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DEADLOCK AND COLLISION HANDLING FOR AUTOMATED RAIL-BASED STORAGE AND RETRIEVAL UNITS

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ABSTRACT

When planning logistics systems with multiple transport objects or systems, modeling requires the implementation of complex control logic to avoid collisions and deadlocks. This paper illustrates a procedure for the development of such control logic on the example of rail-based storage and retrieval units in combinations with lifts in the picking area of an industrial laundry. Typical collision situations and a possible solution approach for avoiding these are described. In addition, a discrete event simulation demonstrates which situations occur most frequently depending on warehouse dimensioning.

1 PROBLEM AND MOTIVATION

While the term "Industry 4.0" is for some only a vague buzzword, the industry creates facts when it comes to robotic automation and equipment. Especially in the logistics sector, there was a massive increase in sold industrial robots compared to the previous years. According to the International Federation of Robotics (IFR), the number of industrial logistic service robots in the industry increased from 26,294 in 2016 to around 69,000 in 2017, an increase of 162 percent (International Federation of Robotics 2018). For simulation engineers, this means that more and more complex modeling of these automated systems will become necessary, and situations will increasingly arise where different transport systems, using different control logic, communicate with each other and create problematic situations such as collisions or deadlocks.

This modeling effort will increase significantly if the level of detail is sufficient. This is especially the case when a logistical system is to be completely re-planned, because then there is no decision logic from a real example. If it then comes to the interaction between different transport objects or even systems, the modeling effort increases significantly again to ensure a collision and deadlock-free behavior of the transport objects.

Therefore, this paper intends to show an exemplary procedure and explains the typical situations in an application scenario. The exemplary situation should enable a transfer to any particular problem and describe the problem more vividly than, for example, the general principles of deadlock prevention in the literature or the specific mathematic solutions for special deadlock situations.

The application scenario follows the problem from a research project called “LOCSys – Laundry Order Consolidation System”. It is a planned automated picking system for industrial laundries, for which the context and concept is explained in more detail in a previous publication (Müller et al. 2018). The example system considered is characterized by length-related resources in the form of shelf rails for moving the storage and retrieval unit (SRU) horizontally and moving resources in the form of lifts to change the height level of the SRU at each end of the shelf. The transport objects are laundry stacks with different dimensions. Figure 1 shows the basic structure of the shelf for the picking system. Since the solution should be flexible

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and applicable for various industrial laundries, the shelf length and the number of shelf levels can be set differently and therefore the system structure is not fixed.

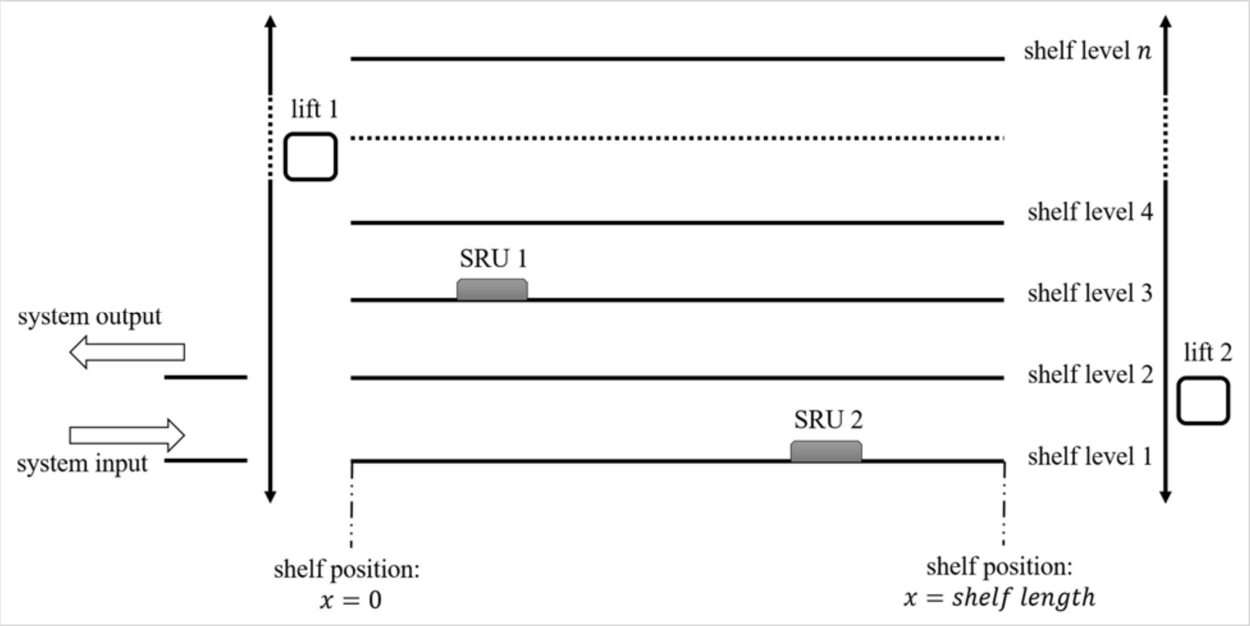

Figure 1: Front view of the conceptual model of the automated storage and retrieval system with two SRUs and two lifts. The ratio of the length of the lines to each other is not to scale but is for illustrative and understanding purposes only.

