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DATA-BASED DIGITAL TWIN OF AN AUTOMATED GUIDED VEHICLE SYSTEM

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ABSTRACT

In recent years, automated guided vehicles (AGV) have matured as a technology to make intralogistics more flexible. However, the integration of fleets of AGVs into existing production facilities still poses challenges. In this paper, a data-driven digital twin model of a system of AGVs is developed. It is based on an analysis of real-time data to replicate the driving behavior of individual vehicles as well as transport order management, vehicle selection, and travel process control more accurately. For the use case of a hybrid flow shop preassembly, the digital twin is used to optimize the number of AGVs required for the target throughput of the factory as well as to compare and select suitable path network topologies. Thus, the digital twin of a system of AGVs can be seen as a tool to increase productivity. Due to the modular design and flexible interfaces, the digital twin can easily be applied in other production scenarios as well.

1 INTRODUCTION

In order to make production systems more efficient, automation efforts are not only focused on manufacturing processes but also on process logistics. The use of automated guided vehicles in intralogistics allows goods to be transported autonomously on demand within production facilities (Gyulai et al. 2020). However, fast, cost efficient, yet safe commissioning for these flexible production systems remains a major challenge. Therefore, simulations of production and logistics processes are often used both to support the planning phase before start of production and to later adjust and optimize existing facilities.

Most simulation software suites offer standard modules for production resources. Such modules are also available for AGVs that move between waypoints. They allow parametrizations e.g. for the maximum speed, acceleration and kinematic properties of the vehicles and provide rudimentary battery models. However, many manufacturers of AGVs do not provide information on the required parameters at all. Even if reference values are specified, such as the battery charging speed, real-world performance and the actual driving behavior of the AGVs may deviate substantially from the given information. Since for selected types of AGVs neither a guidance control system nor the driving model for intralogistics applications in industrial contexts are readily available for simulation purposes, transport times and the resulting material flow processes are not predicted realistically which impairs the accuracy of the overall model.

To face this issue, digital factories and plant models must evolve into even more up-to-date representations of real production systems - not only physically, but also in terms of the logical behavior and control of the manufacturing units (Shao et al. 2016; Kerkenberg 2016). In order to make digital production and material flow planning as realistic as possible, a Digital Twin (DT) can be used (Uhlemann et al. 2017; Zhuang et al. 2018). Since the concept of the DT is one of the major technologies in the context of Industry 4.0, there are many different understandings and applications of this term (Martinez Hernandez et al. 2019). However, the DT always contains a digital representation of the structure and behavior of systems. It can

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represent physical or non-physical processes, resources, or products and their properties. The DT integrates all relevant data associated with the respective entity. It is supposed to increase productivity as it helps to make production smart by using digital counterparts of machines, systems, processes and products (Negri et al. 2017). These digital counterparts are based on models that are updated by real-life data. Thus, the DT model can be adapted and refined during the whole lifecycle of an entity, resulting in a large amount of data that can be processed through advanced analytics (Qi and Tao 2018). By coupling the DT with the real entity, it is possible to forecast, evaluate or influence it (Kamath et al. 2020). In the particular case of AGVs, driving data can be passed on to a DT in order to analyze, predict and optimize logistics processes and subsequent handling processes, but also the products and resources themselves (Korth et al. 2018). Another research focus in the area of AGVs is the development of DTs to virtually analyze the behavior of AGVs and identify potential problems in the actual use case, which can lead to cost reduction when deploying these vehicles in the manufacturing site (Martínez-Gutiérrez et al. 2021; Kousi et al. 2019). DTs are also used in the development of AGVs to save costs and time, since the DT allows virtual tests and thus fewer real prototypes are needed (Braun et al. 2021). A DT can detect weaknesses and identify improvement potentials in the guidance control logic (Gyulai et al. 2020). The DT of logistics, which is currently the subject of much discussion in the scientific community, is increasingly used, as in this paper, to support human production planners in decision making since the DT enables the visualization of complex processes and facilitates their analysis. This, however, requires a holistic approach to model the complete environment including the interactions of the components.

