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Digital Twin and Simulation Analyses for Process Optimization of an Automated Guided Vehicle System

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Abstract: Development in industrial companies aims to digitize processes, ensure traceability and advance automation. Systems with automated guided vehicles (AGVs) can help meet these objectives. A core element of these systems is the higher-level system controller. When an AGV system is operated, some dynamic aspects appear. It is then to identify, that the previous specified rules for scheduling and routing of vehicles are not always proper and practical, which may result in waiting time of AGVs. That means the static performance requirements and the specifications based on them often lead to suboptimal results. A methodical problem-solving approach is to develop a digital twin as a reflection of reality and to carry out strategy analyses using simulation. For this purpose, a digital twin of the concerned AGV system with five vehicles and its technological environment is created using software of plant simulation. Various simulation scenarios are developed to simulate material flows by using different routing and scheduling rules and strategies. Drawing from the insights gained through the digital twin and simulation analyses, this study identifies novel scheduling and routing rules for the AGV system. These rules improve the overall efficiency and effectiveness of the system operations by easing traffic congestion, reducing transit time, and minimizing production downtime.

Keywords: Automated Guided Vehicle (AGV); digital twin; material flow optimization; routing and scheduling; simulation analysis

1 INTRODUCTION

European manufacturing industry is currently facing a number of challenges. These include global competition, high cost pressure, comprehensive sustainability requirements, holistic digitalization and adaptable production processes. The latter are particularly important because the number of product variants is increasing and the product life cycle is becoming ever shorter. In this context, the performance requirements for networked logistics are also increasing.

Against this background, Automated Guided Vehicles (AGVs) and their systems are of great importance. AGVs operate without a driver, are battery-operated, follow a specified driving course and receive their vehicle orders from a higher-level control system [1]. The control system transforms the transport orders into vehicle orders according to specified strategies.

Navigation systems are used to record the driving course and follow it. They are guideline-bound or guideline-free. A guideline-free variant is laser navigation, which enables the driving course to be changed using software. Inductively active and passive as well as optical navigation require physical guidelines that are fixed in or on the ground. Changes to the driving course, for example to generate new route elements, involve mechanical work. The case-specific selection of navigation technology is essentially determined by the conditions of the operation field.

AGV technology and its key components have developed rapidly with the high-tech Industry 4.0 strategy [2]. The result is a robust technology with high performance and availability of the vehicles and the system. In the planning phase, the driving course layout and the strategies must be developed. On this basis, the required number of vehicles must be determined, which is unchangeably interdependent with the driving course and the strategies.

If the developed and defined strategies turn out to be suboptimal, the consequences may be a too high or too low number of vehicles. In the worst-case scenario, this can lead to an impairment of the supply and disposal of production machines and production performance. The strategies of the AGV system concern in detail as follows:

- the right of way rules,
- the prioritization of transport orders,
- the exclusion of deadlocks,
- awarding transport orders to the most suitable vehicle,
- the concept for intermediate charging of the batteries,
- the implementation of transport orders into vehicle orders,
- minimizing the frequency and times of blocking and
- routing specifications.

Since the costs of the vehicles usually represent a significant proportion of the offer price, an excessive number of vehicles affects the competitive situation of the provider on the one hand and the results of the requester's profitability calculations on the other hand. The latter can lead to profoundly bad business decisions.

Conversely, if the number of vehicles is too low, the responsible company, i.e. the planner or the AGV manufacturer, can be blamed for it and must pay for the misjudgments.

An essential prerequisite for correct planning results is a complete and clearly formulated specifications that document the requester's requirements. A relevant part of this is the complete and detailed service description. In the case of AGV systems, the service description must include, among other things, information on sources, sinks, their positioning in the layout, routes and transport orders with reference to the peak hour and the shift model.

Due to unforeseeable production changes, it may well be necessary for an AGV system that complies with the specifications to require additional vehicles after acceptance and a longer period of operation and that the strategies must be adapted or expanded in accordance with the new production requirements.