In the course of the project, it has been found that the throughput of the system is very limited and easy expandability of the system for different industrial laundries should be ensured. As a result, it was reasonable to suggest using multiple storage and retrieval on the same infrastructure to increase throughput and efficiency of the system. In addition, the basic prerequisites for future extensions would have already been created and a possible scaling ensured. With the introduction of additional storage and retrieval units, the operational planning has to face additional collision avoidance problems, which are considered in this paper. Due to the conditions of the research project, the number of storage and retrieval units is assumed to be two. From three units, there would be a few more special cases and there would be also some bottlenecks due to the infrastructure. It is also important to mention that we assume/plan both the system input and the system output left-sided, which affects later rules for the resolution of deadlocks. Changing this assumption would also result in changes to the rules mentioned above. We also assume the use of two lifts, which offers alternative routes for destination finding and more alternatives to avoid collision and resolve deadlocks.

2 COLLISION AVOIDANCE AND DEADLOCK PREVENTION IN LITERATURE

Collision avoidance is a widespread topic in the literature, but heavily characterized by the different applications. Either traffic-logistic collision problems are considered, whereby the mode of transport has considerably more degrees of freedom than in our application case, as for example the collision avoidance on the sea (Chauvin and Lardjane 2008), or in the logistic area industrial robots with gripping devices are considered in detail, as well as any distance measurements to avoid collisions of the gripper with the environment (Wahrmann et al. 2019). Direct problem-oriented considerations regarding our application are rare in connection with the term "collision avoidance", but they do occur (Hung et al. 2018).

Much more frequently, solutions are found in connection with the terms "deadlock" or "deadlock prevention". Although the term basically describes something other than collision avoidance, it seems to appear more often in the context of intralogistics transport systems, although both issues play a role there. A more detailed literature analysis in conjunction with a bibliographic map may provide an answer to this phenomenon, but should not be considered in depth in this application paper.

The term "deadlock" in the context of systems requires a bit of explanation and was explained in detail in 1971 by Coffman et al. They state that the "the deadlock problem is a logical one" (Coffman et al. 1971) and "[...] becomes more complex when a system has different resource types and, in general, more than one resource of the same type." (Coffman et al. 1971). Although the authors use the topic of multiprogramming as an example, their developed conditions for the creation deadlocks are cross-problematic. These four conditions are widely used in the literature and are as follows (Coffman et al. 1971):

1. “Tasks claim exclusive control of the resources they require ("mutual exclusion" condition).”
2. “Tasks hold resources already allocated to them while waiting for additional resources ("wait for" condition).”
3. “Resources cannot be forcibly removed from the tasks holding them until the resources are used to completion ("no preemption" condition).”
4. “A circular chain of tasks exists, such that each task holds one or more resources that are being requested by the next task in the chain ("circular wait" condition). The existence of these conditions effectively defines a state of deadlock.”

Consequently, an attempt is made to break one of these conditions in the development of control logics. In contrast to the collision, a deadlock does not necessarily lead to material damage. However, the deadlock begins with the infinite waiting of two transport objects and usually subsequently also causes the waiting for further transport objects, until finally the entire transport system comes to a standstill, unless the situation is resolved. A simple and common way to avoid this in warehouse logistics is that rack aisles are only reserved for one storage and retrieval unit. Due to this fixed zoning, the devices do not come into contact with each other and there are no conflict situations. As a rule, such an approach leads to a lower efficiency of the overall system, because individual areas are less heavily utilized or additional waiting times occur due to the increased stress of one area. In addition, such a separate division sometimes for practical reasons (for example area requirements) is not even possible.

Lienert and Fottner provide a solution to face the deadlock problem with reserving time slots for the resources. This method requires a sufficiently deterministic system with sufficient information so that the transport orders can be calculated in advance.

3 METHODOLOGY AND SOLUTION APPROACH

3.1 Problematic Situations

Admittedly, we largely discovered the problematic situations during the modeling process in the simulation software and solved iteratively with each additional control rule the collision cases. The introduction of just one other storage and retrieval unit on the same infrastructure raised a few questions that needed clarification. Answering these detailed questions was the task of the simulation engineer, as this expandability of the system was initially only required as a feature of the simulation model and not of the real demonstrator in the research project. First, we identified typical situations that led to collisions that could directly generate software error messages and thus be easily discovered in the model.

