Simulation-based Performance Analysis in Robotic Mobile Fulfilment Systems

Analyzing the Throughput of Different Layout Configurations

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Abstract: A robotic mobile fulfilment system for automated storage and retrieval of goods is investigated to determine reachable throughput as a function of the number of vehicles. The simulation model considers connected zones for manual order picking and replenishment of empty storage units. The results show a strong increase of blocking effects between vehicles if the number of vehicles within the system increases. This leads to a maximal throughput, which further vehicles cannot increase. We will show that changing the storage layout increases throughput. The results also show a linear correlation between the number of vehicles and the throughput for small numbers of vehicles. Here, analytical calculations are admissible since minor blocking effects do occur. However, the end of the linear correlation can only be found by simulation.

1 INTRODUCTION

An automated guided vehicle system (AGVS) is a driverless transport system used to move materials horizontally (Vis, 2006). It consists of at least one automated guided vehicle (AGV), a guidance control system, devices for localization, and equipment for data transmission (VDI 2510). AGVSs are commonly used in manufacturing plants, warehouses, distribution centers, and transshipment terminals (Le-Anh and De Koster, 2006).

Robotic mobile fulfilment systems (RMFSs) are a more recent AGVS application. RMFSs are a new type of automated storage and retrieval systems used for part-to-picker order-picking systems (Lamballais et al., 2017). The products are stored on racks, which are arranged in storage aisles on the ground. The vehicles are considered to be mobile robots in this context, and use a rectangular grid of paths to move within the storage area. They can travel along the storage aisles and underneath the racks as well if the vehicles are empty. Once an order arrives and is assigned to a picking station, a vehicle moves under the rack containing the required item, lifts the rack, and brings it to the designated picking station, where the item is picked. A vehicle subsequently brings the item back to an empty storage location. Figure 1 shows an example of an RMFS.

The main benefits relative to common stacker-crane-based storage and retrieval systems are simple scalability and good redundancy. The whole system can be run with a single vehicle. If needed, more vehicles can be added to achieve a greater throughput. Should a single vehicle fail, the remaining vehicles continue to fulfill the storage and retrieval request and system throughput is only slightly affected.

Several decision problems involving RMFS control have to be solved. First, incoming items need to be assigned to racks on which they are stored. Second, these racks have to be assigned to storage locations within the system. Order processing in a picking station has to be determined, and retrieval tasks have to be assigned to vehicles. Finally, the traffic has to be planned: routing and deadlock-handling strategies are necessary to run the system in a robust and efficient way (Boysen et al., 2017).

An important issue when planning an AGVS in general is to determine the number of vehicles needed to reach a given throughput. A sufficient number of vehicles has to be available to ensure that all transport tasks are performed on time. On the other hand, there shouldn't be too many vehicles,

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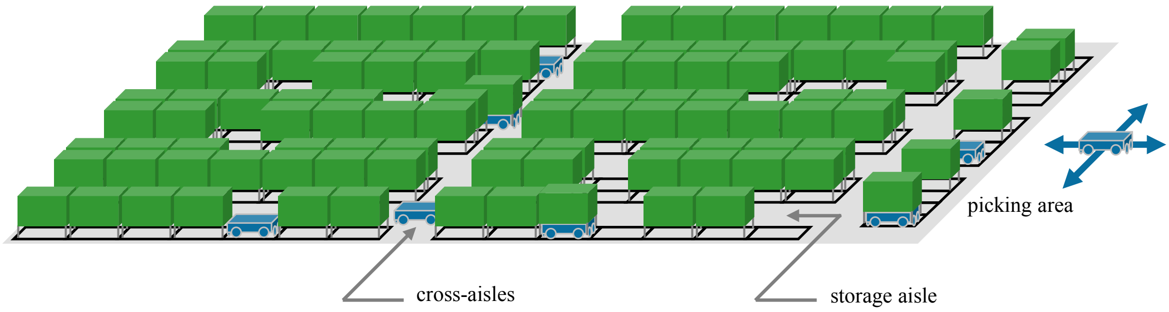

Figure 1: Example of an RMFS.

because vehicles are costly and too many could be unprofitable (Vis, 2006).

In this paper, we describe a case study involving an RMFS. We use a simulation model, which we validate analytically. Simulation experiments reveal reachable throughput as a function of the number of vehicles, taking blocking effects among them into account. We are thus able to show the implications of blocking effects on the usability of static analytic approaches for throughput calculation.

