An Agent-Based Simulation Model for Deadlock Prevention in an Aisle-to-Aisle SBS/RS

Ecem Eroglu and Banu Yetkin Ekren

Abstract Flexibility and high throughput rate in storage and retrieval systems are essential criteria in today's competitive marketing. Recent developments in information technology enable the intelligent design of systems. This study aims to propose a tier-captive aisle-to-aisle shuttle-based storage and retrieval system (SBS/RS) where shuttles can make autonomous decisions to prevent deadlocks and collisions as well as the efficient process of transactions. Deadlock prevention algorithms are one of the primary concerns in today's autonomous vehicle environment. In the considered tier-captive aisle-to-aisle SBS/RS, multiple shuttles can travel between aisles in a dedicated tier. The advantage of this design is that there may be the fewer total number of shuttles running in the system compared to a traditional tier-captive SBS/RS. Due to the complexity of the proposed system and autonomous shuttle-based decision-making target, we utilized the advantage of an agent-based modeling approach by simulating the system. Agent definitions, roles, and behaviors are specified to ensure that no collision and blockage take place in the system. Thanks to the intelligent abilities of agents so that the system can run effectively by using real-time information.

Keywords Agent-based simulation · Deadlock prevention · SBS · RS · Tier-captive · Aisle-to-aisle SBS · RS · Smart decision

Introduction

Warehouses are critical for supply chains. Autonomous vehicle-based warehousing technologies are emerging and providing challenging advantages for the efficient operation of warehouses. Shuttle-based storage and retrieval system (SBS/RS) is

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one of such technologies mostly utilized for large distribution centers due to its high capacity of transaction rate. It is an alternative design for other traditional automated storage and retrieval systems [7, 9]. An SBS/RS is composed of storage racks, shuttles, and lifts. Shuttles perform horizontal travel for storage and retrieval transactions. There is a single lifting mechanism at each aisle installed at an endpoint of the aisle carrying loads (i.e., totes) between tiers. Figure 1 shows a typical SBS/RS design where there is a dedicated shuttle in each tier (i.e., multiple aisles of a tier).

Note that in a tier-captive SBS/RS there is a tier-captive shuttle in a tier of an aisle [2]. It is known to be a traditional SBS/RS design in the literature. In that design, the average utilization of shuttles is usually very low compared to the average utilization of lifts. Namely, lifts are mostly bottlenecks in those designs [1, 3–5, 8, 11, 12]. In an effort to increase the utilization of shuttles and decrease the initial investment cost of SBS/RS, we propose an alternative design for SBS/RS in which shuttles are tier-captive and aisle-to-aisle. In that design, shuttles can travel between aisles within a tier. The advantage of this design is that it may have a relatively lower total number of shuttles and decreased investment cost compared to a traditional design. However, the disadvantage of this design might be the complexity of operational management due to collision and deadlock possibilities of shuttles while traveling in the same area. Thus, developing efficient operation rules for shuttles resulting in efficiently processing becomes a significant issue in this case. In this paper, we study to develop smart operational rules in order to prevent collisions and deadlocks of shuttles by utilizing agent-based simulation modeling.

The first study of SBS/RS was carried out by Carlo and Vis [2]. They focused on scheduling of two non-passing lifts in traditional SBS/RS. They introduced two functions to evaluate candidate solutions and developed heuristic solutions for the problem. Marchet et al. [15] presented an analytical model by using an open queuing network modeling approach for tier-captive SBS/RS to estimate some performance metrics from the system. To validate the models, they compared the results with their simulation results. Later, Marchet et al. [16] studied a simulation-based work

