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COMPARISON OF DEADLOCK HANDLING STRATEGIES FOR DIFFERENT WAREHOUSE LAYOUTS WITH AN AGVS

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ABSTRACT

Automated guided vehicles (AGVs) form a large and important part of logistic systems to improve productivity and reduce costs. When multiple AGVs are running in limited and uncertain environments, lots of issues can occur, such as collisions and deadlocks, which need to be addressed. This paper presents a flexible simulation model for a warehouse with various AGVs. We implemented all three typical strategies to handle deadlocks: prevention, avoidance and detection and resolution. The results show that there is no dominant strategy and that the results strongly depend on the individual case and the input parameters.

1 PROBLEM AND MOTIVATION

The constant internationalization of the markets, stronger customer orientation, and ever shorter product life cycles put companies in almost all industries under increasing pressure (Obermaier 2019). The degree of automation and digitization is gradually growing in many areas to cope with the resulting needs and social developments such as geographical change (Schenk and Schumann 2015). Logistics, as a cross-sectional function, is especially affected by this trend and is undergoing the process of automation. According to a current survey, more than 90 % of the companies surveyed from the logistics sector in Germany rate the use of robots and automation as "significant" or "very significant" (Statista 2019). An important part of this is the use of automated guided vehicle systems (AGVS), which automatically carry out transport orders with specified start and destination locations. About 55 % of the logistics experts surveyed in Germany rate the relevance of AGVS as "large" or "very large" (Statista 2018).

When planning an AGVS, a wide variety of decisions have to be made: For instance, the layout, control logic, and number of vehicles required have to be determined. Many of these parameters cannot be reliably determined in a complex, stochastic environment by static calculations. Simulation models are a typical way to help out with these issues and are, therefore, created to take into account the complexity and dynamics of the system (Ullrich and Albrecht 2019).

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Avoiding collisions and the correct handling of deadlocks is an elementary part of the smooth running of AGVS. A simulation model must also map the correct handling of deadlocks and collisions for a proper representation of the planned system. There are various strategies to handle deadlocks. The literature gives for logistical problems little knowledge-based advice about what might be the best strategy with respect to important figures in logistics.

The aim of this publication is, therefore, to give a simulation-based comparison in which different logistical scenarios in a warehouse with an AGVS which deadlock strategy performs best regarding the key figures. The findings build on our paper from last year, where a rail-based storage and retrieval system handled the deadlocks with an approach of detection and resolution (Müller et al. 2019). In contrast to the 2019 publication, this publication now considers an AGVS instead of an ASRS, and we do not decide in advance for a strategy approach to deadlock handling, as is often the case in the literature, but consider all three strategy approaches under influence of various parameter changes. Furthermore, the resource types are limited to floor-bound sections of the path (no more lifts as different resource type) and the stacking restriction specified by the industrial laundry scenario does not occur with the general problem considered in this paper. Due to the different structure of the logistic system, the strategy approach of detect and resolve is also solved differently in this paper than in the publication of 2019.

2 LITERATURE

There are different, problem-specific approaches to handle deadlocks. Most of these approaches do not come from logistics at all, but from computer science, where this problem has been recognized and discussed since the late 1960s and early 1970s (Coffman et al. 1971; Havender 1968; Holt 1972). Deadlocks occurred primarily in parallel programming or multi-programming, and general strategy approaches were developed to break the conditions for creating deadlocks. Since then, the four conditions by Coffman et al. have been used as starting points for dealing with deadlocks and are also used for current problems (Bashir et al. 2018; Coffman et al. 1971; Palmer et al. 2018; Zheng et al. 2020).

In addition to the focus on breaking one of Coffman's conditions for a deadlock, a distinction was made between three basic strategic approaches to handle deadlocks (Coffman et al. 1971):

- prevention
- avoidance
- detection & resolution

Both early observations by Coffman et al. and later views by, for example, Tanenbaum (2015) saw, from the perspective of computer science, in the strategic approach of deadlock prevention, above all how resources are allocated. They referred to suggestions by Havender (1968). This perspective was not always followed in production and logistics. Either prevention was not clearly delimited to avoidance (Mayer 2009; Mayer and Furmans 2010), or like Lehmann (2006) deadlock prevention meant the design of a logistical system, process, and infrastructure in such a way that no more deadlocks can occur. Ultimately, when designing the system, reference was often made only to the rules on resource use (Kim and Kim 1997; Lienert and Fottner 2017). The authors described this design process as forward-looking system planning, but what is ultimately meant is a corresponding change in the processes involved in order planning. Precisely, the condition of mutual exclusion according to Coffman et al. could also be attacked by skillful infrastructure planning. How an adapted infrastructure planning could prevent deadlocks has not yet been discussed in detail in the literature. In this context, this paper examines the interaction of infrastructure parameters and deadlocks.