The relevance of the aforementioned topic areas has been shown above in the context of the objectives of companies. Since AGV systems are mostly planned and implemented in a tailor-made manner, simple and generally valid findings are not sufficient in many cases. In addition, this is particularly because AGV systems exhibit dynamic behavior. The dynamics and networking complexity increase as the number of vehicles increases.

For simple systems with low complexity, algorithmic determination of vehicle number using material flow matrices can be sufficient. This method of determining the number of vehicles will not be discussed further here. Improving the technological properties of AGVs, for example, increasing acceleration or driving speed, is also not a topic of this paper.

Rather, the focus is on the well-founded selection of strategies for AGVs as a control variable within the overall system. Findings are highlighted that are relevant for strategy selection. Since each AGV system represents an individual, these can be classified as guidelines for strategy selection.

2 CHALLENGES OF THE AGV SYSTEM CONTROL

In production, networking transport is a secondary function and its costs must be minimized. Nevertheless, its performance and quality influence the efficiency of production. In this context, it is crucial to which AGV the transport order executed before a certain arrival time is assigned and in which order the pending transport orders are carried out. In order for the scheduling task to be solvable, the transport capacity of all vehicles must be greater than the transport requirements to be handled.

The travel time from the starting point of the ordered AGV to the source station and the time required to carry out the vehicle order depend largely on the routing, i.e. on the specified route elements to be used, and the blocking situation on these routes.

Both the scheduling and routing tasks are taken over by the higher-level control system. In order to be able to fulfill these tasks, it is necessary that the master control receives all the necessary process data from the operational level in real time. This includes data about vehicle malfunctions or vehicle stops that have occurred, blockages on the route and malfunctions at the source or sink stations.

Discrete data transfer points that lead to "dark phases" for the control system and also for the vehicles must be avoided. Communication between the control system, the vehicles and the stations must be implemented permanently and without interruption in real time in order to ensure that the transport processes run in an optimized manner.

Algorithms are almost exclusively used to solve scheduling and routing tasks, which in turn access the data from the specifications in the planning phase and access the process data in the operational phase. The results determined are established rules that are transferred to the control system and are used in real plant operation.

A number of scientific papers deal with the planning and operational optimization of AGV systems based on heuristics and algorithms. Specifically, these are the following approaches:

- Multi-objective path planning for Automated Guided Vehicles (AGVs) using the improved Cuckoo algorithm [3],
- Algorithms for scheduling and route finding of AGVs [4],
- Use of the Invasive Weed Optimization algorithm to solve the problem of scheduling multi-AGVs in a matrix manufacturing workshop [5],
- Development of a novel multi-task chain scheduling algorithm based on capacity prediction [6],
- Algorithms for the problems of AGV scheduling in a matrix manufacturing environment [7],
- Path planning in dynamic environments with a combination of a Multi-Objective Particle Swarm Optimization (PSO) algorithm and the Dynamic Window approach [8],
- energy-efficient path planning with individual loading in a manufacturing workshop [9],
- Decision support for scheduling through a digital twin, which is a virtual representation of the real manufacturing system [10],
- Route planning based on quick response code technology (QR codes) [11] and
- Algorithms for conflict-free handling of route planning and control of AGVs [12].

The quality of the established rules is identified in real operation under real conditions using key figures. Frequently used key figures are the cumulative route, adherence to deadlines, waiting times at intersections, blocking times, the number of empty journeys, the cumulative empty journey time, the frequency of production stoppages due to delayed supply or disposal transport, etc.

In order to fully meet these challenges, this paper chooses a problem-solving approach in which the planning result or the physical system and its internal logic are depicted as a model in order to then carry out strategy analyzes using simulation. The basis is a real AGV system with five vehicles and a complex technological environment with paternosters.

3 LITERATURE REVIEW

This paper focuses on the planning and operational optimization of AGV Systems using simulation. Basic works are selected during the literature search.