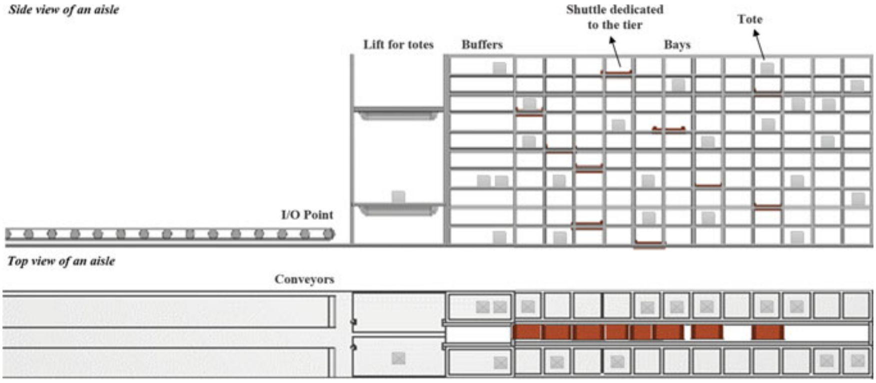

Fig. 1 A typical SBS/RS warehouse with dedicated shuttles

presenting trade-offs in tier-captive SBS/RS designs. Ekren et al. [8] consider a class-based storage policy in the process of SBS/RS, resulting in decreased cycle time.

Lerher [10] developed analytical travel time models for SBS/RS with aisle changing shuttle carriers as one of the most related work to this proposed study. However, there is a single dedicated shuttle for a tier of multiple aisles to prevent any collision or deadlock in the system. Differently, we consider multiple shuttles that can travel between tiers by a separate lifting mechanism in the system and propose collision and deadlock prevention algorithms in the model.

Ekren [3] studied a simulation-based approach for the design of a traditional tier-captive SBS/RS. In order to evaluate the performance metrics based on designs promptly, she draws several graphs under various design concepts. Ekren et al. [6] proposed an open queuing network-based model that can estimate the mean and variance of travel time of lifts and shuttles per transaction in a tier-captive SBS/RS. This tool can also estimate the energy-related performance metrics based on several design parameters. Recently, Ekren [4, 5] has studied an experimental design and multi-objective optimization procedure for the design of tier-captive SBS/RS by considering the optimization of average cycle time per transaction and average energy consumption per transaction performance metrics simultaneously.

The agent-based simulation is an effective tool to evaluate the behavior of complex systems, as we showed in the proposed paper. An agent can be described as anything that can be regarded as perceiving its environment through sensors and taking action upon that environment through effectors [18]. The decision processes of agents can be described by the developers clearly at the micro-level in an agent-based simulation model. The macro-level structure of the whole system emerges as a result of the actions of the agents and the interaction between agents and the environment [19].

As mentioned previously, deadlock prevention is one of the primary concerns in this paper. Deadlock prevention includes defining some rules beforehand to prevent deadlocks. Deadlock avoidance investigates the system state and bypasses deadlocks in real-time. Deadlock prediction is a previous step of deadlock avoidance to learn the location of deadlocks in advance [20]. Lienert and Fottner [13] presented a model applying the time window routing method to move shuttles safely. They focused on tier-to-tier and aisle-to-aisle system configurations. Roy et al. [17] developed protocols for three types of vehicle blocking. Their numerical studies indicated that delays caused by blocking increases transaction cycle time significantly (10–20%).

By the advancement of information technologies enabled the smart design of systems, agent-based simulation modeling is found to be an appropriate approach to analyze such complex systems correctly. We use the ARENA 16.0 commercial software for this purpose. Since the modeling approach focuses on real-time system control and requires real-time information and communication, we utilize a higher level of modeling approach that is agent-based modeling. After developing the proper agent behaviors and decision rules, to test their robustness, we try the models under different scenarios in terms of the number of shuttles in the system.

Methodology

The System Description

The physical warehouse design of the studied tier-captive aisle-to-aisle SBS/RS differs from the traditional SBS/RS warehouse design. Figure 2 shows the physical configuration of the studied system.