Another aspect that occurs frequently in the literature is the quick decision for a certain deadlock handling strategy approach. There are many solutions and algorithms provided in detail for a certain approach (Fanti et al. 2018; Qi et al. 2018; Zhao et al. 2020), but most of these publications only provide one chosen deadlock handling strategy, although in these cases it is usually not sufficiently clear whether the chosen strategy approach is the best one.

3 METHODOLOGY

3.1 Conceptual Model

The considered logistic system is a warehouse with a floor-bound AGVS. A flexible model in infrastructure design allows us to investigate possible deadlocks in the warehouse for many situations. Figure 1 shows the conceptual model of the considered system. There is only one system boundary in the upper left corner, which is fixed and represented by a source and a sink.

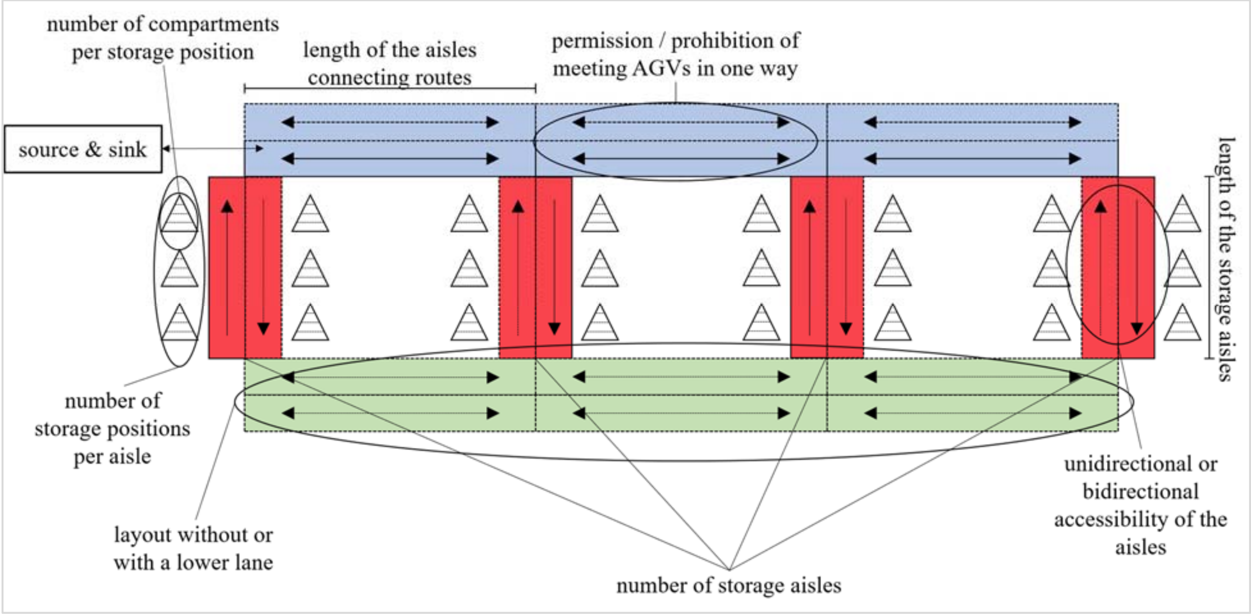


Figure 1: Conceptual model of the adjustable parameters of the warehouse and its infrastructure.

From this system boundary, the routes for the AGVs reach every storage space location with a rectangular shape. The length of each route and the number of aisles is flexible. There is also the option to completely leave out the lower lane (green colored route in the figure), so that the aisles can only be accessed on one side. The horizontal connecting routes (blue and green) can be switched between single and two lanes. The vertical storage aisles are fixed with one lane but can be unidirectional or bidirectional.

We determined six layouts as typical representations of the above-mentioned possible variations of the route types. Figure 2 gives a categorized overview of these layouts. Layouts 1 and 2 represent with unidirectional storage aisles an approach for deadlock prevention inside the storage aisles. In Layouts 5 and 6, the use of just unidirectional routes results in a deadlock prevention policy of allowing only one AGV into a storage aisle at a time.

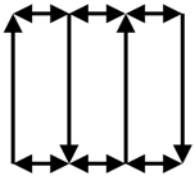
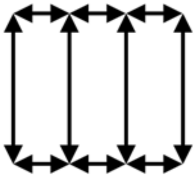
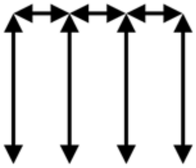
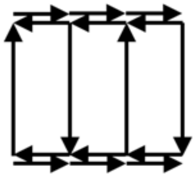
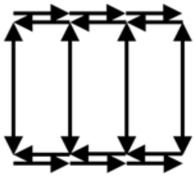
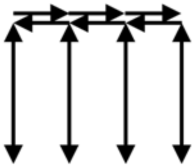
	Unidirectional storage aisles	**Bidirectional storage aisles**	
		Two connection routes	**One connection route**
Connection routes with single lane	Layout 1 	Layout 3 	Layout 5 
Connection routes with two lanes	Layout 2 	Layout 4 	Layout 6 

Figure 2: Variation of layouts in the warehouse system.