In this paper, the systematic development of a digital twin for a fleet of AGVs is presented. It includes a behavioral model of the AGV derived from data-driven analysis. In addition, the fleet management system is also represented by a virtual entity replicating its predominant functionalities like vehicle dispatching and travel order processing. Due to the achieved realistic representation of the guidance control system, the driving behavior and the energy management of the vehicles in their environment, this can be considered a DT of the overall AGV system (AGVS). The DT of the AGVS is then integrated in a simulation model to optimize material flow based on a use case scenario of a real life production plant. Using the DT, the minimum number of vehicles required to achieve the desired throughput could be determined and different layouts of the path network could be evaluated. Thus, the data-driven DT with its more accurate representation of the behavior of the real AGVS leads to cost reduction and efficiency gains.

2 USE CASE

The use case considered in this paper is the production site of a French automotive supplier for the preassembly of ultrasonic parking sensors. The hybrid flow shop preassembly consists of four production steps the material flow of which should be automated using AGVs. For each step, two production islands of the same type are available for parallel production and to achieve the nominal throughput target. Raw materials and semi-finished products for the intermediate production steps are stored on trays, which in turn are transported on trolleys by AGVs as depicted in Figure 1. These trolleys are available for pickup in the warehouse. The AGV loads or unloads the trolleys in designated bays of the respective production systems. Forklift units depalletize the trolleys and feed the material to the processing island. After processing, the forklift unit removes the material and pallets it on the already delivered empties. Based on the results of a market research, the comparatively compact AGV system of Bosch Rexroth, the so-called ActiveShuttle, is considered for the automated material transport of trolleys. It comprises a fleet management software that acts as a guidance control system for the vehicles to assign und plan transport orders generated by the order management and production planning system.

3 DEVELOPING A DIGITAL TWIN OF THE AUTOMATED GUIDED VEHICLE SYSTEM

The AGVS consists of a fleet management system and a fleet of individual AGVs. The main functionalities of the fleet management system considered for the Digital Twin model are the guidance control system

Figure 1: Use case scenario as Digital Twin simulation model (left) and real shopfloor (right).

and the path network designer. It comprises transport order management, vehicle selection and travel order processing. The driving behavior of AGVs is influenced by a vehicle control system that determines driving behavior, monitors energy consumption and implements safety zones during operations using laser scanners. As to the path network designer, the ActiveShuttle fleet management system offers five different types of waypoints. At least one *charging_station* with an *entrance_to_charging_station* has to be assigned when deploying the AGVS. Moreover, to reach production islands, a *target_point* and a corresponding *entrance_to_target_point* has to be introduced. To connect these essential waypoints, waypoints of the type *connection_point* can be added where necessary.

To set up the digital twin model of the AGVS, the simulation suite Plant Simulation is used. A data