3.1 AGV Systems

As early as 2007, Schulze and Zhao [13] discussed both advantages and challenges of implementing AGV systems as well as predicted the worldwide growing importance of AGVs for optimizing logistics and production processes were discussed. Our AGV statistics "Worldwide commissioning of AGV systems from European AGV manufacturers" up to 2023 also shows this trend.

An analysis of the implementation of AGVs and their effects on the efficiency and flexibility of logistical processes uses case studies to show how AGVs can contribute to optimizing material transport and warehousing in practical use [14]. In this context, the research results on an intelligent maintenance architecture for AGVs should be mentioned [15]. Implementing predictive maintenance and condition monitoring aim to minimize AGV failures and maximize uptime. A concept for integrating sensors and data analysis is being developed.

The study of strategies for efficient route planning and control of AGVs in a square topology is the focus of a paper by Matopolski [16]. By using algorithms, optimal solutions for AGV control are developed. The relevance of targeted planning and control of AGVs for sustainable and efficient operations in industrial environments is highlighted.

A study by Fragapane et al. [17] examines the potential for increasing flexibility and productivity in production networks that can be achieved through the use of AGVs and intelligent intralogistics. It has been proven that the use of technologies such as artificial intelligence and machine learning can optimize workflows.

The requirements of small and medium-sized enterprises (SMC) for AGV systems are specific and take into account their scarcity of resources [18]. It becomes clear that the implementation of AGVs poses particular challenges for SMEs. The focus is on aspects such as costs, flexibility and user-friendliness. The authors consider the importance of a tailor-made and robust solution as well as upstream system planning for the successful use of AGVs to be fundamental.

Schulze et al. [19] present the basics and principles of AGVs as well as their use in various application areas. Aspects such as navigation, control and integration into existing factories are examined in detail. The article provides an overview of the state of the art of AGV systems and emphasizes their potential for optimizing logistics and operational processes.

The current advances in the control, navigation, route planning and coordination of AGVs are discussed in the article by De Ryck et al. with the focus on new approaches for control algorithms [20].

Fragapane et al. [21] have compiled a comprehensive literature review for the planning and control of autonomous mobile robots in intralogistics and identified existing gaps and challenges. These results inform a research agenda that focuses on navigation, route planning, task assignment and coordination of AGVs.

The development of a simulation platform for the application of mobile robotics is carried out by Hegedić et al. [22]. This platform makes it possible to test different scenarios and evaluate the performance of mobile robots in a virtual environment. The work represents a contribution to supporting the development and implementation of AGVs and identifying potential problems at an early stage, i.e. before implementation.

3.2 Simulation and Digital Twins

Agalianos et al. [23] examine the areas of application of discrete event simulations and digital twins in logistics in their work. They outline the possible uses of these technologies and identify the challenges that can arise from the integration of simulation modules and digital twins.

The application of simulation technologies in logistics and the associated challenges of modeling logistics processes are certainly challenging. This is also underlined by the results of a survey on automatic model creation for material flow simulations in discrete manufacturing. Reinhardt et al. [24] present in their work various approaches and technologies for the automatic generation of simulation models and discuss their advantages and disadvantages. It is shown, which measures can be used to reduce the modeling effort and improve the efficiency of material flow simulations.

Chen, J. C. et al. [25] present a method based on meta-models to optimize the performance of AGV systems depending on the charging concept of the vehicle batteries. The authors analyze and develop a simulation model that shows the performance of the AGVs under different charging conditions and thus also influences the vehicle demand. The time for model creation is significantly shortened by the developed meta-models.

The simulation of the supply of workplaces in a digital factory environment by AGVs is the focus of a study by Neradilova and Fedorko [26]. By simulating various scenarios, potential bottlenecks and deadlocks could be identified in a planned system and optimization measures could be implemented.

The work of López et al. [27] presents a developed framework to enable efficient simulation and control of AGV-based transport systems in different environments. The results help to make the planning and implementation of AGV Systems more efficient.

The analysis of performance indicators for automated driverless vehicles is the focus of research that investigates different scenarios using Design of Experiment methods [28]. The aim is to identify factors that are significant for the performance of the AGV system under consideration. Using simulation, these factors are tested under different conditions.