Unlike a classical design, there are transition points considered for the travel of shuttles between aisles. We develop a generic simulation model such that the physical design (e.g., the number of aisles and transition points) can be changed. Except for the transition points, to prevent the deadlocks, we consider escape points attached to the waiting points. Note that after a shuttle completes a process and it becomes idle, it travels to the closest decision point not to cause a deadlock. When a busy shuttle tends to pass through a decision point, and there is an idle shuttle waiting in that point, then that idle shuttle moves to the closest waiting point and then to the escape point attached to that waiting point. The intersection points of aisles are the points where shuttles make decisions for where to travel. Namely, a shuttle first stops at the intersection point and then navigates to the target address or a new decision point. In

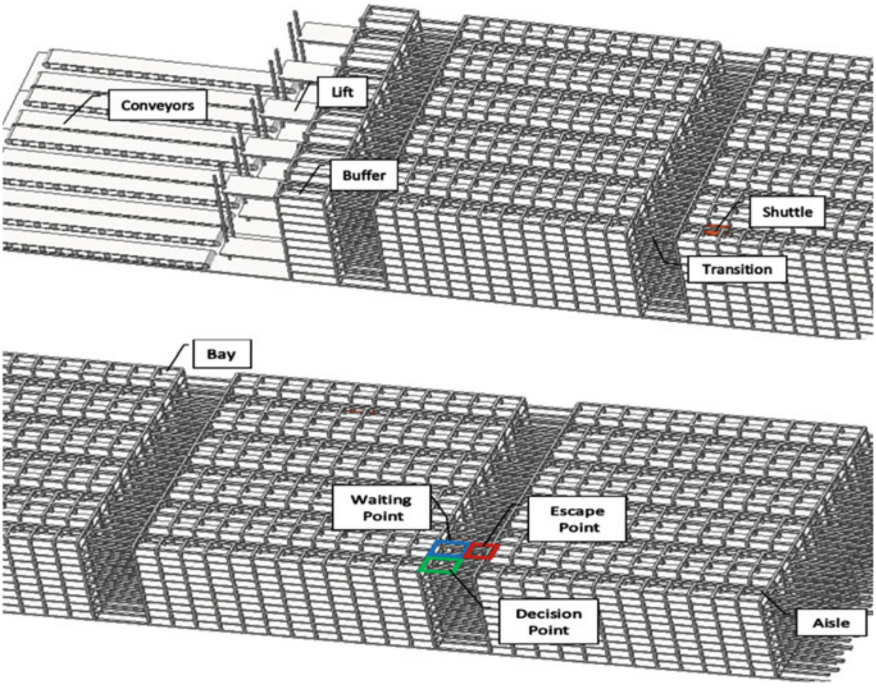

Fig. 2 The physical warehouse design of tier-captive aisle-to-aisle SBS/RS studied

this paper, three different number of shuttle scenarios in a tier are tested. These are one, two, and three number of shuttles.

To detail, there are two types of transactions arriving at the system, storage and retrieval. For storage transactions, the shuttle picks up the load from a buffer location to transfer it to its storage address (i.e., bay). For retrieval transactions, the shuttle carries the load from a bay address to a buffer location.

Agent Definitions and Roles in the Simulation Model

A typical agent-based model has three elements. First is the set of agents, their attributes, and their behaviors. Second is the set of agent relationships and methods of interactions. The third is the environment of the agents. Agents interact with their environment as well as other agents [14]. In the proposed model, three types of agents are defined:

1. Demand agent,
2. Shuttle agent, and
3. Deadlock control agent.

Each agent is modeled such that it can make an independent decision. The agent interactions, i.e., communication of agents and the environment, are shown in Fig. 3.

All the agents interact with the environment. Shuttle agents making decisions as a result of communication are in bidirectional communication with the other agents. Real-time information on system status is provided by all agents, and all can evaluate those pieces of information. The usage of this communication in decision-making is called a bidding strategy that is essential in agent-based simulation. A description of