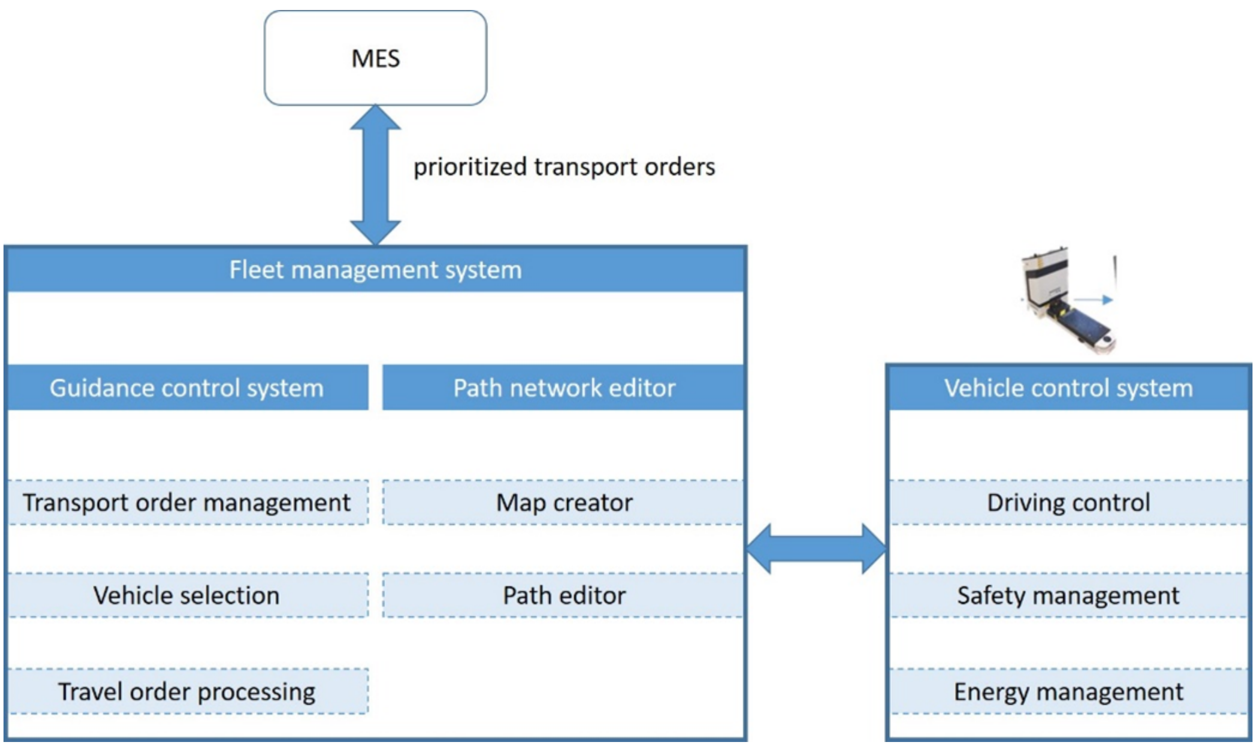

Figure 2: Tasks and functions of the AGVS.

driven approach is pursued to create a realistic model of the AGVS. The DT should accurately replicate the driving behavior of individual vehicles, the guidance control functionalities of the fleet management system and the interaction with the manufacturing execution system (MES) as depicted in Figure 2.

3.1 Analysis of Real-Time Vehicle Data

For this purpose, real-time vehicle data was acquired, visualized and analyzed to model a virtual vehicle control system. A Web Socket interface was used to obtain real-time AGVS data specified in JSON format which was further processed and visualized by a Python based analysis tool. In this way, the current position, rotation, speed, state of charge and state of the lifting platform of each AGV combined with a timestamp were collected. A total of 872.367 snapshots of driving behavior and energy states were stored. From this data, mathematical models could be set up for the range as well as the charging behavior of the AGV. As depicted in Figure 3 (right) for charging, the battery state of charge *SOC* as percentage of the total capacity of 17Ah for the ActiveShuttle can be approximated as a linear function

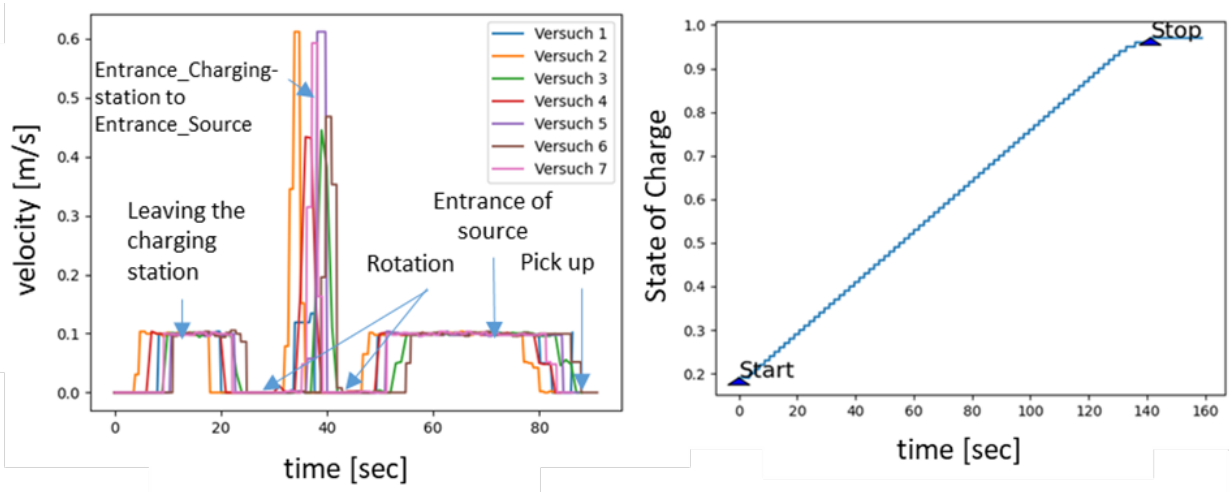

Figure 3: Visualization of real-time vehicle data: Speed profiles for various route sections (left), state of charge (right).