We further investigate the influence of different layout configurations to answer the following questions:

- Is using two lanes (one for each direction) within each storage aisle to achieve more throughput worth the significantly greater space required?
- Is assigning a direction to each single-lane storage aisle helpful or should bidirectional traffic be allowed instead?
- What is the influence of cross-aisles? They provide more flexible vehicle-routing options. However, do they hence lead to greater throughput due to less congestion?

The remainder of the paper is organized as follows: We first briefly review the literature on research to date into determining the optimal fleet size for AGVSs. We subsequently describe the considered RMFS in more detail before we present the simulation model used for the study. In section five, we describe the simulation experiments conducted and discuss their results in section six.

2 LITERATURE REVIEW

To determine the optimal AGV fleet size, several factors have to be taken into account besides the number of transports. These include, for instance, the vehicles' speeds, loading and unloading times, the system's layout, traffic congestion, and vehicle-dispatching strategies. (Müller, 1983).

Both Ganesharajah et al., and Vis provide literature reviews concerning approaches to fleet-size determination, which comprise deterministic and stochastic methods. (Ganesharajah et al., 1998; Vis, 2006).

A lower bound for the fleet size of an AGVS can be obtained by dividing the total travel time by the length of the planning horizon. The total travel time includes time for loading and unloading, loaded travel and empty travel. Empty travel occurs when the next transport task's starting point differs from the previous task's completion point. The loaded travel time can be calculated using the From-To chart, assuming that AGVs travel the shortest path to complete their assignments. In reality, conflicts with other AGVs may cause an AGV to take a longer path. (Ganesharajah et al., 1998)

Additionally, getting the From-To chart becomes increasingly difficult with a rising number of possible start points and ends of an assignment. If AGVs operate in an RMFS, assignments can lead from any storage location or picking station to any other. The associated From-To chart comprises one value for each pair of start and end points. Instead of calculating each individual travel time, one can use the mean travel time between a picking station and any storage location, or between two storage locations, respectively. This approach has been applied to storage and retrieval systems for many decades. As it neglects blocking effects between AGVs, it has to be considered a static approach. (Großeschallau, 1984; Gudehus, 2010)

The influence of vehicle-dispatching rules makes estimating empty-travel time a complex task. Malmborg presents an analytical procedure to estimate empty-vehicle travel volume considering different dispatching rules. (Malmborg, 1991)

Additionally, the more vehicles are moving within the system, the more blocking among them will occur (Schmidt, 1989). Static approaches are insufficient to quantify these blocking effects. A simulation study has to be conducted instead. Scant literature exists on RMFS fleet size. Lamballais et al., analyze the performance of RMFS with and without storage zones serving single-line and multi-line orders. They use an analytic approach based on a queueing network model to estimate maximum order throughput, average cycle time, and vehicle utilization. For modelling, they assume that aisles allow only unidirectional travel and that no vehicle blocking or congestion occurs in the aisles. (Lamballais et al., 2017)

Yuan and Gong use a queueing network model as well to compare different strategies for RMFSs. They compare the performances of pooled and picker-dedicated vehicles and calculate the optimal number and velocity of the vehicles. (Yuan and Gong, 2017)

The literature mentioned above shows that there exist different analytical approaches for estimating the number of vehicles. But as Le-Anh and de Koster mention, impractical assumptions in the analytical models may cause the estimated number of vehicles to differ considerably from that really needed. A simulation modelling specific operational conditions should therefore be used to reevaluate the estimated number. (Le-Anh and De Koster, 2006). The complex nature of the issues involved in determining fleet size seems to make simulation the most promising tool. (Ganesharajah et al., 1998).

Finally, we would like to emphasize why we are analyzing different layout configurations regarding direction of travel within the storage aisles. According to Le-Anh and De Koster, the way in which vehicles travel through the system (unidirectional or bidirectional) influences vehicle-fleet size. (Le-Anh and de Koster). The main reason for unidirectional traffic is simplicity of layout design and traffic control. But as Egbelu and Tanchoco showed by simulation, the use of bidirectional traffic can increase productivity, especially if fewer vehicles are required (Egbelu and Tanchoco, 1986).