3.2 Detection and Resolution

The detection and resolution strategy was not implemented for the layouts 5 and 6, due to the lack of alternative routes. For the other layouts, the routes of the AGVs are calculated based on the shortest distance. An AGV does not enter a single lane section if another AGV is driving in the opposite direction. If such a circumstance arises, one of the vehicles has to be redirected to avoid a potential deadlock. Therefore, the respective AGV is determined based on previously defined criteria and redirected in a second step. If additional vehicles are driving in the same direction as the former redirected AGV, the other AGVs have to be redirected as well.

Figure 3 shows four identified deadlock cases considering if these cases can occur in the defined layout types. The figures declared as "possible solution" are not the only methods, but just serve as an example. The selection of the vehicle that has to change its route can be deviated from the example procedure shown.

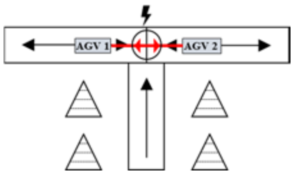
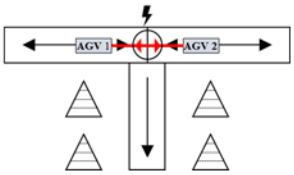
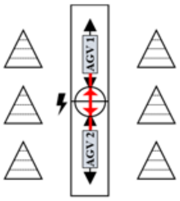
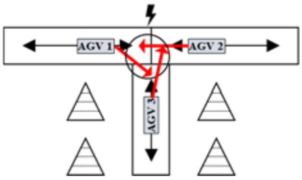
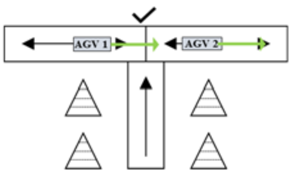
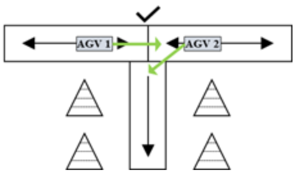
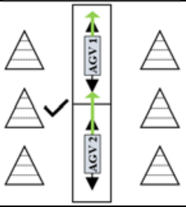
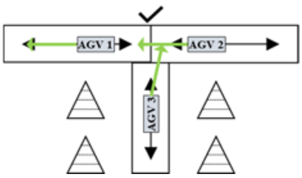
	Case 1 Layout 1 & 3	**Case 2** Layout 1 & 3	**Case 3** Layout 3 & 4	**Case 4** Layout 3
Deadlock situation				
Possible solution				

Figure 3: Typical examples of deadlock situations and possible solutions.

3.3 Deadlock Avoidance

The basis of the process of deadlock avoidance is the term “reservation” which means blocking the opposite direction of travel. Therefore, a section of the lane is not reserved for a single AGV but a single direction.

Figure 4 shows the flow chart of the deadlock avoidance algorithm. The algorithm starts by checking whether the destination of the AGV corresponds to the actual destination. If this is not the case, the interim destination is set as the destination if the interim destination was not created immediately before. To find the route, the first successor of the vehicle location (a route section) in the same direction of travel is added to the route and a subroutine is started which iteratively checks the successors until the destination is found.

