MODELLING AGV OPERATION SIMULATION WITH LITHIUM BATTERIES IN MANUFACTURING

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ABSTRACT

This paper describes the development of a production simulation model with automated guided vehicle (AGV) operation to prepare relevant production data validating an approach using AGV batteries as energy storage to reduce peak loads in a manufacturing company. First, the definition of AGV and the simulation modeling approach are introduced. Then, the systematic literature review methodology is described to explore relevant existing simulation models with AGV operation. With the help of this information, a simulation model is designed and developed. The last sections include the experiments performed with the simulation model, analysis, and the following results. The results show that the developed simulation can be used to generate data to evaluate the above-described approach in production.

INTRODUCTION

Industrial manufacturing faces significant challenges due to the increasing importance of sustainability and the rise of complexity in markets. First, unlike conventional transportation systems, battery-driven AGVs produce little emissions and have high energy efficiency. Still, reducing energy consumption is essential to reach a firm's own or external greenhouse gas reduction goals and, at the same time, to benefit economically from lower energy costs and higher energy security (Roesch et al. 2019). Compared to conventional vehicles, battery-driven AGVs need more time to charge. Consequently, energy consumption and charging time can be very volatile, which has to be considered in real-life use cases to manage a possible decrease in costs and emissions (Ma et al. 2021; Pfeilsticker et al. 2019; Zhu et al. 2018). Second, the steady increase in the complexity of markets poses a challenge on manufacturing companies, and their value creation networks increasingly facing new challenges (Bauernhansl et al. 2014). The manufacturing companies are forced to respond to such events with non-automated operations, high stock levels, and significant lead times. As a result, decisions can be postponed, and remedial action can occur late. To solve these problems, simulations can forecast the planned changes in manufacturing because they acquire relevant results for practical implementations (VDI-Gesellschaft Produktion und Logistik 2014). With the new developments in the AGV field (Shihua Li et al. 2018), the relevance of using AGVs for companies is growing (Kunst 2018). To achieve the goal of optimal production despite the challenges of volatile power consumption and complex markets, simulation models can help companies to gather data for validating real-life use cases. This paper aims to generate realistic data for validating the approach of using AGV batteries as energy storage in production to minimize peak loads. Next, the problem statement and objective target of this paper are introduced.

PROBLEM STATEMENT AND OBJECTIVE TARGET

Manufacturing companies face a complex environment regarding current and future energy supply with their factories. The companies are charged for electricity based on two principles. One is for energy consumption and the other for peak demand. Besides the energy consumption contracts, the companies should agree with the electricity providers on contractual price models depending on the highest peak production load. The manufacturing companies experience these peak loads in their production and pay high amounts of money for generating them (Kurnik et al. 2017). Different concepts and applications of the energy storage systems such as stationary and electric vehicle (EV) batteries were studied and developed in manufacturing plants to minimalize peak loads and enhance savings for the companies.

In this paper, only the electrical energy storage devices of the AGV are considered to achieve the same goals. To validate this approach, some data such as AGV and energy consumption data is needed from a company. After contacting the different companies, one manufacturing company agreed to cooperate. The cooperated company sent the energy consumption data for one year. However, the company does not possess any

AGV. Therefore, it is planned that a simulation should generate the required AGV data. The goal is to develop a simulation model according to the company's logistics processes that simulate a production line with AGV. The simulation model should generate availability, position, state of the charge status of the AGVs, and availability of the charging stations. In summary, the scope of this paper is to develop a simulation model to generate and analyze the data on the energy consumption of AGVs.

STATE OF THE ART

In the following, first, AGVs are defined. Then, the definition of a simulation and a recommended approach to develop a simulation are introduced. Last, the systematic literature review identifies the existing AGV simulation concepts.

Automated Guided Vehicles

AGVs are in-plant, ground-based material flow systems consisting of automatically controlled vehicles whose main task is to transport the material (VDI-Gesellschaft Produktion und Logistik 2005). The most crucial flexibility criteria for material handling technology include the ability to be integrated into an existing production environment, transport a wide variety of goods, and adapt to productivity fluctuations.