3 CONSIDERED SYSTEM

Figure 2 shows the investigated RMFS's basic layout (floor plan). The white boxes represent the stored items placed on small racks, further called storage units. These storage units are assembled into twelve horizontal rows with six aisles for vehicle movement in between. Each row is thirty storage units long. The picking zones are located on the layout's far right side. Each of the four zones has five picking locations (black boxes) where the storage units are placed during the picking process. On the layout's far left side, there are ten replenishment locations (gray boxes). If a storage unit becomes empty during picking, it is brought to one of these locations for replenishment before being stored again. Dotted lines in the layout indicate possible AGV movement paths. Two lanes are apparent within the aisles, between the replenishment locations and the storage area, and between the picking zones and the storage area. All lanes are unidirectional in opposite directions.

The different vehicles are all equally and permanently assigned to one of the picking zones

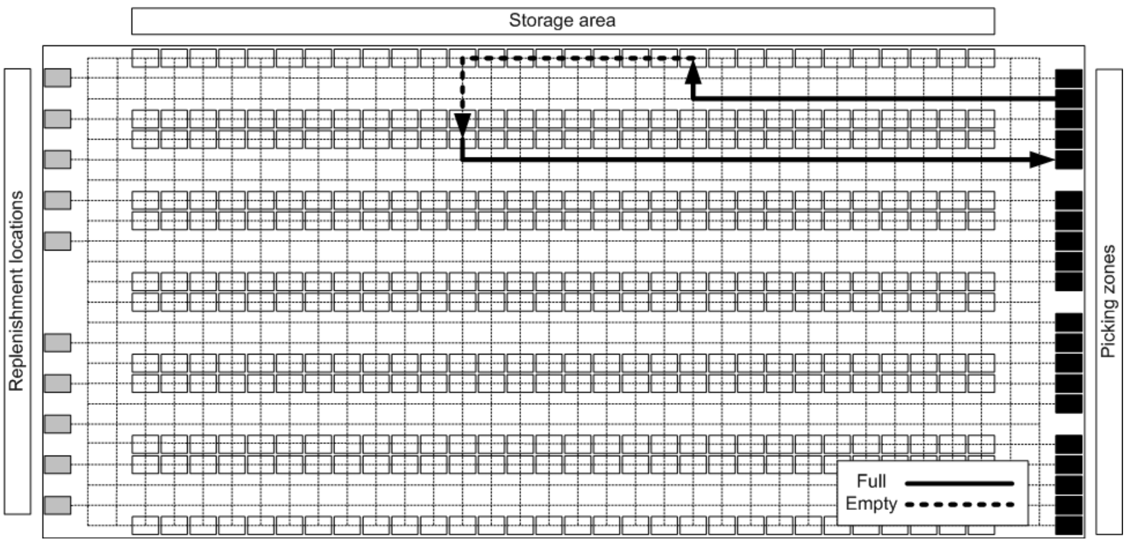

Figure 2: Floor plan of the investigated RMFS with a sample dual cycle.

(picker-dedicated). Thus, they start their cycle at one of their assigned picking zone's picking locations and end it at one picking location in the same zone. The same applies to the storage units, which are always stored into the aisle from which they were earlier retrieved. The items are randomly distributed (chaotic storage).

The AGVs perform three different cycles to maintain material flow between storage locations, picking zones, and replenishment locations. The first and most common is the dual cycle. The AGV loads its current picking location's storage unit, transports it to a random empty storage location in the same aisle from which it was earlier retrieved, and stores it there. Now a new storage unit is randomly selected. The AGV moves to the selected location, loads the unit, and transports it to an empty picking location. The dual cycle with empty rack commences if the storage unit is empty after the picking process. In this cycle the empty storage unit is transported to an empty replenishment location (preferably one in the same layout half—top or bottom—as the current picking zone). Afterwards a new storage unit is gathered and transported to the picking location. The last cycle consists of three phases and is therefore called the triple cycle. It is executed if a storage unit has been replenished and is waiting to be stored again into the same aisle from which the new storage unit must be retrieved. In this case, the storage unit of the current picking location is stored into a random empty location in its assigned aisle, the storage unit of the replenishment location is retrieved and stored into its assigned aisle, and the new storage unit of the same aisle is gathered and transported to the picking location.

The described cycles generally apply to all numbers of vehicles. However, there are small differences in the AGVs' controls if there are four or fewer as opposed to five or more per picking zone. In the case of four or fewer AGVs, the vehicles move underneath the storage unit that will be picked next after they've brought a storage unit to the picking location. With five or more AGVs, the vehicles do not change their storage units at the picking station. Instead, they wait until the picking process for the current storage unit is finished and store that unit afterwards. If more than five AGVs are assigned to one picking zone, they have to check whether there is an empty picking location at their assigned picking zone after loading the new storage unit at its storage location. Only then do they move to this location. If not, they wait at the current storage location until a picking location becomes empty. We thus avoid vehicles blocking the main aisle while they wait in front of the picking stations.