Figure 2 shows the four identified cases we considered in detail. In the first case, one SRU is on a lift and wants to move onto the shelf rail. However, there is already a SRU on this shelf rail that may be on the way to the target position of SRU 2. The second case arises when two SRUs are located on each lift at the same time and want to move to the same shelf rail within a narrow time interval. The target positions on the shelf rail could possibly be crosswise. Case 3 occurs, if in case 1 is allowed for SRU 2 to move onto the shelf rail because SRU 1 is not on the way to the target position of SRU 2 or in case 2, if the target positions are not crosswise. If we would decide for a complete reservation of a shelf rail, as soon as a SRU is located on it, case 3 would never occur. We anticipate at this point that we did not decided for a complete reservation because to be able to work more effectively with two SRUs on one shelf rail, especially on longer shelves on high frequented shelf levels. Case 4 considers the special features by the arrangement of the system boundaries. The system input and output are on a different shelf rail, which are not attached to the shelf, but to a transfer point. This leads to intersections with respect to the directions of movement and to critical resources, since exactly one destination has to be approached for each loading or unloading of laundry stacks. Case 4 includes both the case of an occupying SRU on the system input rail as in Figure 2 and the also possible situation that a SRU is blocking the system output rail.

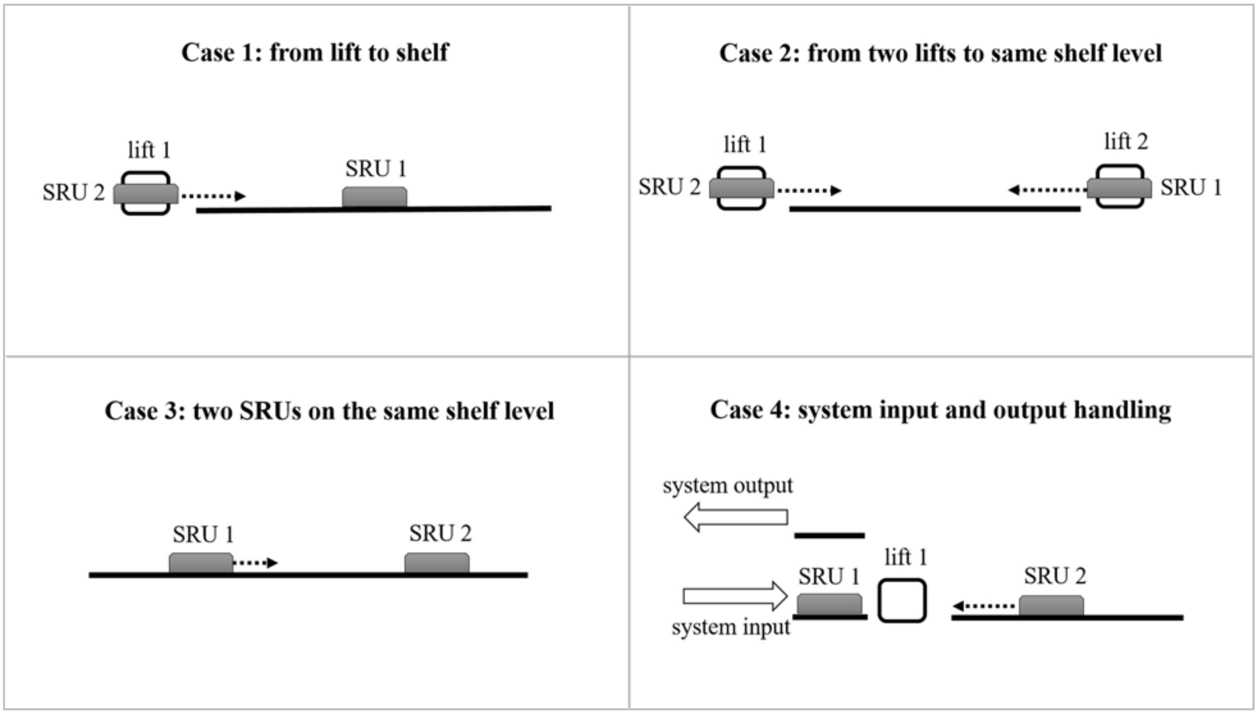

Figure 2: There are four typical problematic situations to handle to prevent collisions or deadlocks.

In the example of the figure SRU 2 wants to move to the system input, which is blocked by SRU 1. A simple rule could avoid a collision by just let SRU 2 wait for SRU 1 to leave the system input. However, if SRU 2 has already reserved lift 1 for itself or even is already in the process of getting on the lift, the situation leads to the problem of what occurred in the second phase of the technical implementation of the two SRUs: deadlocks.

In the considered system in conjunction with our assumptions the following three resource types are used for the transport of laundry stacks:

- Two storage and retrieval units: R_{SRU1}, R_{SRU2}
- Two lifts: R_{lift1}, R_{lift2}
- n shelf rails: R_{railIn}; $R_{railOut}$; R_{rail1}, R_{rail2}, … R_{railn}

These resources are related to each other by a requesting task T. The relation between the resources can be illustrated in a state graph where the nodes are the resources R and arrows represent the requesting tasks T (compare: Coffman et al. 1971). Figure 3 shows as an example the state graph for case 4, assuming that SRU 2 is already requesting lift 1. In this case R_{SRU2} waits for the resource R_{railIn} to get released while occupying R_{lift1} and R_{rail1} and R_{SRU1} waits for the release of R_{lift1} while occupying R_{railIn}. All four conditions for a deadlock are met: The request tasks claim exclusive control (capacity of one SRU on R_{railIn} and R_{lift1}), the tasks hold resources already allocated, the allocated resources cannot be removed easily and the next tasks create a chain circular of resource requests.