In a study, Fu et al. [29] with the approach of combining discrete event simulation and the response surface methodology, i.e. a statistical method. The aim is to identify the complex dependencies on various variables and understand how these affect the performance of the AGV system or the number of AGVs required.

Vavrik et al. [30] present the application of computer simulation as a tool to optimize logistics using automated driverless vehicles. Their approach focuses on improving the performance and efficiency of logistics processes through the use of AGVs. The authors demonstrate how computer simulations can be used to analyze different scenarios and determine the optimal configuration of AGVs in logistical environments.

The development of digital twins for automated vehicles and their fleet management is of great importance. In the work of van der Valk et al. [31] and Matei et al. [32] the benefits and challenges associated with the implementation of digital twins are discussed. It shows how this technology can help improve the efficiency and transparency of managing fleets of automated vehicles. The results are based on a case study on the implementation of a digital twin for fleet management. Korth et al. [33].present the development of a simulation-ready digital twin for the real-time management of logistics systems. The approach integrates advanced data modeling techniques and real-time data processing to create a digital twin that reflects the actual operating conditions of a logistics system. By using real-time data, the digital twin is continually updated and its performance is improved. Gartner [34] classifies the development of Digital Twins as hype, the goals of which will probably only be achieved in five to ten years.

4 THE CONCERNED AGV SYSTEM

The concerned AGV System in this paper is a system being operated in a metal processing company. There are four production lines, each of which has a supply requirement for two loading units of products every hour. In dynamic buffers, the preliminary products on gondolas are treated as loading units. Before further processing, the preliminary products are subjected to pretreatment and then returned to a buffer. The pretreatment gives the material the properties required for successful further processing on the production lines. The buffers are equipped with paternosters and each paternoster can hold 15 gondolas as loading units.

The logistical networking between pre-production, the buffers, the pre-treatment and the production lines is realized by AGVs. Fig. 1 shows the layout of the networking, including buffers I to IV (green), the four production lines (framed in orange), the waiting station for empty vehicles (framed in yellow), the pretreatment (framed in blue) and the driving course of the vehicles (gray). In the system, the AGVs can communicate in real time with the higher-level control system. When the vehicles have completed their vehicle order and are not assigned another transport order, they always drive to the waiting station to receive another transport order.

Every production line needs 30 minutes to process a completely filled loading unit. Each line is equipped with a transfer station for handling the products. Either buffer I or buffer II has five sections and each section is equipped with four paternosters, i.e. in total each buffer has a capacity of 20 paternosters with a total of 300 places. The minimum time a loading unit stays in a buffer corresponds to the process time. For either buffer it is 24 hours. Buffer III includes three paternosters with a capacity of 45 loading units. The process time is 4 hours. Buffer IV contains twelve paternosters and therefore offers a buffer capacity of 180 parking spaces. The loading units stored here have already undergone pretreatment and are only transported to the production lines as required. The load is picked up and delivered by the AGVs directly in conjunction with the gondolas of the paternoster. The gondolas must be in the transfer position for load transfer, which requires higher-level coordination between the paternoster control and the higher-level master control of the AGVs.

There are five automated guided vehicles in the system, all of which are constructed the same and have identical attributes. The vehicle length is 1.8 m, the vehicle width is 0.9 m and the maximum driving speed is 1.0 m/s. The maximum driving speed applies to both load and empty travel as well as when cornering. A minimum distance of 1.0 m must be maintained between two vehicles driving one behind the other. The capacity per vehicle is one loading unit. The load transfer time, i.e. the time for load acceptance and load transfer, is 40 seconds each.