AGVs offer the highest degree of flexibility among all automated material handling technologies. Other advantages of AGVs include minimal infrastructure measures, use of existing paths, and the possibility of easy replacement with another vehicle or a conventional forklift. Concerning energy flexibility, AGVs can also serve as storage units that establish resilience by creating buffers (Roesch et al. 2019). This is particularly important for enabling companies to create energy flexibility, which is the base for trading in dynamic energy markets (Pfeilsticker et al. 2019). Because of the wide range of possible applications, there are almost no restrictions on the design of the AGV (Steegmüller & Zürn 2014; Ullrich & Albrecht 2019).

Simulation Modelling

This section introduces the definition of a simulation, a recommended approach to generate a simulation, and simulation modeling methods. A simulation represents a physical system and its related processes in a model. Its goal is to obtain transferable results for practical applications (VDI-Gesellschaft Produktion und Logistik 2014). The terms system and model are related to the term simulation. The system is a collection of components and their properties, which are connected by interdependencies (Hall and Fragen 1956). A model is an abstract image of a system (Eley 2012). If computers are used for the necessary calculations in the simulation, this is called a computer simulation. For this purpose, the model must be available in a mathematical-logical form and implemented in a computer program. These computer programs are considered simulation tools (Eley 2012).

A simulation experiment is the reproduction of the behavior of a system with a model over a certain period of time (VDI-Gesellschaft Produktion und Logistik 2014). This particular period is called simulation time. On the other hand, the simulation time represents the time progressing in the existing system (Eley 2012). According to (VDI-Gesellschaft Produktion und Logistik 2014) the following approach is recommended to create a simulation:

1. formulation of problems,
2. test of simulation-worthiness,
3. formulation of targets,
4. data collection and data analysis,
5. modeling,
6. execution of simulation runs,
7. result analysis and
8. documentation.

The approach above is used to create a simulation model in this paper. The following section describes the systematic literature review to identify existing AGV simulation concepts.

RELATED WORK

The approach for finding related literature is based on the systematic approach according to (Jan Vom Brocke et al., 2009). It represents a patterned system for identifying and selecting relevant literature for the research field. (Jan Vom Brocke et al. 2009) identified five required steps for a literature review. In these steps, first, the research framework is established, second, the topic is conceptualized. Then, the literature review and literature analysis are conducted. Finally, a research agenda completes the research (Vom Brocke et al. 2009).

This literature search aims to find existing research approaches and implementations of AGV use in simulations. To conduct the literature search, search terms are created by using synonyms and closely related terms illustrated in Table 1.

Table 1: Search terms

Context Synonyms	**Scope**	**Topic Synonyms**
production	simulation	"AGV battery"
manufacturing	routing	
	modeling	

After that, Boolean operators are used to merge the search terms into a search string. Wild cards (*) are used to consider the plural of search terms and exclude forms of words in the literature search. The following search string is applied to find relevant literature in different databases.

("Production*" OR "Manufacturing*") AND ("simulation*" OR "routing*" OR "modeling*") AND ("AGV*" OR "AGV* battery*")

Five different databases are chosen to conduct the search string to find relevant papers. The databases' technical orientation and the search results' scientific relevance are considered in the selection of the databases. Figure 1 shows the selected databases and the methodology of the multi-stage filtering system of the search results.