$$SOC(t) = C \cdot t + SOC(t_0)$$

with the constant C-rate C determined as $0.0055\,\frac{1}{s}$ for charging and $-0.00050\,\frac{1}{s}$ for discharging during operation. Driving characteristics such as maximum speed are adjusted by the vehicle control system depending on the route sections. Figure 3 (left) shows that at the entrance of a source or sink, the vehicle speed is reduced to $0.1\,\frac{m}{s}$ while higher speeds up to $0.6\,\frac{m}{s}$ were reached between those waypoints. To improve accuracy, transport orders were repeated seven times and the interpolated position data were compared with each other. The recorded lateral and horizontal deviations for identical routes were 0.025 m in x-direction and 0.02 m in y-direction, respectively. The identified driving parameters are given in Table 1.

Table 1: Parameters of AGV driving behavior.

Parameter	**Value [Unit]**
mean acceleration	$0.289\,\frac{m}{s^2}$
mean deceleration	$-0.564\,\frac{m}{s^2}$
mean speed of rotation	$-19.5\,\frac{rad}{s}$

3.2 Modeling the Vehicle Control System

As a result of this analysis, the driving behavior and energy management of the ActiveShuttle were modeled. Hence, the standard module "Transporter" of the simulation suite Plant Simulation was modified to incorporate the identified AGV behavior. Since the speed, direction of travel and the state of the lifting platform are dependent on the route section they could not be specified as standard parameters in the module. From the performance analysis, five state classes for the route sections were determined in which the parameter values of the driving behavior are specified, see Table 2. Each class contains the following parameters:

- v: speed of the vehicle, $0.1\,\frac{\text{m}}{\text{s}} \leq v \leq 1\,\frac{\text{m}}{\text{s}}$
- DOT: direction of travel, DOT $\in \{\text{Forward,Backward}\}$,
- LP: state of the lifting platform, DOT $\in \{0,1\}$ where 0 represents the lowered base and 1 the raised transport position of the platform.

The class specification was stored as an array in Plant Simulation. All waypoints of the generated path network were stored as well. Within the developed guidance control system, a method then parses the waypoints of each transport order (c. f. Section 4). It queries which type two successive waypoints have using the attribute "*Waypoint_Type*" assigned by the waypoint generator. The driving parameters are then set according to the associated class of Table 2. Additionally, the trolley platform is raised up when the AGV arrives at a source *target_point* in lowered base position and lowered down when it arrives at a destination *target_point* in raised transport position.
Finally, the safety management was implemented based on safety zone control. A collision detection mechanism monitors the hazardous zone in the direction of travel and reduces the speed up to a safety rated stop in front of obstacles.

Table 2: Class specification of route sections.

case	description	occurrences	parameters
1	slow maneuvering entrance to source	(1) *entrance_to_charging_station* to *charging_station* (2) *entrance_to_target_point* to *target_point (source)*	$v \leq 0.1\,\frac{\text{m}}{\text{s}}$ DOT = {Forward} LP = 0
2	slow maneuvering entrance to destination	(1) *entrance_to_target_point* to *target_point (destination)*	$v \leq 0.1\,\frac{\text{m}}{\text{s}}$ DOT = {Backward} LP = 1
3	slow maneuvering exit source	(1) *entrance_to_target_point* to *target_point (source)*	$v \leq 0.1\,\frac{\text{m}}{\text{s}}$ DOT = {Forward} LP = 1
4	slow maneuvering exit destination	(1) *charging_station* to *entrance_to_charging_station* (2) *target_point* to *entrance_to_target_point (destination)*	$v \leq 0.1\,\frac{\text{m}}{\text{s}}$ DOT = {Forward} LP = 0
5	regular maneuvering	(1) *entrance_to_target_point* to *entrance_to_target_point* (2) *entrance_to_target_point* to *connection_point* (3) *entrance_to_charging_point* to *entrance_to_target_point* (4) *entrance_to_charging_point* to *connection_point* (5) *connection_point* to *entrance_to_target_point* (6) *connection_point* to *entrance_to_charging_point* (7) *connection_point* to *connection_point*	$v \leq 1\,\frac{\text{m}}{\text{s}}$ DOT = {Forward} LP = 1

3.3 Properties of the Virtual Guidance Control System

The guidance control system models the behavior of the ActiveShuttle fleet management system. It consists of the transport order management, the vehicle selection and the travel order processing.