The picking process itself works according to the principle of "first come, first served." Therefore, the storage unit that arrives first at the picking zone gets picked first.

For the different tasks within the RMFS (picking, replenishment, loading/unloading of storage items), various times spans are needed. They are listed in Table 1.

The picking time is set to a relatively short time span to prevent the picking process from limiting the system, since the intent in this paper is to investigate maximum throughput based on the AGVs. Table 1 also gives the mean speed of the AGVs horizontally and vertically. Acceleration and deceleration are not taken into account. The vehicle's wheels must be rotated to change the direction of motion from vertical to horizontal or from horizontal to vertical. The corresponding time span is also listed in Table 1.

Table 1: RMFS parameters.

Picking time	5 s
Replenishment time	100 s
Loading/Unloading time	5 s
AGV speed horizontally/ vertically	0.5 m/s
AGV turning time	5 s

Although the considered system features some specific aspects such as control at the picking zone, it is mostly standard. Only one in 20 picks empties a bin, which causes 5 % of all cycles to be dual cycles with an empty rack and another 5 % of all cycles to be triple cycles. Most of the cycles in a layout with parallel aisles are thus standard dual cycles. Moreover, whether a vehicle changes picking location only accounts for short times in comparison to the whole cycle time.

4 SIMULATION MODEL

To answer the questions in the scope of this paper, we follow the typical approach of simulation studies, which is to derive a conceptual model from the system under consideration and to translate it into a computerized model. (Rabe, 2008)

The simulation model consists of four modules for different functions that establish a transparent, adaptive and reusable structure: the *assignment*, *routing*, *evaluation*, and *layout modules*. Whenever an AGV needs a new assignment, a request is passed to the assignment module. The answer comprises the order of pick stations, storage locations, and a possible supply location that the AGV has to visit during the cycle.

The routing module takes over when the AGV starts the cycle's next phase. It calculates the fastest route between start and end points of this section, e.g., between pick station and the storage location where the picked item has to be stored. To find the fastest route, we apply the *Time Window Routing Method* (Lienert and Fottner 2017). Not only is this method guaranteed to find the fastest route relative to the currently planned routes of other AGVs, but it does so without the risk of causing deadlocks. The whole AGV system can collapse due to an infinite blockage if deadlocks are not reliably excluded. In case of single-lane bidirectional storage aisles, for example, a deadlock occurs if two loaded AGVs meet each other driving in opposite directions. As they cannot simply "switch" places, the aisle as well as both AGVs are blocked if the control can't resolve the situation.

To apply the Time Window Routing Method, the layout has to be modelled as a graph. The graph's nodes represent picking, replenishment, and storage locations as well as aisles and cross-aisle intersections.

Both the assignment module and the routing module are connected to the layout module. It consists of AGVs, storage locations, aisles, picking stations, and supply locations according to the system described above. The resulting computerized model is implemented in *Tecnomatix Plant Simulation 11*. Figure 3 gives an impression of the area around the picking locations and part of the aisles in the computerized model.

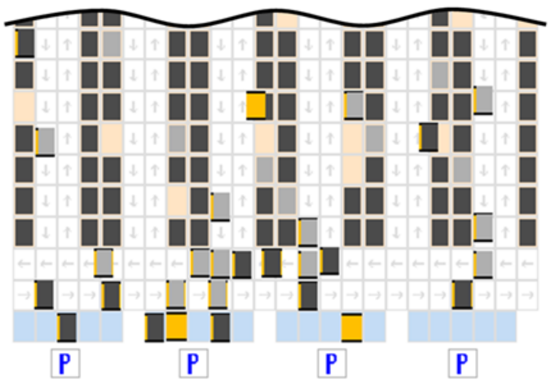

Figure 3: Screenshot from the simulation model. Every rectangle represents a node in the underlying layout graph.

The evaluation module monitors the RMFS's behavior with relevance for the performance figures. Thus, it collects, processes, and stores data from consecutive experiments and allows for a thorough evaluation with regard to the questions in the scope of this paper.