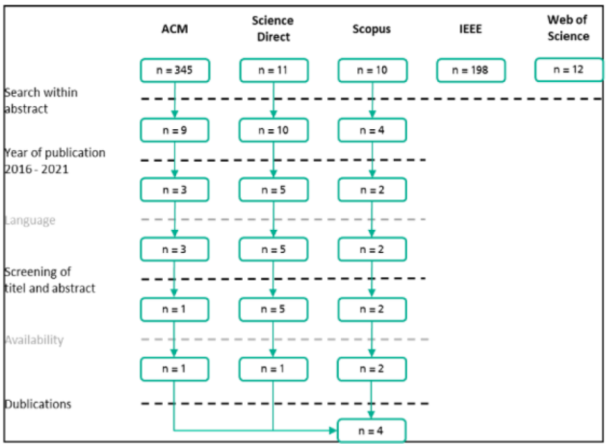

Figure 1: Results of the literature search with the multi-stage filtering system

Four relevant publications are found after conducting the literature search with the methodology of the multi-stage filtering system. In the next section, these publications are described in detail.

Existing AGV Simulation Concepts and Applications

The four different papers on AGV simulation concepts in production are introduced in this section.

The research paper by Ndiaye et al. 2016 introduces an AGV transportation system defined by a layout, several vehicles, several parking spaces, and a vehicle management policy. First, a simple formula determines the minimum required number of vehicles. Then, a discrete-event simulation model is used to evaluate different layouts and vehicle-dispatching policies. Initially, eight vehicles were required to meet the transportation demand, but with some optimizations, this number could be reduced to four vehicles. While these optimizations reduce the number of vehicles, they incur additional costs during the implementation phase. This means that savings achieved by reducing the number of vehicles are lost during the implementation phase in terms of software. The paper focuses on reducing the number of AGVs. However, generating the AGV and charging station data is required to verify the above-described approach.

Zhan et al. 2019 describe two-stage battery-charging strategies proposed for AGVs equipped with lithium-ion batteries to improve utilization. In stage 1, two routing decisions are developed. These are the nearest charging station (NCS) and the charging station with minimum delay (MDCS). In stage 2, the duration of each operation is reduced considering the charging characteristics of the lithium-ion battery. A real case is adopted to illustrate the applicability and effectiveness of the proposed approach. These methods help to improve manufacturing at a short-term capacity to meet the market demand. This paper shows that the loading strategy of MDCS performance is better than the loading strategy of NCS, in terms of AGV utilization and overall performance. This means that improving the utilization of AGV contributes to increasing the production of the system. The charging station with minimum delay methodology idea was taken from this paper and implemented in the new simulation. Nevertheless, the work of the researchers does not solve the problem statement described in the paper.

The research of Mousavi et al. 2017 used a fuzzy hybrid genetic algorithm (GA)-particle swarm optimization (PSO) algorithm with a comparison with three other algorithms (GA, PSO, and hybrid GA-PSO). Comparing the four algorithms results showed that the Fuzzy Hybrid-GA-PSO yields the lowest production time and AGV numbers. However, a difference was observed between the performance of Fuzzy-Hybrid-GA-PSO and Hybrid-GA-PSO. The only significant improvement over Hybrid-GA-PSO concerned the computation time. The AGV system simulation with Flexsim software proved the practicality of the developed model and the studied algorithms. The focus of this paper was to compare different optimization algorithms. Therefore, the results of this paper cannot be used for the described problem statement.

Mousavi et al. 2017 focused on multi-objective AGV scheduling in a flexible manufacturing system (FMS) using GA, PSO, and hybrid GA-PSO algorithms. A model for AGV task scheduling was developed. The comparison of the three algorithms shows that the hybrid GA-PSO provides the lowest production runtime and AGV numbers. It was found that after optimization, despite a slight increase in the total AGV running time (loaded and unloaded), reducing the idle time of the AGVs improved the operating efficiency of the AGVs. Consistent with the experimental results, FlexSim software has been used to prove the feasibility of the developed model and the suitability of the optimization algorithms for the scheduling problem. The developed model can be applied to any FMS. It can be applied to optimize the objectives separately or in a combinatorial way. Various algorithms are reviewed to enable and optimize the multi-scheduling of AGVs. This paper was out of scope because the problem statement could not be solved with the help of this paper.