- Transport order management: After a transport order of the MES has reached the fleet management system, the order is first checked for feasibility, i. e. whether the source and sink *target_point* exist in the corresponding simulation model. For each combination in the network, the set of shortest routes and travel times are computed based on Dijkstra's algorithm (Cormen et al. 2009).

- Vehicle Selection: Each feasible order is assigned to the AGV that is available and has the shortest travel time to the source *target_point*.
- Travel Order processing: The transport order is then divided into two partial orders: one order from the current location of the selected AGV to the source *target_point* and one order from the source *target_point* to the sink *target_point*. For the first partial order, the route is split into individual sections between waypoints. For these individual sections, it is checked whether the section is unoccupied at the required time. If so the section is reserved for the AGV and thus becomes occupied for other AGVs. If this is not the case, it is checked whether the AGV can wait at the previous waypoint or travel the previous section more slowly. If no free time slot can be found for the corresponding section, the order is rescheduled in an attempt to find another route. Once a suitable route has been found, the AGV successively travels each individual section. The travel behavior for the section between waypoints is adjusted according to the class specification of Table 2. If no further trips are scheduled or the AGV has reached the reserve level of the battery, a travel request to the charging station is generated mimicking the real behavior of the AGV.

4 PRODUCTION AND MATERIAL FLOW PLANNING

The DT model of the AGVS can be used in various production scenarios. The general process to set up a complete simulation model is illustrated in the following for the use case of Section 2.

4.1 Instantiation of Production Scenarios Using a Parametric Model Generator

For the described use case, the Hybrid Flow Shop production scenario with eight production islands is instantiated in the simulation software Plant Simulation using a parametric model generator (Lichtenstern et al. 2021). It processes layout and machine data of planned or already existing factory layouts thus importing the dimensions and positions of the production islands as well as process parameters like cycle and setup times. The production islands are color-coded for each production step, see Figure 4.

4.2 Generation of the AGV Path Network

For the instantiated production layout, a path network connecting the individual production islands has to be created. Different topologies such as grid structures, spider web, or star formations are possible. These topologies allow the AGV to travel different routes and can be optimized to reduce delivery times, distances or energy usage of the AGVs. In this work, an automatic path generator was implemented in Plant Simulation that can create star or spider web topologies for the given hybrid flow shop use case. To implement a star formation for the path network, a central connection point is defined as midpoint of the positions of the production islands. Waypoints for all bays and loading stations are automatically inserted into the table of the path generator. More precisely, for each waypoint the corresponding waypoint type is assigned and a connection with the central waypoint is created in the route table. Moreover, for each waypoint, all possible destination points are defined where AGVs can load or unload trolleys. It is also defined whether the journey to the waypoint is a dead end or not. This becomes relevant later for the routing control as for dead ends this route section has to be reserved in both directions. The generated path network for the star formation is depicted in Figure 5. The spider web topology expands the star layout by adding additional connections between nearest neighbors.

4.3 Interfaces to Enterprise IT Architecture

For the use case of the hybrid flow shop preassembly, an SQL interface to the manufacturing execution system (MES) is used. The MES contains information about production orders as well as available stock