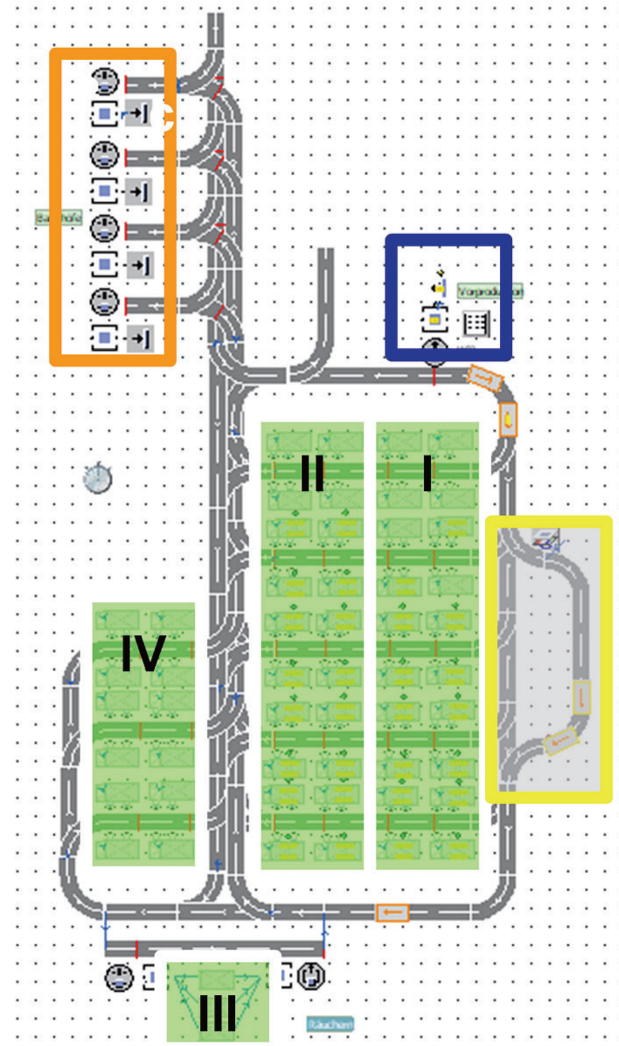

Figure 1 Overview of the System

The vehicle's accumulators are charged by inductive, i.e. contactless, energy transfer when stationary and while driving. Failure profiles of the technological units of the system, return transport due to quality defects in the products and intentional decommissioning of vehicles, e.g. due to maintenance work, are not taken into account.

5 SIMULATION AS A SOLUTION GENERATOR

In order to analyze the effectiveness of scheduling rules for the running AGV system, the best solution is to create a digital twin of the system in the form of a simulation model. The static and dynamic factors of the whole system including production lines, buffers, vehicles etc. should be considered in the model. That means, the interactions of between AGVs and all influencing neighboring units are modeled.

Based on the model, the following three different scheduling rules and their influences on the number of vehicles and the connected production lines and in particular on the upstream buffers can be analyzed.

- Rule 1: Shortest empty route for the AGVs
  The AGVs' empty journeys are minimized. After the final execution of a vehicle order, the transport order is selected for the vehicle in question that results in the shortest empty journey.
- Rule 2: Longest queue of transport orders
  The location with the longest queue of transport orders is given priority when converted into vehicle orders. For the affected vehicles, this means that they are assigned a transport order regardless of the empty route. At the same time, the formed queue shows, to what extent the maximum performance of the AGV system is sufficient.
- Rule 3: Longest waiting time for transport orders for supply
  The supply of the production lines is crucial for the efficiency of the system. If there are orders for supplying production, the transport order that has the longest waiting time is selected from this order pool. This is then assigned to the vehicle that was the first to complete its vehicle order and is therefore available for dispatch.

Since this is a dynamic system with events whose time of occurrence is not deterministic but stochastic, an event-oriented simulator is used. In general, the events and the time at which they occurred are recorded, as is the condition of the object in question. The simulation tool "Product Lifecycle Management Software Tecnomatix Plant Simulation" was used for the simulation experiments, which supports the modeling, simulation, visualization and analysis of operational processes. Plant Simulation is ideal for optimizing the resource utilization of production and the material flow of complex, not easy to analyze systems and production lines.