The systematic literature review results show no existing AGV simulation to solve the above-described problem statement. Therefore, it is decided to develop a new AGV simulation to generate the required data that can be applied to a realistic situation. The next section describes the case study, including the concept of the simulated logistics process. After that, the simulation model is described.

CASE STUDY

Introduction of the company

The company for which the simulation was developed is a chemicals manufacturer in the synthetic leather and textile coating industry. The company's factory embraces 4000 m^2 and consists of a warehouse and two production lines. The company's warehouse is located between two production lines (with a diameter of 30 meters). Between 70-100 tons of products are transported per day. Two employees work three shifts per day in the company, and one employee transports a barrel with a forklift truck during one trip. With the help of this information, the assumptions of the concept are described in the next section.

Concept Description

The simulation model should be developed with the AGV operation. The following assumptions in the simulation model are made for the logistics processes of the company to realize a realistic simulation:

- The simulation duration is set to 1-year simulation time from 01.01.2021 to 31.12.2021, because, to calculate how many peak loads can be covered with AGV batteries, AGV data for one year should be generated.
- The transport processes of two products (chemicals) are considered.
- The interval of the production orders (min. in 3 minutes and max. in 27 minutes) is calculated for one year per day using the respective energy consumption data integrating it into the simulation.
- An AGV has an average speed of 1 m/s (approx. 4 km/h).
- The SoC limits of the AGV are predefined (20-90% for the lithium battery saving). If the lower SoC limit is exceeded, AGV should drive to the charging station, which has a minimum delay to charge the AGV battery.
- All AGVs have an initial value of 50% for the charge state of the battery.
- One AGV garage is located in the factory layout and consists of two AGVs. The employees have been replaced with AGVs.
- AGVs can transport the products to both production lines.
- Two charging stations are simulated so that AGV batteries are charged.

The data from Kuka KMP 1500 AGV (KUKA AG 2016) is used as the AGV data. It is shown in Table 2.

Table 2: Kuka AGV data

Feature	Value
maximum payload	1,500 kg
battery capacity	104 Ah (extended battery version)
charging current	52 A
charging voltage	96 V
battery energy density	9,984 Wh
charging time	2 hours (up to 100%)
driving consumption	13 A (min. 8 hours)

After the assumptions are determined, the simulation model is developed. The next chapter presents the model description.

MODEL DESCRIPTION

The simulator *Tecnomatix Plant Simulation* (SimPlan AG 2021) was chosen for its wide selection of objects used in production processes and pre-existing models using battery-driven AGVs. In addition, the simulation can be precisely adapted to the case study using custom-written *SimTalk* program language. The simulation model (see Figure 2) is based on Steffen Bangsow's training example which includes AGVs using tracks (Bangsow 2021).

At the beginning of the simulation, the AGVs launch in the garage below the transport routes. The number of spawned AGVs is defined through the variable *numAGV*, which, according to the concept, is set to two. The source of the products is connected to a buffer out that transfers the products to the AGVs. There are two products ("Part1", "Part2") in the simulated scenario that have the same characteristics but different destinations. According to the table *Workplan* that defines the routes of the products, one part must be transported to the first station on the right side, and, accordingly, the other part to the second station on the left side of the model. Therefore the AGVs operate on two separate paths which provide for collision avoidance. Besides the production sequence, *Workplan* defines the setup and processing times of the stations as well. These are set to avoid AGV queues before the source. If there would still occur, the following AGV would wait until the demanding one has received the product. This model is flexible and can be extended by adding more stations as long as the *Workplan* gets updated continuously.

The number of products generated by the source in each interval can be varied. The interval is set to one day in the case study. Thus, the daily production quantity can be defined. This was implemented in the simulation by a generator that changes the time gap in which the source generates the products according to the table *ProductInterval*. The two endpoints of the transport routes are represented by two station objects in the simulation. In front of each station is a buffer that deals with the incoming products. In the simulation, the buffer serves the purpose of holding parts if components in the station cannot be processed in time. For the simulated case, a buffer is not crucial because capacities, setup, and processing times are calculated accordingly so that the products can be dispatched at the right time. However, since the simulation should be extendible in the future, the buffer was retained as a linking component. The buffer type is set to a queue. Consequently, products exit the buffer in the same order as they arrived (First-In-First-Out-principle).