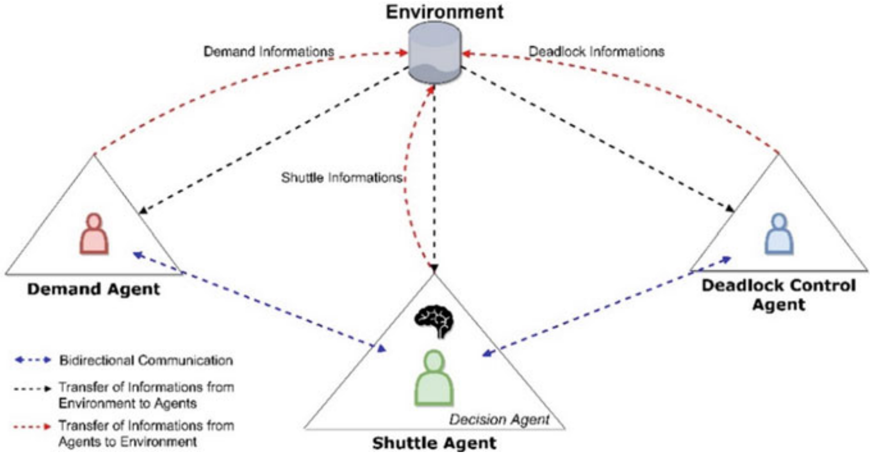

Fig. 3 Agent interactions

the rules for these behaviors is provided below. Agents in the system act under those predefined rules.

Agent Behaviors

Decisions about the system can be divided into two as design and control. Agent behaviors corresponding to the control level decisions are presented in Table 1.

Demand Agent

It tracks the arriving transaction type information as storage and retrieval requests in the system.

Distance Calculation

All, either idle or busy shuttles in the system, are candidates for any waiting demand (i.e., transaction) to be allocated. When a shuttle becomes available to process a transaction, the demand agent calculates the total travel distances based on all waiting transactions' addresses and shuttles' points. Namely, it calculates the total travel distance of a transaction when it is paired with all possible shuttle options. If the calculated shuttle is busy at that time, in travel distance calculation, the destination address of that shuttle is considered. Based on the distance results, the assignment of a transaction to the idle shuttle is decided. These decisions are taken by the shuttles. For that, first, the calculated distance pairs are sorted in increasing order, and the regarding the transaction is assigned to that idle shuttle. For instance, if there is a transaction waiting in queue whose total travel distance is the minimum one for that idle shuttle, however when it is paired with a busy shuttle its total travel distance

Table 1 Agent behaviors corresponding to control level decisions

Agent	The behavior of the agent
1. Demand Agent	1.1 Distance Calculation
2. Shuttle Agent	2.1 Demand Assignment
	2.2 Dwell Point Policy
	2.3 Decision Point Policy
	2.4 Deadlock Control Policy
	2.5 Direction Decision
	2.6 Triggering Policy
	2.7 Alternative Way Policy
3. Deadlock Control Agent	3.1 Deadlock Case–Control

is much smaller than that idle one, then this transaction is not assigned to that idle shuttle. The idle shuttle selects the next option for it.

Shuttle Agent

The action (i.e., transaction selection) decisions in the system are taken by the shuttle agents. The rule is explained below.

Demand Assignment
By considering the total travel distance values calculated by the demand agent, the available shuttle selects the shortest possible transaction to process. Namely, it does not always select the shortest travel distanced transaction if this transaction's total travel distance is less when it is paired with a busy shuttle.

Dwell Point Policy
An idle shuttle always waits at a decision point located at the upper level of its current condition. If this point is full, a triggering policy is applied.

Decision Point Policy
Shuttle always travels at a decision point through its direction. While a shuttle is traveling, if that target decision point is occupied by another shuttle then, a triggering policy is applied.

Deadlock Control Policy
A deadlock control policy is activated when a shuttle notices a collision possibility. Accordingly, a triggering policy or direction policy is applied.

Direction Decision

Depending on the direction of the demand, this decision selects a proper decision point to proceed.

Triggering Policy

Trigger to go to Waiting Points:

An active shuttle triggers the waiting shuttle at the decision point that is on its way to let it go to a waiting point. The active shuttle waits until it reaches to the waiting station.

Triggering to Escape Station Policy:

When an idle shuttle is at a waiting point, an active shuttle may trigger it to the escape point if it is on its way.

Alternative Way Policy:

While a shuttle tends to go to a wait point, if the decision point on its way is full then, this shuttle creates a new route towards its target wait point.