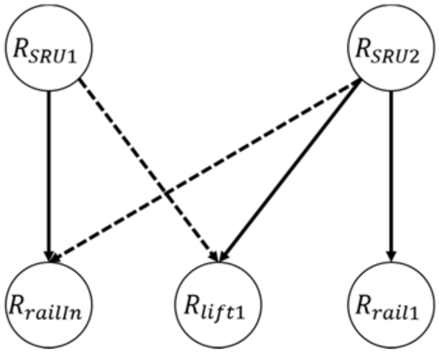

Figure 3: State graph of case 4.

Deadlocks are more difficult to detect than collisions in the simulation model. In the case of collisions, the simulation model (at least in our software used) stops immediately and the situation can then be investigated directly. Deadlocks, on the other hand, only bring the transport objects to a standstill and generally do not generate an error message. When simulating without animations, unknown deadlock situations can only be detected by proper interpretation of the simulation results, such as an unexplained reduction in throughput or crowded queues.

3.2 Solution Strategies

The collision and deadlock avoidance are in a certain conflict with each other. If the rules for collision avoidance are formulated too strictly, for example by generous reservation of resources or to extensive "wait until"-commands, it quickly creates unnecessary deadlock situations. Too lax collision avoidance rules, which do not consider for example some special situations, inevitably lead to collisions if there is a longer simulation period or a lot of simulation repetitions.

In the case of collision avoidance, case 3 in particular is the last instance to bear, as it is also triggered when a second SRU moves on a shelf rail with an SRU and case 1, for example, did not trigger. The incoming SRU would trigger the collision avoidance method in this case. The SRU, which is already on the shelf rail, would be treated as a so-called "occupying SRU". With this definition, the usual situation shown in Figure 4 results on a shelf rail. In this case, the occupying SRU can always be classified into one of two position categories: Either it is an obstacle on the way of the entering SRU (position 1) or it is not on this planned route (position 2). Then the direction of movement is considered in terms of acceleration and speed. Position 2 is the more favorable case, since at standstill of the occupying SRU or the same direction of movement as the incoming SRU there is no risk of collision. However, if the occupying SRU is moving into the direction of the entering SRU, the target x-position of the occupying SRU must be considered. If the target position is on the way of the entering SRU, the occupying SRU must perform an evasive maneuver. This usually takes place on the same shelf rail. However, if the space is no longer sufficient, the lift at the end of the shelf is used as a resource to perform the evasive maneuver.

Position 1 is the worst case. In this position in the case of a standstill or the movement to the incoming SRU, an evasive maneuver is in any case initiated for the occupying SRU. If the occupying SRU has the same direction of movement as the entering SRU, the target position must be considered again. If this is outside the front position of the entering SRU plus the minimum distance between two SRUs, the method of collision avoidance is successfully terminated; if this is not the case, an evasive maneuver must also be performed.