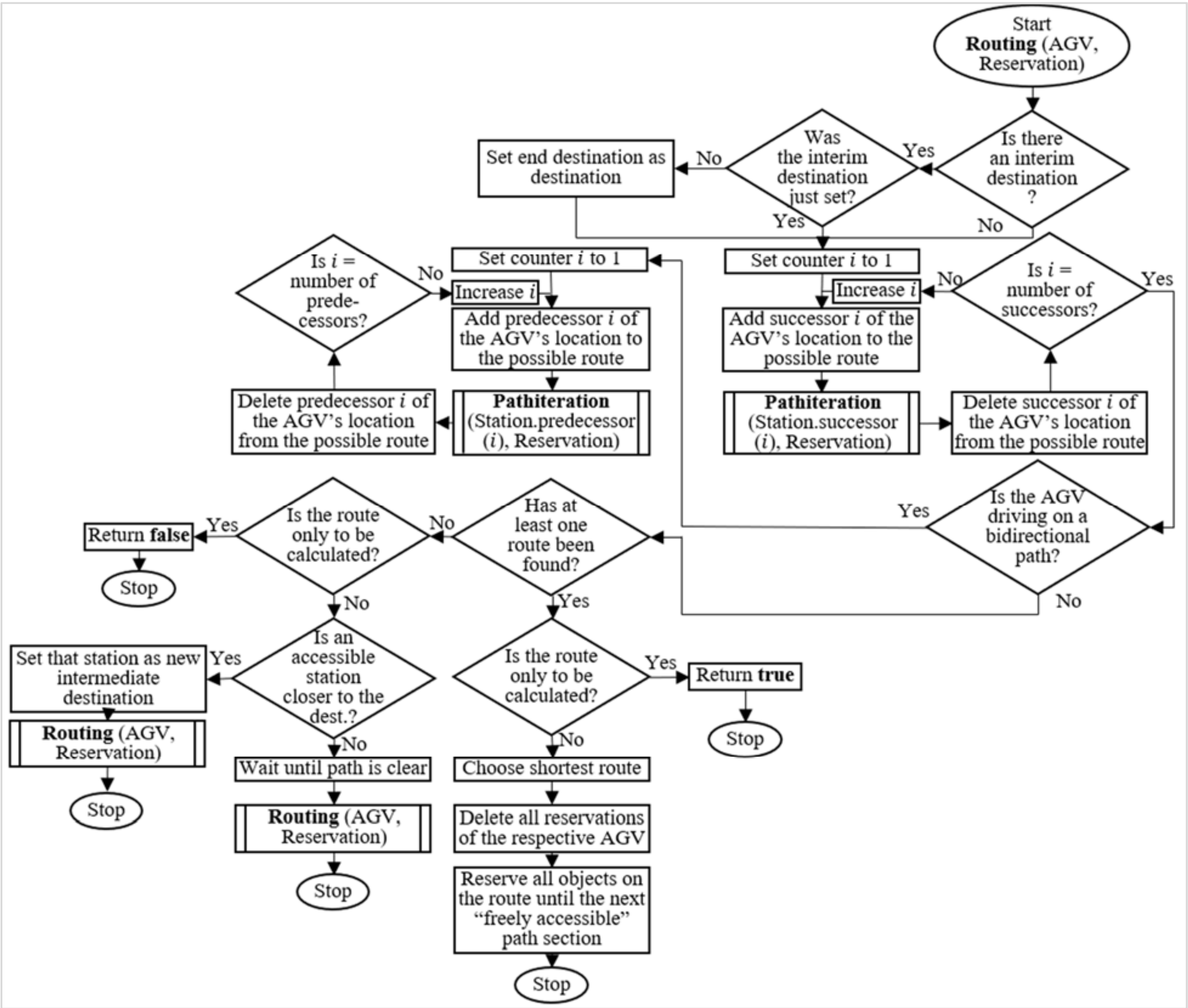


Figure 4: Flow chart of the deadlock avoidance algorithm.

If all options have been determined here, this successor will be deleted from the potential route before the next one is considered. In the event that the AGV is on a two-lane path and the opposite direction is not blocked, the route search is also carried out according to the same principle against the direction of travel. After all potential starting points have been checked, a query is made whether at least one route has been found. If this is not the case, the value "false" is returned if the procedure was called in the "Calculate only" mode. Otherwise, it is checked whether a section of the route can be reached that is closer to the destination than the current location. In this case, this is set as an interim destination and the procedure is restarted. If there is no such route, the system waits for something to change in the system before the destination determination is restarted. If at least one route has been found, a query is also made as to whether the route should only be calculated – for example, to decide whether the AGV can take over an order or not. In this case the return is "true" and the algorithm is ended. Otherwise, the shortest route is selected and assigned to the vehicle. In the next step, all reservations for the AGV are deleted before the opposite direction is blocked for all sections of the route. If there is an object within the route that can be freely navigated (e.g., the connection route if it is navigable on two lanes), reservations will be made only at this point at a later point in time. For this purpose, the destination determination on this section of the route is called again.

4 SIMULATION MODEL AND EXPERIMENT PLAN

The experiments were carried out in the simulation software “Plant Simulation” version 15.1.1. We programmed the methods with the integrated programming language “SimTalk 2.0”. Figure 5 shows an overview of the simulation model. The way sections and storage blocks on the left side are dynamically created at the beginning of a simulation run depending on the input parameters (green area). The orange area consists of tables and methods to calculate statistics, e.g., about fulfilled transport orders or the accumulation of waiting time of the AGVs. The yellow area represents all relevant results of a simulation run. The brown area contains most of the methods and is responsible for the control of the material flow. Typical methods are the calculation of the shortest path, the distribution of transport orders, and the methods for deadlock handling. The blue area consists of the control of the experiments and the methods for the initialization of the simulation model. The blue area has some miscellaneous variables, which are mostly relevant for the export of data into Excel.