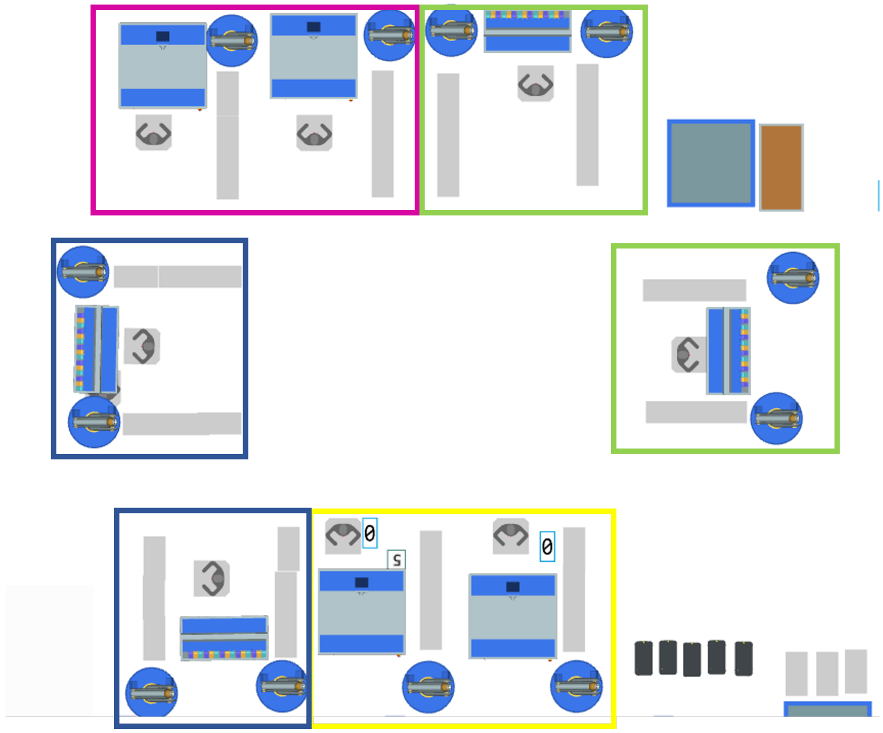

Figure 4: Generated hybrid flow shop simulation model.

from the warehouse management. Among other things, the MES stores transport orders in an SQL database, which are then to be processed in the simulation model. The simulation model queries the transport orders via an ODBC interface. It also provides feedback of the processed transport orders via this interface. A more detailed explanation of the planning and control functionalities of the MES as well as its integration can be found in (Lichtenstern et al. 2021). The digital twin model of the AGVS described in Section 3 thus can be included in the simulation model and executes the transport orders as shown in Figure 6. Different interfaces for other enterprise IT architectures are possible as well.

5 RESULTS

In the following, experimental results of the hybrid flow shop preassembly with the integrated DT of the AGVS are presented. For comparison, two transport orders of 144 sensors each are simulated, which represents the standard trolley size. First, the Optimum Theoretical Target Time (OTT) of 01:16:46 h was calculated for a production job of 144 sensors. The OTT only takes into account the processing times for each sensor during each production step as well as palletizing and depalletizing, but discards any transport times. The information about the processing times was taken from the use case description and transferred to the simulation model as part of the parametric model generator. The OTT can never be reached in practice as the transport between the production islands, the warehouse and the final assembly is neglected. The closer the simulated transport time is to the OTT, the less time is needed for intralogistics.

5.1 Recommendations for the required number of AGV

To find the minimum number of AGVs, simulations for fleets between one and six AGVs were carried out. As shown in Figure 7, five AGVs yield the slowest throughput time of 01:46:00 h. If more than five AGVs are available, these additional vehicles are not commissioned so that the throughput time remains constant. However, a profitability analysis has to evaluate whether fewer AGVs might cause an overall

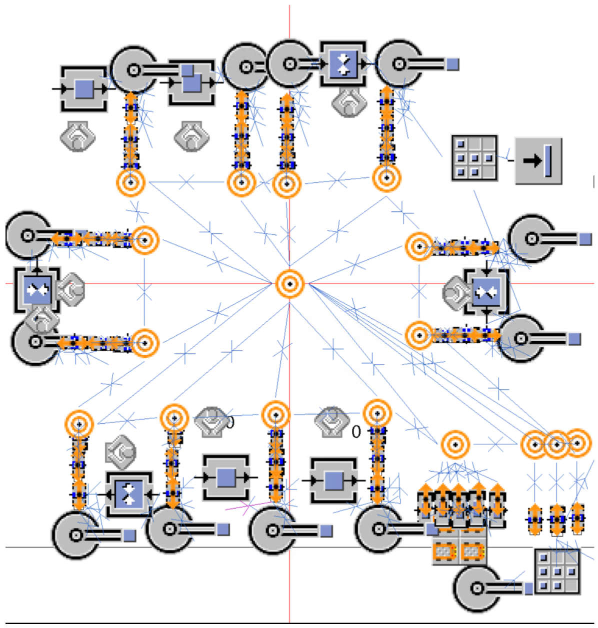

Figure 5: Routes generated by path network generator.

benefit since the marginally longer throughput time for four and three AGVs of additional 8 seconds and 4:34 minutes, respectively, may be compensated by lower invest and operational costs.