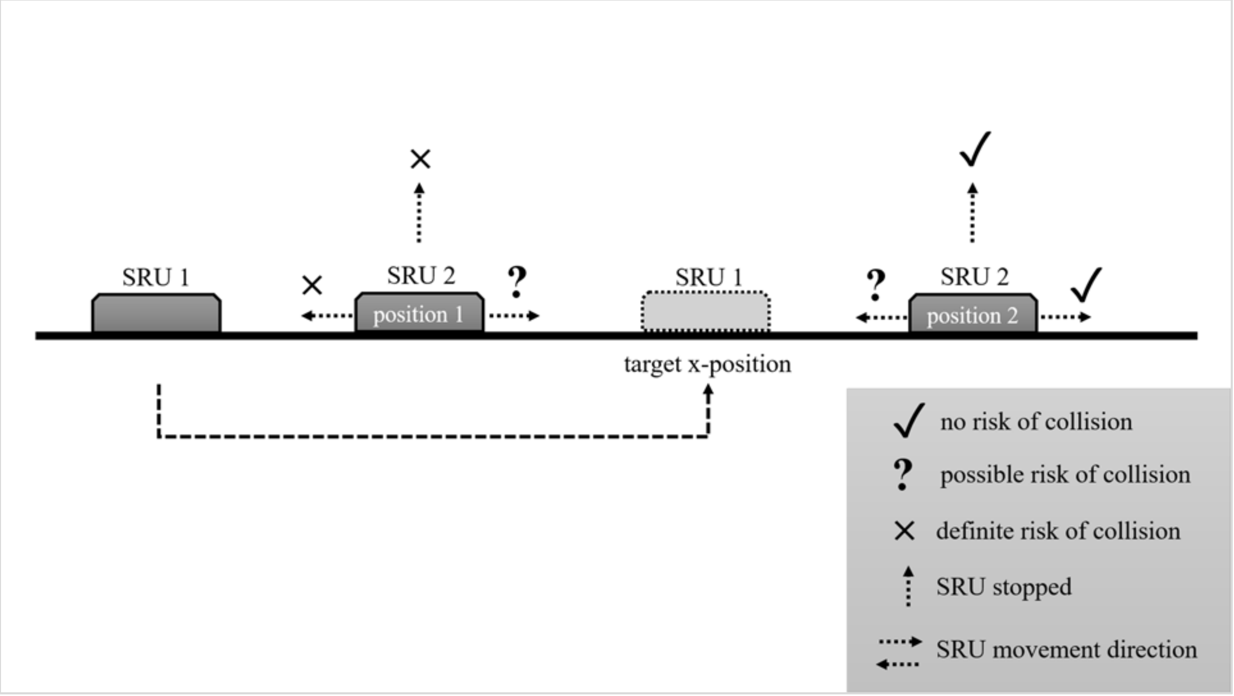

Figure 4: SRU 1 wants to move to its target x-position. A possible second SRU could be in the way. The movement direction of the second SRU is important to determine, if there is a risk of collision.

We also assume at this point that the acceleration and maximum speed values are the same for both SRUs. Otherwise, the cases for the same direction of movement of both SRU would have to be considered more closely (SRU 1 could be faster than SRU 2). These and other conceptual considerations of collision situations then result in flowcharts for algorithms. As an example, Figure 5 shows the same case as in Figure 4 as a flowchart. Various if-statements have to be checked and the initial situation (relative position of the SRU to each other) is clear. Already in this small extract of the control it is noticeable that some if-statements occur several times. Although loops would be a typical solution to reduce these statements, they are also particularly vulnerable to deadlocks if some of the conditions are not met again.

Another strategy to prevent deadlocks is the use of asymmetric control rules. Due to the arrangement of the system input and output, we have decided for a left-sided priority of SRUs if it is necessary to start an evasive or waiting maneuvers. That means only the right SRU has to wait or dodge. If the right SRU is the occupying shuttle, it may still finish its transport order and it will then be checked whether a conflict situation continues to prevail. As a result, the already heavily used intersection between system input, lift 1 and shelf rail 1 is not additionally claimed by evasive maneuvers. In the future, this rule should be extended by the urgency of a picking order, to ensure that in particularly urgent cases an avoidance maneuver could also claim critical resources as the system input rail, in order to assure a punctual delivery.

Despite the selected special cases we can derive a general process chain, which is used to avoid collisions and deadlock in our approach. Figure 6 shows the different process steps, whereby not every time every step is considered. First, it is checked whether an evasive maneuver takes place for the triggering SRU and, if necessary, it is waited until the evade process has ended, in order to avoid that several evasive procedures are triggered. It then checks on which infrastructure the SRU is located in order to limit the class of problem cases. It then checks to see if there is another SRU on the destination infrastructure (not the final destination but the successor infrastructure in the movement route). Subsequently, the relative position is clarified to know which SRU is left or right and therefore has priority. Finally, a reaction occurs that either ignores avoidance maneuvers when there is no conflict, or the SRU is waiting or initiating an evasive maneuver.