Before conducting experiments, the simulation model has to be verified and validated. We first use a structured walkthrough to prove that our model's implementation is free of mistakes and thus can be regarded as verified. In a second step, we compare the cycle times of AGVs in our simulation model with those from the static analytical approach to calculate mean cycle times (see Großeschallau, 1984 or Gudehus, 2010). As this analytical approach does not take into account blocking effects, we use a single AGV to conduct dual cycles, dual cycles with an empty item, and triple cycles randomly using all possible picking stations, storage locations, and supply locations. We also consider the empty travel time between two picking stations in case of five or more AGVs and single-lane bidirectional aisles (see Section 3). To calculate cycle times analytically, we split the cycle into time needed for turning, loading/unloading and into segments of one-dimensional, constant travel. Although turning and loading/unloading are easily counted, the segments' travel times depend on mean length and the AGV's velocity. The cycle time is then composed of these components. The comparison of calculated and simulated cycle times shows that the deviation reaches a maximum of 1 %, which is acceptably low (cf. Table 2). The simulation model is thus regarded as valid.

Table 2: Validation of cycle times.

	Calculation	Simulation	Delta
1–4 AGVs			
Dual cycle	244 s	245 s	0 %
Dual cycle with empty items	309 s	306 s	1 %
Triple cycle	392 s	394 s	0 %
5+ AGVs			
Dual cycle	225 s	225 s	0 %
Dual cycle with empty items	289 s	286 s	1 %
Triple cycle	372 s	374 s	0 %

5 EXPERIMENTS

The validation results show that a comparison between simulation and static analytical calculation is only possible for basic cycles of a single AGV. Blocking effects as well as different layout configurations are beyond the scope of analytical models. But using our verified and validated simulation model, we can include both aspects and run experiments to find out more about how each affects the system. In the experiments, we compare three different layouts. Layout 1 corresponds to the current system layout with two unidirectional lanes per aisles. Layout 2 only provides a single lane per aisle that can be used in both directions, whereas Layout 3 allows only unidirectional traffic along a single lane per aisle (cf. Figure 4). Furthermore, we investigate the performance of each layout with and without cross-aisles. We use two cross-aisles located at one third and at two thirds of the aisle length.

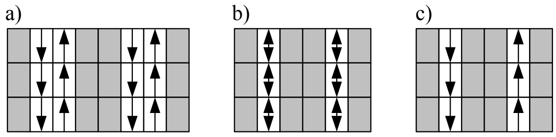

Figure 4: Section with two lanes for a) Layout 1, b) Layout 2 and c) Layout 3.

With each layout, we vary the number of vehicles from four (one per picking zone) to 60 (15 per picking zone) in steps of four. Simulation time is set to 24 hours and a simulation run is repeated ten times with each setting.

6 RESULTS

In this section, we present and discuss the results obtained by the simulation. Figure 5 provides an overview of the results without cross-aisles. The curves look similar for all three layouts, and we will see that this holds for cross-aisles as well (cf. Figure 3). In all cases, performance scales nearly linearly with the number of vehicles until it reaches saturation. The curves show a small knee between 16 and 20 vehicles or four and five vehicles per picking zone, respectively. This is where the cycles change as AGVs do not have to change the picking location anymore between arrival and departure. As soon as the saturation begins, the gain per additional vehicle decreases to zero. At this stage, more vehicles within the system do not further increase performance. Blocking effects caused by the additional vehicles result in a loss of performance across all vehicles, which exactly counterbalances the additional vehicles' performance contributions.

A look at the time spans that the AGVs spent on different activities helps to prove this. Figure 6 shows these amounts for Layout 2. There are four possible activities: driving, loading and unloading, waiting blocked during driving, and waiting loaded at a storage location until a picking location is ready for the next item. The last activity only occurs when there are six or more vehicles per picking zone, as each picking zone only provides picking locations for five vehicles simultaneously. The increasing amount of waiting due to blocking reflects the blocking effects. With 60 vehicles in the RMFS, a third of the time is spent blocked, whereas minor blocking occurs with eight and 16 vehicles and throughput rises linearly with the number of vehicles.

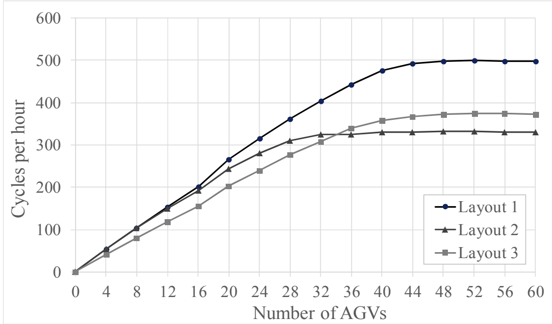

Figure 5: Throughput of all three layouts without cross-aisles.