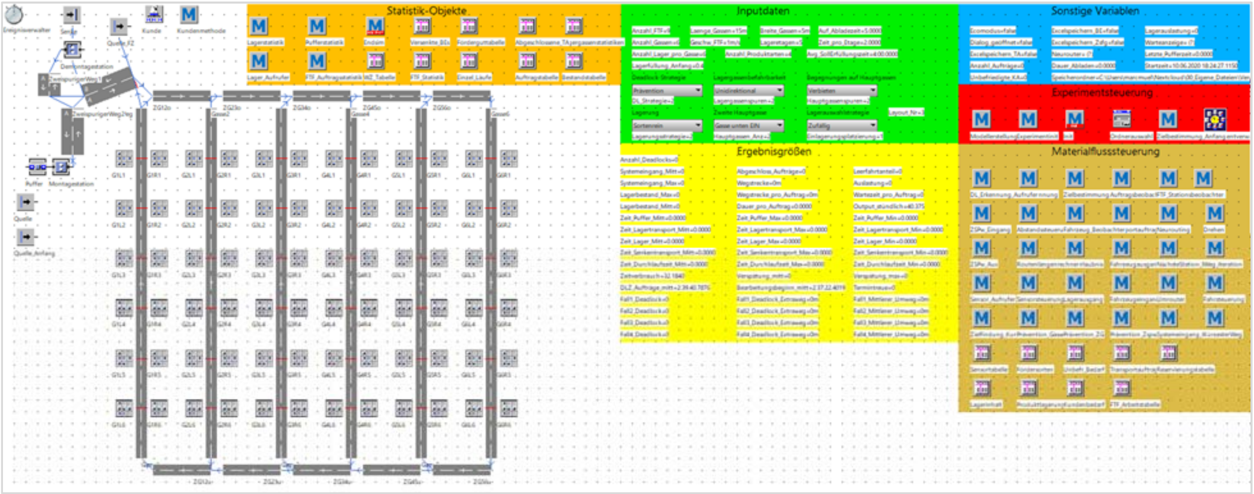


Figure 5: Overview of the simulation model.

There is no objective indication of the validity of a simulation model (Rabe et al. 2008). We carried out various methods to validate the simulation model. The validation of the simulation model was possible just to a limited extent because of a missing real example scenario. The first method for validation we used was “Structured Walkthrough”, where we checked each statement of the code until we were convinced of the correctness of the statements (Rabe et al. 2008). Through the method “Animation” (Rabe et al. 2008), in which the visualization function of the simulation software is used to observe whether the processes in the model appear plausible and realistic, we could also validate the simulation model without a real model. The “Internal Validity Test” is based on a stochastic model in which several simulation runs with different random number seeds are carried out with the same parameters. Unexplainable deviations indicate possible errors in the simulation model (Rabe et al. 2008). We carried out these internal validity tests until there were no more unexplainable deviations.

There is no warm-up time in the simulation runs. We decided to work with initial stocks in the warehouse and were unable to determine any particularities at the beginning of the simulation when looking at the inventory history. We set the following inputs parameters:

1. The variety of products is limited to four types.
2. The maximum speed of AGVS is set to 1m/s.
3. The time spent on loading and unloading of AGVS is assumed to be 5 s and 2 s.
4. The warehouse layout includes six storage aisles.
5. The input material flow follows a triangular probability distribution: (25, 30, 35) s.
6. Each 30 s a new outsource request is in the system.
7. A sorted storage strategy assigns a storage bin to the order arriving at the system.

Table 1 shows the adjustment parameters for the first series of experiments. The simulation period was eight hours, and ten simulation runs were performed per experiment. To evaluate the deadlock handling strategies and warehouse performance, we conducted experiments to compare different combinations of strategies and layout designs based on different lengths of bearing lanes and number of AGVs.

Table 1: Adjustment parameters for the first series of experiments.

Deadlock handling strategy	Warehouse layouts	Number of AGVs	Length of storage aisles	Number of combinations
Prevention	1, 5, 6	3, 4, 5, 6, 7, 8, 9	15 m, 30 m, 45 m	**63**
Avoidance	1, 2, 3, 4, 5, 6	3, 4, 5, 6, 7, 8, 9	15 m, 30 m, 45 m	**126**
Detection and recovery	1, 3, 4	3, 4, 5, 6, 7, 8, 9	15 m, 30 m, 45 m	**63**
			Total experiments	**252**

In a second series of experiments, we investigated the influence of changing the number of storage aisles (4,6,8,10). The number of AGVs became a fixed input parameter and was set to 7. All other input parameters stayed the same. The second series of experiments consisted of 144 experiments of 10 observations each.

5 RESULTS

The throughput of the logistic system is one important key figure to evaluate the performance of the system. Figure 6 shows the average throughput per hour of layout 1. P represents the deadlock strategy prevention and A represents avoidance. The throughput heavily depends on the warehouse dimensions. With increasing length of the storage aisles, the warehouse becomes less effective for handling the input material flow and needs more AGVs to reach the maximum possible throughput. The pattern of the diagram in Figure 6 is almost the same for the layouts 3 and 4. The average throughput of the prevention strategy is always lower than the average throughput of an avoidance strategy with the same adjustment parameters. An exception here are those configurations in which the maximum possible throughput has already been reached. In this case, the difference between the deadlock handling strategies is not statistically significant. The difference in throughput per hour comparing detection and resolution with avoidance is in general not statistically significant.