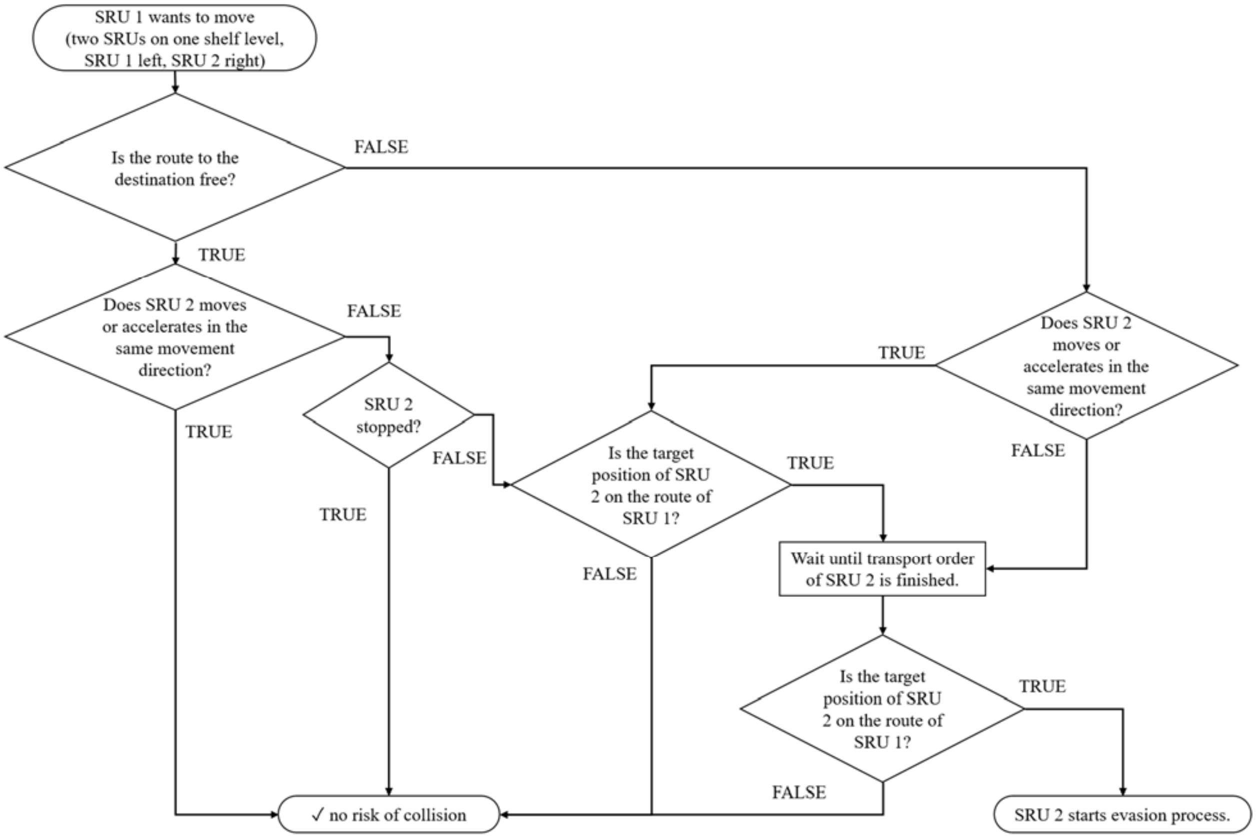

Figure 5: This flowchart shows the algorithm for collision handling for case 3. This decision part only triggers if the triggering SRU is on the left side.

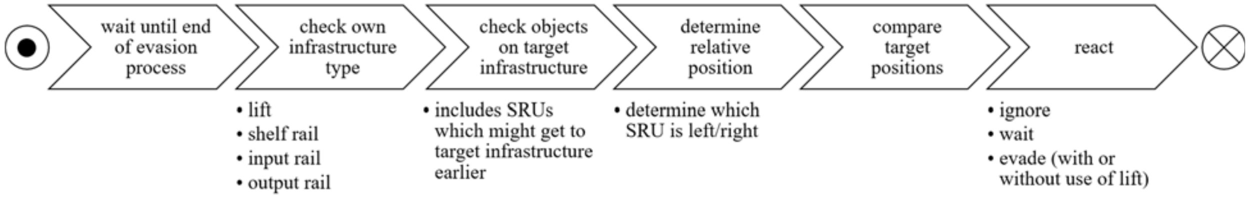

Figure 6: Process chain for collision and deadlock avoidance in the application scenario.

4 EXPERIMENT PLANNING

The aim of the simulation experiments is on the one hand to gain knowledge about the proportion and the fluctuations of the respective problem cases and to identify possible influencing factors on the composition of the considered cases. Our hypothesis is that the most occurring case is case 3, as it also triggers when a second SRU enters the shelf rail and the least occurring case would be case 2 because the short time window of two SRU on each lift seems to be a rare occasion. The shelf length should be examined as an adjustment variable with regard to its influence on the results. The other considered variables for experiment planning are the input parameters listed in Table 1. We hypothesize that the most common case 3 occurs more frequently with longer shelves, as more SRUs remain on the same shelf level because there is less need to store laundry items on higher shelf levels. The considered simulation period is 24 hours and 20 simulation runs per experiment are performed.

Table 1: The input parameters represent the material flow in a small industrial laundry. The system load roughly corresponds to the approximate limit of throughput of the automated picking system.

input parameter	value
amount shelf levels	6
laundry items per day	5,000
proportion of incoming full laundry stacks on the entire incoming material flow	0.7
SRU loading time	5 s
SRU unloading time	5 s

The shelf length is the only adjustment parameter and varies from 5 to 15 meters with an increment of 1 meter. This leads to 11 experiments and in total 220 simulation runs.

5 RESULTS

The variation of the shelf length also influences the limit of the throughput of the system. Too small shelf lengths lead, as Figure 7 shows, to a sharp decrease in material flow. The large fluctuations indicate that in some simulation runs the system was able to deal with the incoming material flow, but in others it came to a standstill due to the overcrowding of the warehouse. This depends on the randomly distributed input sequence and arrival times of the incoming laundry stacks. Of course, small shelves have the shorter transport routes. The successful simulation runs of the short shelf lengths therefore have even better values and in some cases reach nearly the maximum of the possible 500 picked laundry stacks. Due to the strong fluctuations, the upper confidence interval limit is set above this maximum value. The results also show that with increasing shelf length, the picking performance gradually decreases.