Deadlock Control Agent:

This agent exists to control and prevent deadlock situations.

Deadlock Case-Control:

If any deadlock case is shown in Fig. 4 (Case 1, 2, or 3) takes place, then a deadlock prevention policy is applied, also shown in the same figure. For instance, Case 1 is the case where two shuttles are to collide through their route. For the solution of this, 2.6.1 policy "Trigger to go to Waiting Points" is applied. For Case 2 problem, where a decision-making point is full while another shuttle heads to there, policy 2.6.2 "Triggering Policy" is applied, so on.

Simulation Assumptions

The system is simulated by using the Arena 16.0 commercial software. The simulation model assumptions are summarized as follows:

- The mean arrival rate for storage and retrieval transactions follow a Poisson distribution with equal mean.
- Mean arrival rate values are adjusted such that we obtain 95% average shuttle utilization in the system design (see Table 2).
- Arriving storage or retrieval addresses are specified randomly.
- The required time to load and unload the totes onto/from the shuttle is ignored.
- The maximum velocity that shuttles can reach is assumed to be 2 m/s. The acceleration and deceleration values for velocity are 2 m/s^2.
- The distance between all bays and points (i.e., buffers, decision, waiting, escape points) is assumed to be 0.5 m.
- It is considered that there are 10 aisles and 50 bays with a double side. Therefore, the warehouse capacity is 1,000 bays for each tier.
- The simulation run length is two months with a one-day warm-up period that is decided by the eye-ball technique.
- The model is run for five independent replications.
- The system performance metrics are considered to be the average flow time per transaction, the ratio of waiting time to flow time, and the number of transactions processed during the simulation run.
- Shuttles do not breakdown during the simulation.
- Verification and validation are done by debugging and animating the models.