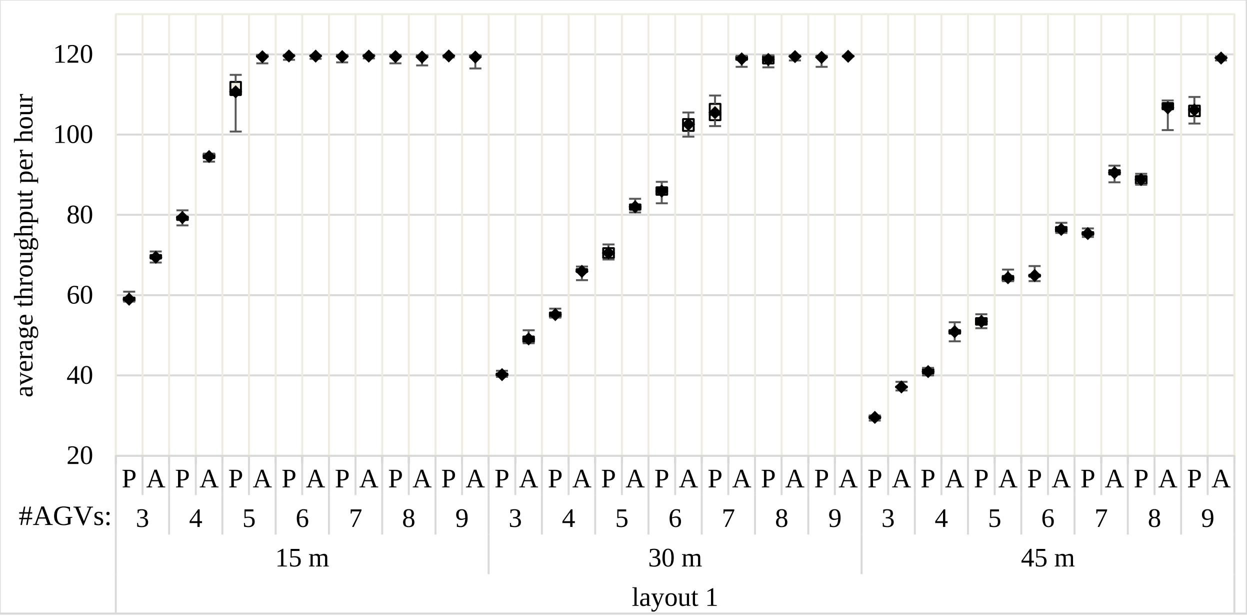


Figure 6: Average throughput per hour of layout 1.

Figure 7 shows a different behavior of the throughput while increasing the number of AGVs for layout 5. An increasing number of vehicles for the prevention strategy leads from a certain point (ca. 5-7 AGVs) to a significantly reduced throughput. Furthermore, the maximum throughput with a storage aisle length of 30 m or 45 m can be achieved by neither a prevention nor an avoidance strategy.

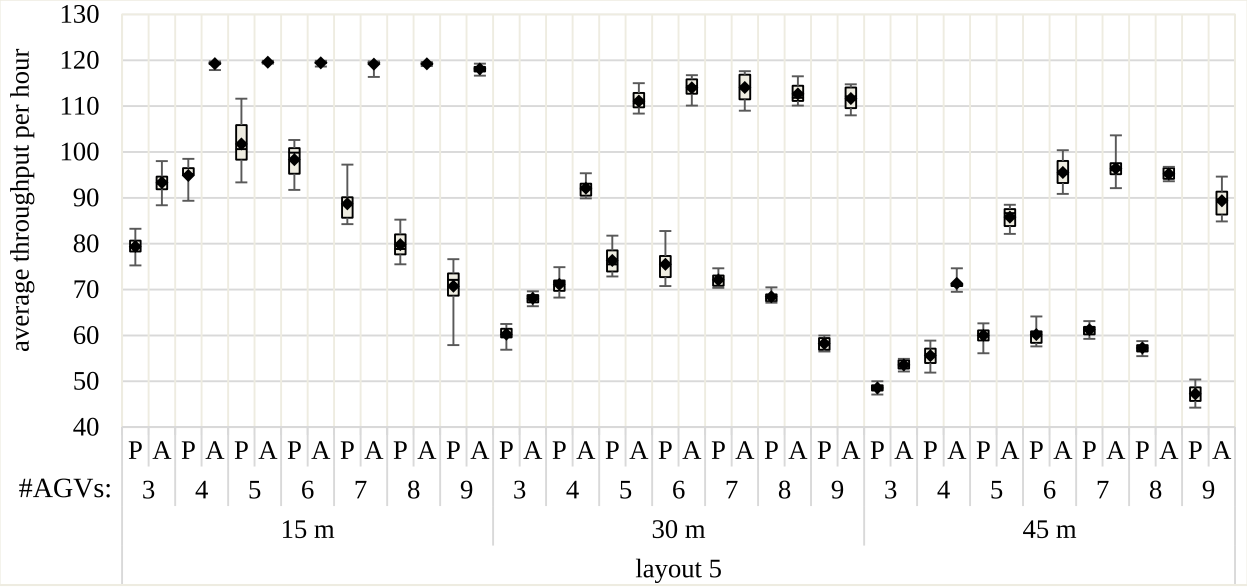


Figure 7: Average throughput per hour of layout 5.