Layout 1 provides the greatest throughput, which one would expect due to two unidirectional lanes per aisle. It is remarkable, however, that for fewer vehicles, Layout 2 outperforms Layout 3. The former's aisles can be used in both directions, which shortens the calculated paths. The more vehicles are working within the system, the heavier the congestion becomes. After a certain number of vehicles is reached, allowing only unidirectional traffic—as in Layout 3—is beneficial. Doing so requires no changes in the physical layout and offers a promising way to increase throughput using control measures alone if insufficient space is available to use Layout 1.

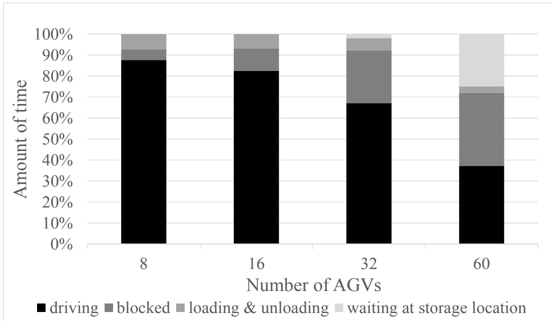

Figure 6: Amounts of time spent per AGV during the four possible activities.

The second layout feature we tested is the existence of cross-aisles that enable vehicles to switch aisles not only in the front and back of, but also at regular distances along the aisles. Figure 3 compares the throughputs of the different layouts with and without cross-aisles. As mentioned above, all curves look similar with a linear increase and a small knee between 16 and 20 vehicles before reaching saturation. Cross-aisles help to increase throughput for every layout. The larger number of routing options reduces blocking effects as expected. Vehicles can more easily circumvent congested parts of the layout thereby smoothing traffic.

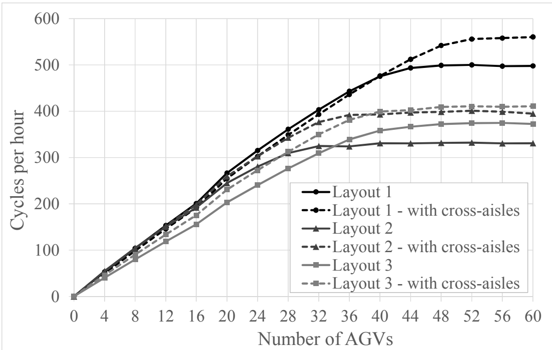

Figure 7: Throughput of all three layouts with and without cross-aisles.

Table 3 provides an overview of the maximum throughput per layout and the number of AGVs that was needed to reach that throughput. We define maximum throughput as the first throughput that increases less than one percent with the addition of one vehicle per picking zone. Furthermore, the differences in number of nodes within the storage area is given with Layout 1 as reference. For instance, Layout 1 with cross-aisles provides a significantly greater throughput, but requires 26.7 % more aisle nodes than Layout 1 without cross-aisles does, whereas Layout 3 with cross-aisles achieves less throughput (90 fewer cycles per hour) but requires 40 % fewer aisles nodes.

Table 3: Comparison of performance and space requirements.

	Max. cycles per hour	AGVs	Nodes
Layout 1	489.9	48	-
Layout 1 with cross-aisles	556.2	52	+26.7 %
Layout 2	324.7	32	−50.0 %
Layout 2 with cross-aisles	391.8	36	−40.0 %
Layout 3	372.3	48	−50.0 %
Layout 3 with cross-aisles	409.0	48	−40.0 %

From the curves in Figure 7, one can figure out how many AGVs are needed to reach a certain throughput. Furthermore, they hint at whether a static approach that does not take blocking into account also holds. For example, if a throughput of 200 cycles per hour is needed, the curves of all six layouts are in the linear section. A static approach is thus applicable. For a throughput of 450 cycles per hour, however, a static approach results in a fleet size of about 36 to 48 vehicles for the different configurations. These numbers can be roughly estimated by extrapolating the linear parts of the curves up to 400 cycles per hour. The simulation, however, shows that Layouts 2 and 3 reach saturation below 450 cycles per hour. The system would be unable to reach the desired throughput if these layouts were chosen.