5.2 Experiments with Path Networks

In addition, different path networks were investigated using the automated path network generator. For the considered use case, a spider web and star topology were compared. The different network structures are shown in Figur 8. In the experiment, the spider web topology improved throughput time by 6:23 minutes compared to the star topology. This can be attributed to its denser path structure that reduces blockages or deadlocks but occupies more space within production facilities. Other topologies e.g. for already existing shop floor layouts can be analyzed using the same approach.

6 CONCLUSION

In this paper, a data-driven digital twin for AGVS was presented. For this purpose, real-time driving data of an AGV was acquired and analyzed. Both the driving behavior, energy management and safety functions of the specific AGV used in this work could be classified as reproducible after the performance analysis of real-time data. The resulting mathematical model for the vehicle behavior was incorporated in the "Transporter" module of the simulation suite Plant Simulation. Similarly, the guidance control system with its core functionalities was implemented to obtain a full DT of the AGVS.

The DT of the AGVS was then tested in a use case scenario to automate material flow in a hybrid flow shop production. To facilitate the use of simulation models, a parametric layout and a path network generator were programmed. The realistic Digital Twin can be used to support the integration of the AGVS in the real production environment by optimizing the number of required vehicles as well as by choosing the suitable network topology.

As future research, the bidirectional connection between the real AGVS and its DT shall be used to influence the real entity. For example, the experiments performed in simulation could be used to automatically pre-set real-world speeds and add new waypoints and routes as needed. This work also demonstrated how the linking the individual Digital Twins – virtual representations of the AGVS and the

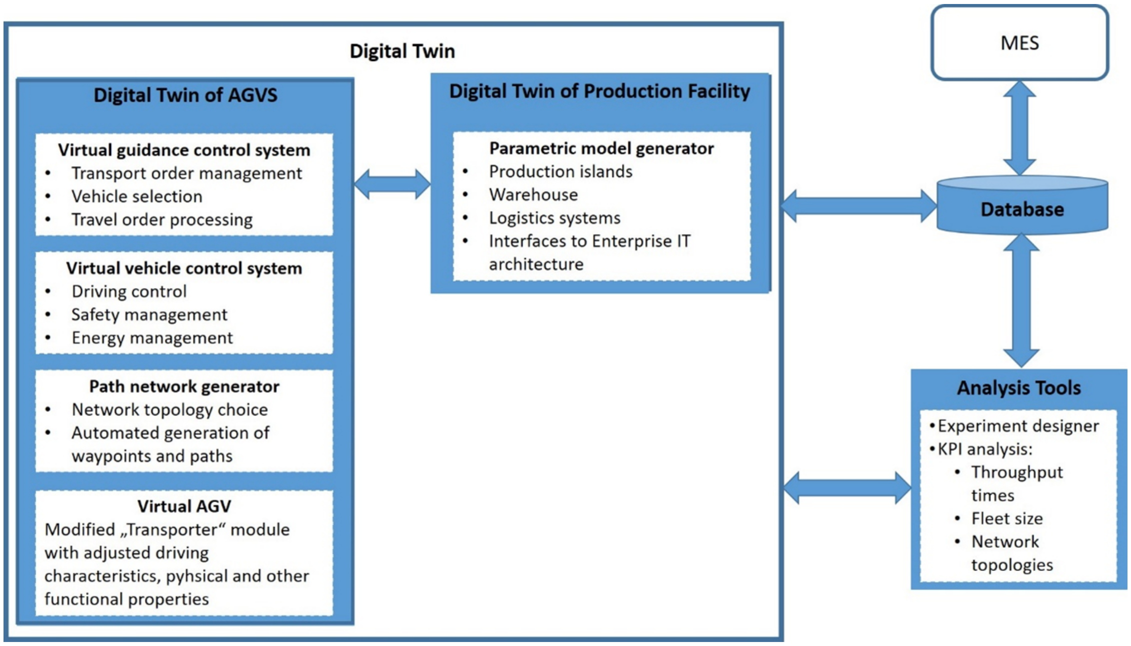

Figure 6: Interfaces of the DT with Enterprise IT architecture.

production islands – can be combined to create a holistic Digital Twin of the whole production site. A dynamic and real-time image of the shop floor can provide detailed information of manufacturing and logistic processes at any time. In the future, the Digital Twin could thus visualize, influence, predict and control all elements and processes in production. Using this data would also improve the performance of production planning. Due to the interconnection with higher levels of enterprise IT systems, scheduling algorithms on the MES or ERP level could become more performant through the use and feedback of the Digital Twin. Predicting the arrival times of AGVs more accurately, the MES could, for example, control subsequent processes in a timely manner or reschedule accordingly in the event of error messages.