The main reason for the worse performance of the prevention strategy is the increased average waiting time per transport order. The waiting time is increasing with more AGVs. However, it depends on the layout and even the number of AGVs in the same layout if the detection and recovery strategy or the avoidance strategy is better regarding the average waiting time. Figure 8 shows this aspect for layout 3. The average waiting time for a small number of vehicles for the detection and resolution strategy (DR) is higher than for an avoidance strategy. This applies in particular to the experiments with a storage aisle length of 15 m, in which this effect proves to be significant up to and including six AGVs. This could be due to the fact that the vehicles only have to wait a short time for a free route with the avoidance strategy, while the AGVs in a detection and resolution strategy may have to wait relatively long behind loading or unloading AGVs. The fact that this occurred above all with the shortest storage aisle length supports the argumentation above, since reserved sections of the route are released relatively quickly. For the remaining experiments of this length of aisle, the detection and resolution is the strategy with less waiting time. For the two configurations with longer storage aisles, the detection and resolution strategy is the significantly better strategy for four (30 m) and five (45 m) vehicles.

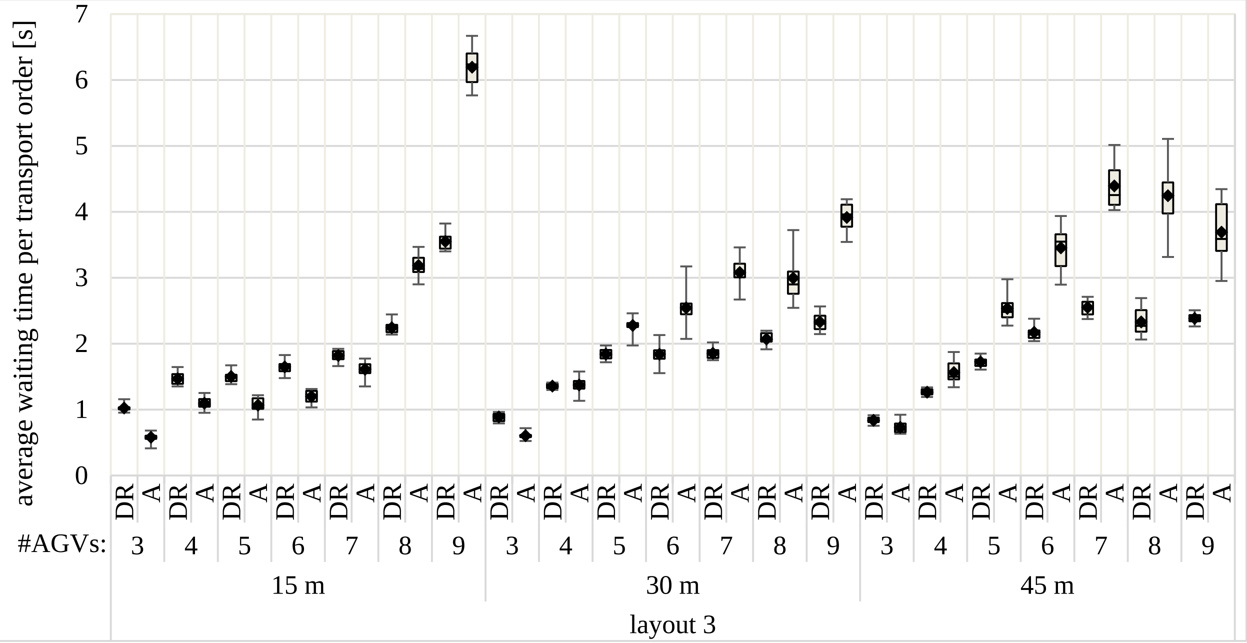


Figure 8: Average waiting time per transport order of layout 3.

The occurrence of the four different identified deadlock situations depends also heavily on the chosen layout. While, for example, in layout 1 only deadlocks of the case 1 and 2 occur, all four cases of deadlock occur in layout 3. Figure 9 shows the average amount of identified deadlocks of layout 3. The number of identified deadlocks increases with an increasing number of vehicles. However, this finding is not significant for all configurations: the increase becomes too small with a storage aisle length of 15 m and 30 m and a quantity of more than six AGVs to make statistically correct statements between an increment of one AGV. The most common deadlock situation is case 3.