All objects must be provided with the correct parameters to ensure that the correct production sequence can be created and automated later on. The simulation's most important object is the AGV itself. It is equipped with custom methods that define the logic of its operation. The most relevant method is *doJob*, which defines that an empty AGV should drive to the source to pick up a new part and afterward drive to the destination of the new job. The method also describes the procedure of battery charging. If the AGV's charge level goes below the defined battery reserve threshold, the vehicle checks the availability of the charging stations and drives to the next unoccupied station. This only occurs when the AGV is idle and therefore has no current job. After arrival, the AGV charges up to the specified capacity (90% of maximum capacity).

In *Plant Simulation,* properties of objects and process logic can be automated by so-called methods written in the programming language *SimTalk*. Methods can rely on tables and/or write new data in existing tables. The presented simulation consists of eight methods that ensure the correct execution of the aspired process. For this paper, the methods were adapted to the described conditions. In addition, the method *writeData* was created to save the data generated during the simulation in tables.

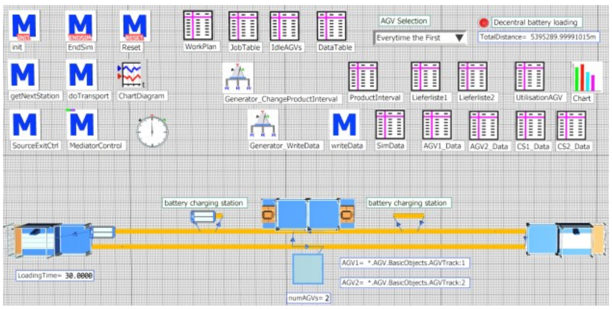

Figure 2: Production simulation model with AGV operation

RESULTS

The results of the developed simulation experiment are shown and interpreted in this section. The simulation time is set to one year for collecting data per minute so that the AGV batteries' approach can be validated. The simulation generated data for two AGVs and two charging stations. A total of 525,600 data was created per AGV and charging station in this simulation experiment. The simulated example charging station data is illustrated in Figure 3. They are current time, charging station ID, and charging station availability.

Identifier	CurrentTime	csID	Measurement	csAvailability
0	2.0100	1	ChargingStation	1
1	1:00.0000	1	ChargingStation	1
2	2:00.0000	1	ChargingStation	1
3	3:00.0000	1	ChargingStation	1
4	4:00.0000	1	ChargingStation	1
5	5:00.0000	1	ChargingStation	1
6	6:00.0000	1	ChargingStation	1
7	7:00.0000	1	ChargingStation	1
8	8:00.0000	1	ChargingStation	1
9	9:00.0000	1	ChargingStation	1
10	10:00.0000	1	ChargingStation	1

Figure 3: Charging station simulation data

The simulated example AGV data is shown in Figure 4. They are current time, AGV ID, AGV availability, state of charge of the AGV battery, AGV position on the X-axis, and the Y-axis, AGV velocity.

Identifier	CurrentTime	agvID	Measurement	agvAvailability	socAGV	agvLatPosition	agvLngPosition	velocityAGV
0	2.0100	1	AGV	0	50.00	13.50	0.00	1.00
1	1:00.0000	1	AGV	0	49.88	0.80	2.00	1.00
2	2:00.0000	1	AGV	0	49.82	0.80	2.00	1.00
3	3:00.0000	1	AGV	0	49.76	0.80	2.00	1.00
4	4:00.0000	1	AGV	0	49.69	0.80	2.00	1.00
5	5:00.0000	1	AGV	0	49.63	0.80	2.00	1.00
6	6:00.0000	1	AGV	0	49.56	0.80	2.00	1.00
7	7:00.0000	1	AGV	0	49.50	0.80	2.00	1.00
8	8:00.0000	1	AGV	0	49.44	0.80	2.00	1.00
9	9:00.0000	1	AGV	2	49.28	24.20	2.00	1.00
10	10:00.0000	1	AGV	0	49.20	27.20	2.00	1.00

Figure 4: AGV simulation data

After the simulation data was collected, the following AGV results were obtained and shown in Table 3. Both AGVs work approximately only 9% of their time. The simulation results show that they have over 81% idle time per year. The idle time allows the AGVs to be used not only as transport vehicles but also as energy storage in this company to reduce peak loads in production.