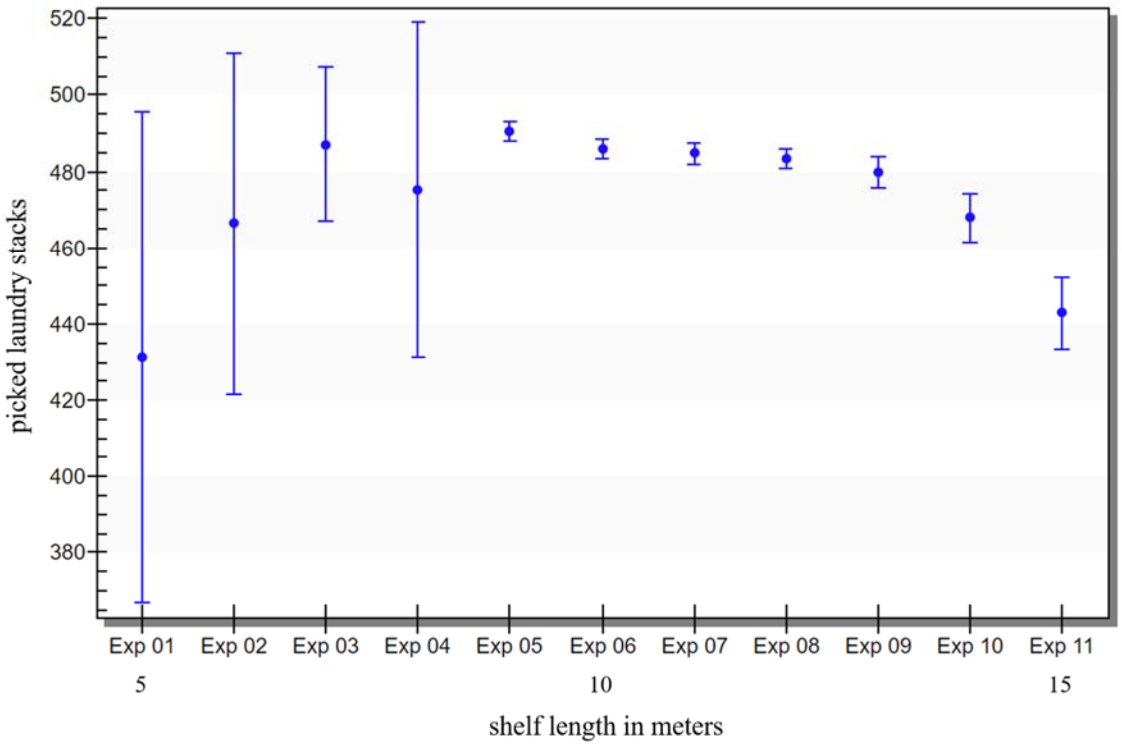

Figure 7: The confidence interval and average number of picked laundry stacks leaving the sink in dependence of the shelf length.

Starting with a shelf length of 9 meters in experiment 5, the automatic picking system is capable of handling the incoming material flow in each simulation run. Therefore, to compare the change in composition from the number of occurrences of the four problem cases, experiment 5 should be compared with experiment 11 to see biggest impact on composition. Figure 8 shows this comparison and also shows that the increase of shelf length leads to a big increase of case 4 and a decrease of case 3. Case 2 can be considered as a special case with just 1 to 3 percent occurrence.

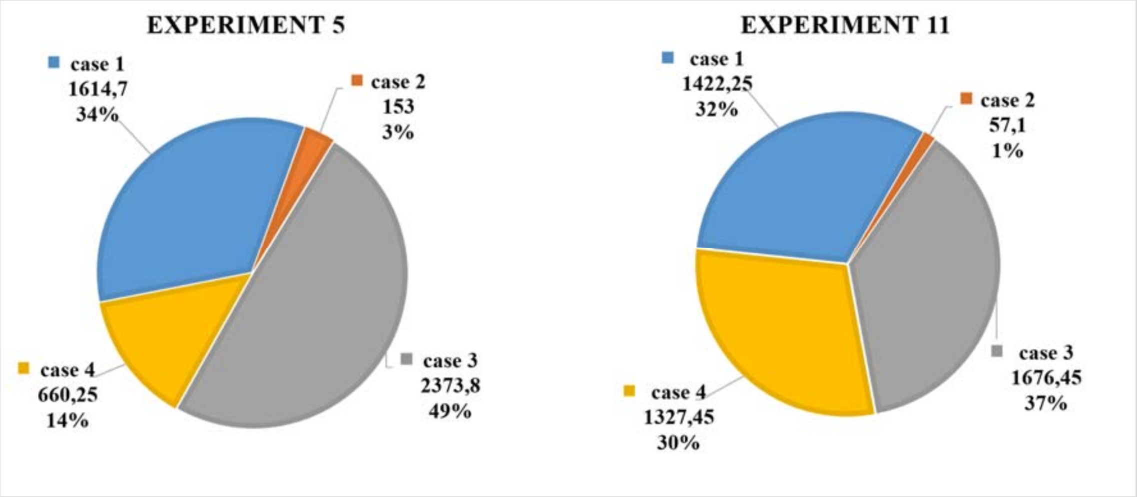

Figure 8: The two pie charts show the composition of the occurring problem cases for collision and deadlock handling.