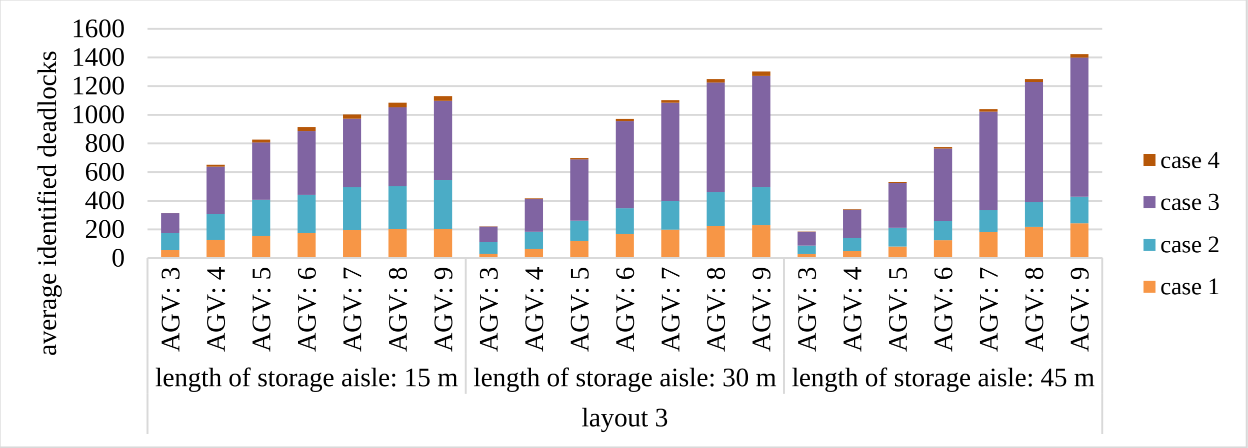


Figure 9: Average amount of identified deadlocks of layout 3.

It is not just a matter of how often deadlocks occur, but what costs they generate. It has already been shown that the waiting time is a factor that arises. There are also additional routes that are created when an AGV needs to reroute to resolve a deadlock situation. Although the throughput can be increased by a strategy of detection and resolution, the higher wear of the vehicles and the associated costs with it should be considered by a logistics planner. Depending on the deadlock situation, these detours differ significantly on average. Figure 10 shows the average detour for each deadlock case of layout 3. Cases 1 and 4 result in a longer detour on average than deadlock cases 2 and 3. This significance does not exist for the experiments with a length for storage aisles of 30 m or 45 m.

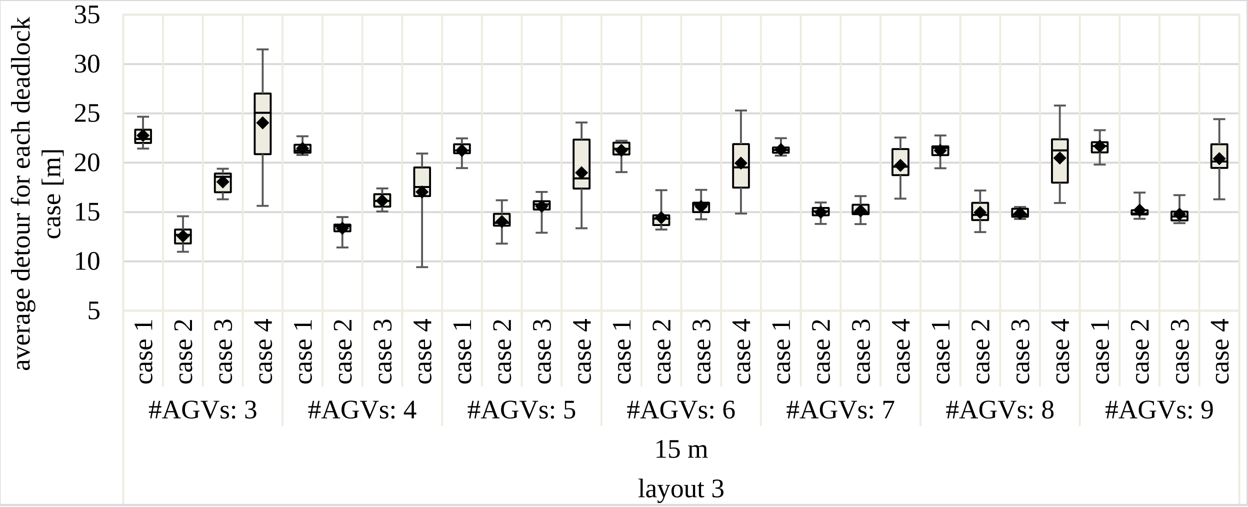


Figure 10: Average detour for each deadlock case of layout 3 with a length of storage aisles of 15 m.

6 CONCLUSION AND OUTLOOK

Not only the dimensions of the infrastructure, but even small restrictions on how the infrastructure can be used heavily affect the behavior of deadlocks and, thus, important logistic key figures. Even in logistics scenarios that appear very similar at the first glance, it is not clear which strategy for deadlock handling will turn out to be the best in terms of logistic key figures. For example, the fact that an increase in the number of AGVs results in another strategy approach to dealing with deadlocks proving to be better is important for systems that are planned so that they can simply be expanded later. An initial strategy approach may turn out to be sub-optimal in the future. Unfortunately, we could not present every result for every situation we tested, but we hope that the reader can conclude that the fast decision in literature for a strategy approach for handling deadlocks could be sub-optimal. Additionally, there is the aspect of how the individual strategy is actually implemented.

Our future work will involve conducting experiments with a change in the input parameters, e.g., changing the storage and retrieval strategies. There are also many more key figures as results of the simulation that we want to use to evaluate the performance of the deadlock handling strategies. With regard to the overall performance of the system, it is then also conceivable to combine different strategy approaches. A combination of avoiding deadlocks and recognizing and resolving them seems to us the most promising approach.

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