				Leer16	.UserObjects.Palett_Trolley	1
Tact_time	00:00	Leer6				Leer21	.UserObjects.Palett_Trolley	2
Simulationtime	8:55:00	Voll11				Leer26	.UserObjects.Palett_Trolley	2
		Leer11						
		Voll16						
		Leer16						
		Voll21						
		Leer21						
		Voll26						
		Leer26						
		Voll_ aus						

Figure 68.: Example 5: pre-set file

B.10. Results of example 5

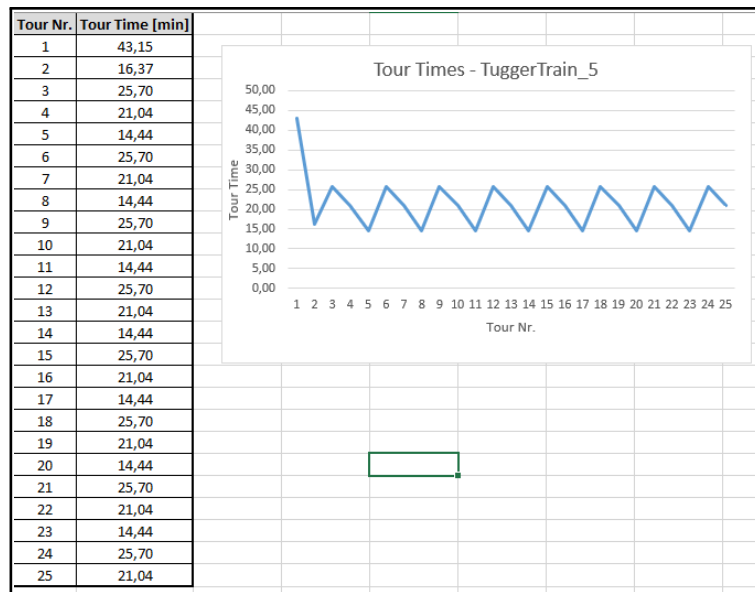


Figure 69.: Example 5: Tugger Train output file