7 DISCLAIMER

No approval or endorsement of any commercial product is intended or implied. Certain commercial software systems or AGV-systems are identified in this paper to facilitate understanding. Such identification does not imply that these software systems are necessarily the best available for the purpose.

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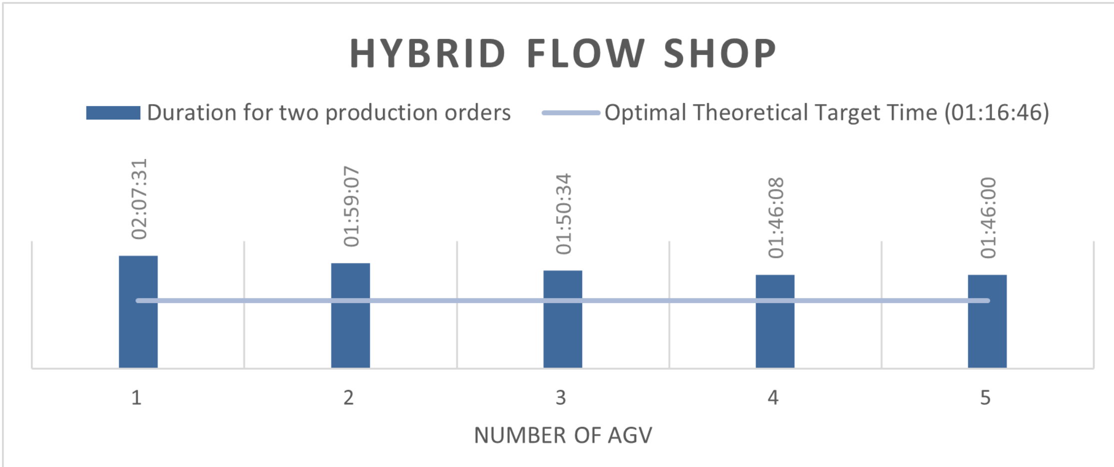

Figure 7: Throughput times with different numbers of AGVs used.

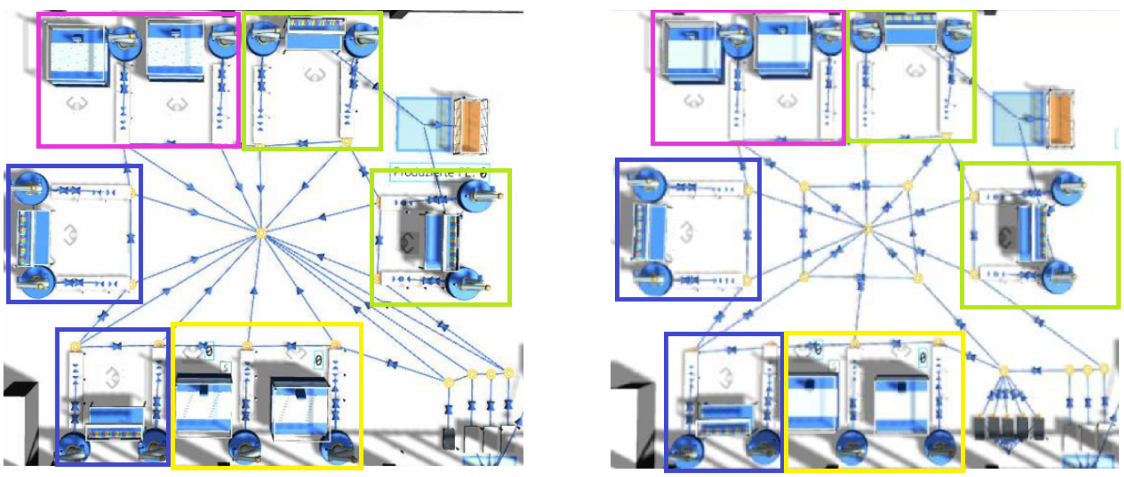

Figure 8: Star (left) and spider web network topologies (right) for the hybrid flow shop preassembly.

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