This means that the hypothesis is rejected and more shelf length leads to more handling of system input and output situations. One explanation is that one SRU could occupy the first shelf level most of the time because many transport orders could be fulfilled with picking and consolidating in the first shelf level. Therefore the second SRU probably waits for a free system input rail most of the time.

In total the amount of problematic situations decreases in average from 4,801.75 to 4,483.25 if you increase the shelf length from 9 to 15 meters. This reduction however does not mean that the situations improve. For example, the amount of case 3 situations decreases by 697.35 but, as Figure 9 shows, the total waiting time in this case increases. The total waiting time emerges if one SRU waits for another SRU to finish its transport order or evasion process.

6 CONCLUSION AND OUTLOOK

This paper describes a rule-based and reactive algorithm for collision avoidance of storage and retrieval units. It has been shown that using multiple SRUs on the same infrastructure raises a whole range of questions. Many of them can be solved by logical considerations, but must be formulated in detail and clarified. In the simulation model, the search for deadlocks is sometimes very cumbersome because they are rare and difficult to find, especially for very special problem cases. The experiments have shown that there are influencing factors that significantly influence the number and the proportion of possible collision situations. Nevertheless, the resulting waiting time must always be considered in order to be able to make a meaningful statement. This rating could be extended by further results, such as the ratio of on-time deliveries.

Especially for systems with a large number of SRUs, a considerable coordination effort is required, since SRUs that perform collision avoidance also have to perform a collision check on other SRUs. Therefore, the behavior of the system can be described as coordinated but not cooperative. In the genuinely cooperative joint planning of all units involved in the process, which coordinate their driving trajectories to achieve an overall process goal (maximize throughput), there is considerable potential for increasing efficiency. Further work will therefore examine recent research approaches from mobile robotics and from cooperative automated vehicles for their suitability and transferability to the application scenario (Lagoudakis et al. 2005).

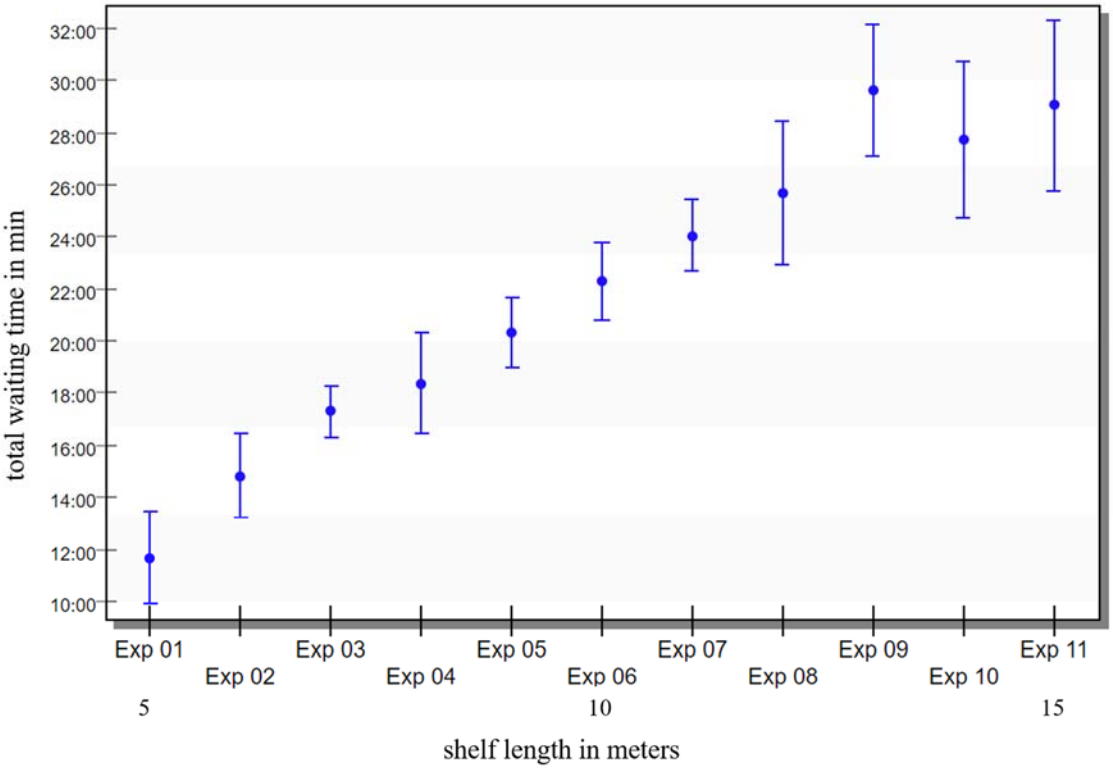

Figure 9: The confidence interval and average amount of total waiting of case 3 in dependence of the shelf length.

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