In future work, an economic analysis will be conducted to analyze different implementation strategies whether the AGVs' number should be reduced to save investment costs or whether the AGVs should be implemented in the simulation to reduce the peak load costs.

Table 3: AGV simulation results in one year

AGV status	AGV1	AGV2
working	8,9 %	8,5 %
idle	81,2 %	81,7 %
charging	9,9 %	9,9 %

Table 4 indicates the simulation results of the charging stations in one year. It is observed that the second charging station was nearly not used by AGVs.

Therefore, reducing the number of charging stations to one for this use case would be conceivable. However, it has to be investigated whether it is economical to have a second charging station when the AGVs discharge their batteries in peak times to support the company grid to reduce peak loads in production.

Table 4: Charging station simulation results in one year

CS status	CS 1	CS 2
working	20,5 %	0,2 %
idle	79,5 %	99,8 %

The simulation results of the AGVs on the highest (26.09.2021) and lowest energy consumption day (02.07.2021) are illustrated in Table 5. The results show that the AGVs on the day with the highest energy consumption work significantly longer than average working time and are charged more. For this day, it can be examined whether the AGVs have additional availability to minimize arising peak loads in the production. The results on the day with the least energy consumption highlight that the AGVs tend to have above-average idle time. It must be verified whether the charging times can be increased to enable the AGVs to pull more energy in off-peak times to use later.

Table 5: AGV simulation results during the highest and lowest energy consumption day

	Highest energy consumption day		Lowest energy consumption day	
AGV Status	AGV1	AGV2	AGV1	AGV2
working	15,9 %	17,2 %	6,7 %	5,5 %
idle	74,0 %	67,8 %	83,2 %	84,4 %
charging	10,1 %	15 %	10,1 %	10,1 %

The simulation results of Table 6 support the interpretation of Table 4. When it is cost-effective to utilize the second charging station for peak power reduction with AGV batteries, the charging station can be deployed. Otherwise, it is recommended to reduce the number of charging stations to one. However, (Weeber et al. 2020) show that machine availability is key to energy-efficient manufacturing. Because machine availability is dependent on the supply of materials by AGVs, in case of doubt, more charging stations than needed are appropriate.

Table 6: Charging station simulation results in the highest and lowest energy consumption day

	highest energy consumption day		lowest energy consumption day	
CS status	CS 1	CS 2	CS 1	CS 2
working	25,4 %	0 %	21,9 %	0 %
idle	74,6 %	100 %	78,1 %	100 %

CONCLUSION

A production simulation model has been developed with AGV operation to generate production data for the validation of the approach. It aims to apply AGV batteries as energy storage devices to mitigate peak loads in a manufacturing company. To realize this simulation model, first, the applied approach for the simulation modeling is presented. Then, the related work of different researchers is introduced, which created different AGV simulation concepts in production. After making sure that a simulation for the problem statement described has not yet been developed, a new concept of the simulation model with a case study is described. Considering the assumptions of the new simulation model concept, a simulation model is developed and presented in this paper. The simulation model results indicate that the generated data from the simulation model can be used to validate the described approach above. The results also show that the AGV’s energy consumption can vary widely. In addition to the parameters of energy consumption and associated costs, the increasingly important energy flexibility issue must be considered. As a next step, the generated data will be entered into a software system to calculate whether using the AGV batteries as energy storage to minimize peak loads is cost-effective.

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