The digital modeling of the system under consideration is supported by predefined blocks that are stored in libraries in Plant Simulation. For example, Automated Guided Vehicles can be created in the "AGVPool". "Single Station" is used to simulate a production line. Each production line is assigned two load transfer stations. One only realizes the input and a second only the output. "Parallel Station" together and "Single Station" are used simultaneously to model carousel. Many sensors are integrated in the model for modelling the actions and events. The rules to be analyzed are programmed with the internal programming language.

6 RESULTS

The results of the simulation experiments concern the scheduling rules and a number of improvement approaches for system operation. The effects of rules 1 to 3 compare to the results achieved in real operations. In reality, the basic rule "The transport orders are transformed into vehicle orders in the chronological order in which they were created" is followed. With regard to transport orders, a "first in – first out" policy is practiced. The length of the route of the affected vehicle is not taken into account. The transport order is assigned to the empty vehicle that has been waiting the longest without an order.

"Rule 1: Shortest empty journey for AGVs" does not contribute to reducing the number of vehicles, but rather tends to increase the need for vehicles. The cumulative travel distance is shortened, resulting in lower energy requirements. The efficiency of the production lines and the pre-treatment facilities drops slightly to 95.8 %.

Scheduling according to "Rule 2: Longest queue of transport orders" and "Rule 3: Longest waiting time for transport orders for supply" improves the efficiency of the production lines as well as that of the pre-treatment facility. At 119.6 %, the efficiency values of the production lines that were determined using Rule 3 are significantly higher than those achieved with Rule 2.

Setting up additional waiting stations significantly reduces empty journeys. In this case, one vehicle can be saved for the same production output. The paternosters represent a complex dynamic at the time when a transport order is issued to a vehicle. In reality, the transport order is assigned to a vehicle without taking the gondola position of the target paternoster into account. If the destination gondola is positioned only after the vehicle has arrived, waiting times will arise.

The simulation has shown that a ten-minute lead time for generating vehicle orders significantly shortens waiting times. Compared to the real situation in which transport orders are assigned directly to vehicles without lead time, the approach of earlier generation and allocation of vehicle orders reduces the waiting time of vehicles by more than half by 55.6 % and at the same time increases the security of supply on production lines.

In a simulation experiment, the vehicle order was only started when the travel time of the vehicle corresponded to the positioning time of the target gondola. The aim is that when loading units are delivered, the positioning of the destination gondola is completed when the delivering vehicle arrives. The same applies to the collection of loading units. This made it possible to marginalize waiting times to 18.3 %.

Taking all the measures mentioned, the simulation shows that four vehicles are sufficient for the same production output. This means that one vehicle at a time could be available as a reserve or be subjected to preventative maintenance. In all cases, the buffer capacity of the paternoster did not represent a bottleneck.

7 CONCLUSIONS

Systems with automated guided vehicles will play a central role in the modern production and logistics landscape of many companies in the future. The use of AGVs increases efficiency, optimizes material flow and reduces the need for human intervention. New technologies, including sensors and control systems, and vehicle innovations will shape the future. The autonomy of automatic vehicles has already arrived in companies.

In order to optimally plan and improve the use of AGVs, the "tool" simulation is indispensable. It allows different scenarios and configurations to be tested virtually before being implemented in the real world. Through simulation, factors such as layout, material flow and resource utilization can be optimized with the most suitable strategies. The aim is to maximize the performance and efficiency of the AGVs and to avoid over- and under-sizing.

An important part of these simulations is the integration of digital twins. This virtual representation of a physical system or product simplifies the development of simulation models. They make it easier to virtually map the behavior and performance of individual vehicles or entire fleet management. By linking real-time data with the digital twin, companies can monitor, analyze and optimize the operation of their AGVs.

In this context, artificial intelligence (AI) methods will play a crucial role in the future in connection with AGVs, simulations and digital twins. AI algorithms can help identify patterns and relationships in the data to perform predictive analysis and predict future developments. In addition, AI-assisted decision systems can be used to realign simulation models and continuously optimize the operation of AGVs.

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