7 CONCLUSIONS

In this paper, we considered a robotic mobile fulfilment system with six storage aisles, four picking zones, and ten replenishment locations. We conducted a series of simulation experiments to compare the performances of different layout configurations. We varied the number of vehicles and analyzed the throughputs reached.

A bidirectional single lane layout is recommended for fewer vehicles. However, maximum throughput is reached with two unidirectional lanes per aisles, although this layout requires the most space. Using cross-aisles generally yields greater throughput.

We were able to show that the more vehicles are working within the system, the less throughput each additional vehicle provides. For fewer vehicles, the throughput is nearly a linear function of the number of vehicles. Here it is admissible to analyze the throughput of a single vehicle analytically and forecast the throughput for more vehicles. But the analytical approach underestimates the required number of vehicles as soon as increasing blocking effects among vehicles causes departure from linearity. The crucial point is that numbers of vehicles for which linearity holds is unknown. The completion of a simulation study is therefore essential for obtaining reliable performance results.

Based on this conclusion, we identify two possible fields of future research: First, the scope of the simulation model has to be extended towards other aspects of planning like different storage policies and dispatching rules. Both influence the vehicles‘ travel distances and system performance. Additionally, we assumed that the vehicles are available without restrictions. However, battery management and emergency policies in case of a vehicle break down affect the system performance. Using our simulation model, the effects of both can be analyzed during planning.

Second, to generalize our findings, a next step can be to analyze at which number of vehicles the performance starts to deviate from the linear, analytical curve. If that is the case at a similar ratio of vehicles per area in different layouts or layout sizes, it would be an indication on whether a simulation study has to be conducted. For systems with an analytically calculated number of vehicles around this ratio or higher, planners would have a rule of thumb of when to reevaluate their findings with a simulation.

REFERENCES

Boysen, N., Briskorn, D., Emde, S., 2017. Parts-to-picker based order processing in a rack-moving mobile robots environment. *European Journal of Operational Research* 262 (2), pp. 550–62.

Egbelu, P.J. and Tanchoco, J.M.A.,1986. Potentials for bi-directional guide-path for automated guided vehicle based systems. *International Journal of Production Research* 24 (5), pp. 1075–10097.

Ganesharajah, T., Hall, N.G., Sriskandarajah, C., 1998. Design and operational issues in AGV-served manufacturing systems. *Annals of Operations Research* 76 (0), pp. 109–54.

Großeschallau, W., 1984. *Materialflussrechnung – Modelle und Verfahren zur Analyse und Berechnung von Materialflusssystemen*, Springer. Berlin.

Gudehus, T., 2010. *Logistik – Grundlagen Strategien Anwendungen*, Springer. Berlin, 4th edition.

Lamballais, T., Roy, D., De Koster M.B.M., 2017. Estimating performance in a Robotic Mobile Fulfillment System. *European Journal of Operational Research* 256 (3), pp. 976-990.

Le-Anh, T., De Koster M.B.M., 2006. A review of design and control of automated guided vehicle systems. *European Journal of Operational Research* 171 (1), pp. 1–23.

Lienert, T., Fottner, J., 2017. Development of a generic simulation method for the time window routing of automated guided vehicles. In: *Tagungsband 13. Fachkolloquium der WGTL*. WGTL.

Malmborg, C.J., 1991. Tightened analytical bounds on the impact of dispatching rules in automated guided vehicle systems *Applied Mathematical Modelling 15*, pp. 305–11.

Müller, T., 1983, *Automated Guided Vehicles,* Springer. Berlin, Heidelberg, New York, Tokyo.

Rabe, M., Wenzel, S., Spieckermann, S., 2008. *Verifikation und Validierung für die Simulation in Produktion und Logistik*, Springer. Berlin.

Schmidt, F., 1989. *Komplexe Fahrerlose Transportsysteme – Fahrzeuganzahl, Investitionsaufwand, Wirtschaftlichkeit,* Verlag TÜV Rheinland. Köln.

VDI-Richtlinie 2510, 2005. *Automated Guided Vehicle Systems*. Beuth. Berlin.

Vis, I.F.A., 2006, Survey of research in the design and control of automated guided vehicle systems. *European Journal of Operational Research* 170 (3), pp. 677-709.

Yuan, Z., Gong, Y.Y., 2017. Bot-In-Time Delivery for Robotic Mobile Fulfillment Systems. *IEEE Transactions on Engineering Management* 64 (1), pp. 83-93.