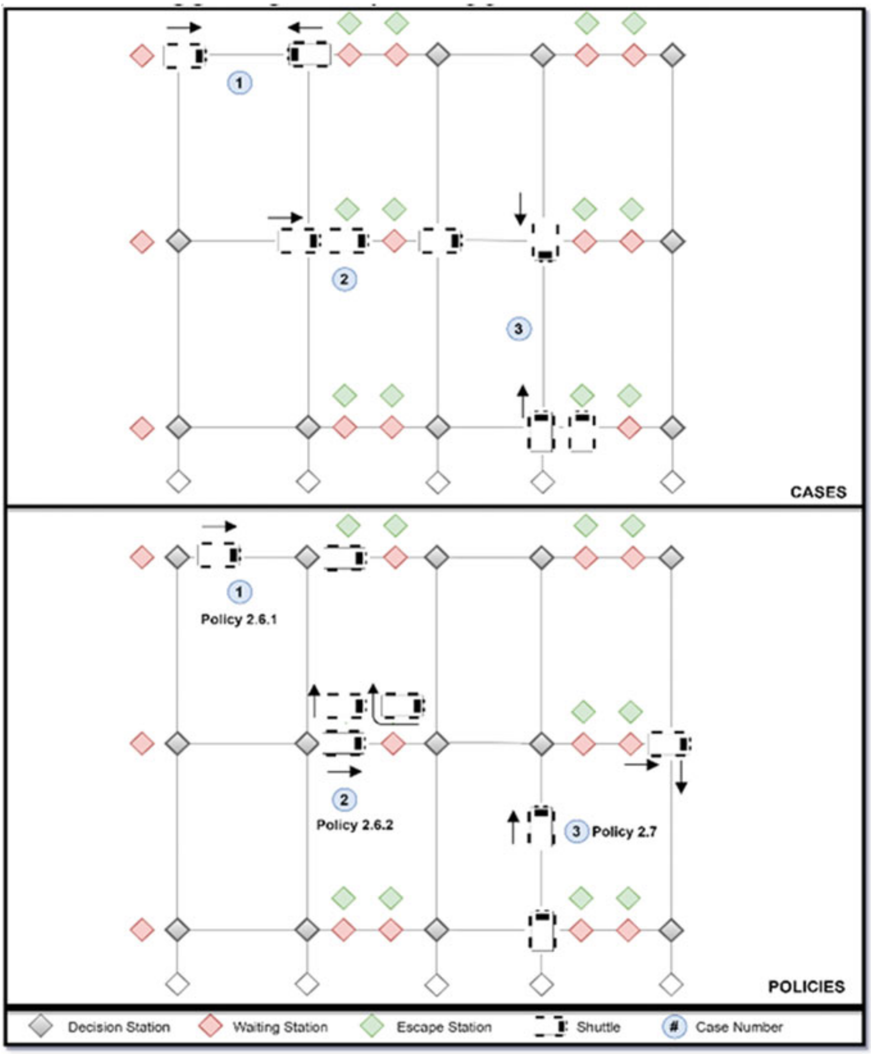

Fig. 4 Deadlock cases and applied policies to solve them

Table 2 Simulation results for 95% shuttle utilization

Number of shuttle	Average flow time per transaction (s)	The ratio of waiting time within flow time	Number of transaction processed (for 2 months)
1	78.94 ± 1.22	80.2%	314,890 ± 748
2	72.24 ± 0.96	65.0%	388,910 ± 983
3	58.16 ± 0.55	54.0%	547,040 ± 760

Results

The performance metrics for the different number of shuttles with 95% average shuttle utilization values are shown in Table 2. The results are summarized for 95% confidence intervals.

In Table 2, the system performance is evaluated in terms of three performance metrics: average flow time, the ratio of waiting time within average flow time, and the total number of transactions processed in two months. Table 2 scenarios are also tested for different transaction selection rules such as first-come-first-served (FCFS), and shortest processing time (SPT). Note that, the Table 2 results are for the agent-based (i.e., bidding-based) decision-making results. By also experimenting with the FCFS and SPT, our aim is to test how the bidding-based assignment policy affects the system performance. Figures 5 and 6 summarize the overall results. Figure 5 shows the results for the total number of transactions processed versus the number of shuttles for all experiments. Figure 6 shows the ratio of waiting time within average flow time versus the number of shuttles results for all experiments.

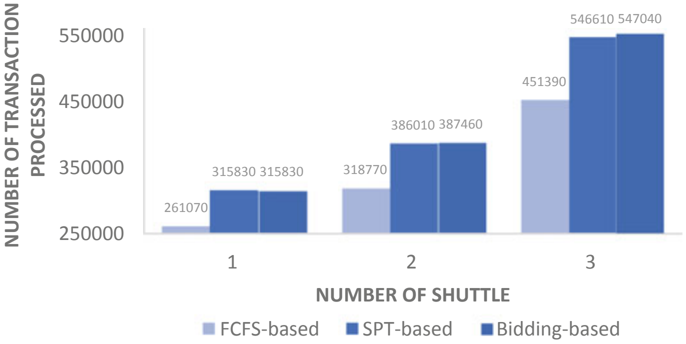

Fig. 5 Number of transactions processed versus number of shuttles results

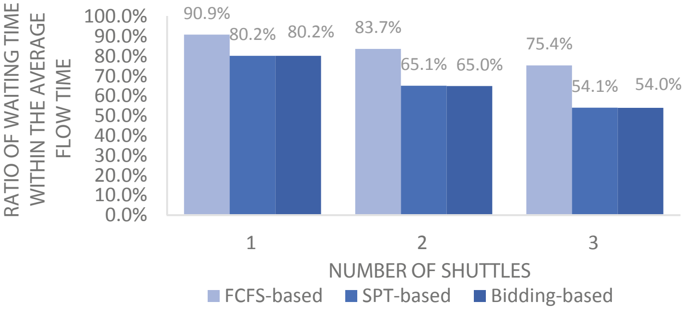

Fig. 6 Ratio of waiting time within the average flow time versus number of shuttles results

The results show that the worst performance metrics are always obtained at the single shuttle case as well as in the FCFS scheduling scenarios. From Figs. 5 and 6 it is also observed that both bidding and SPT scheduling algorithms produce close results. Bidding is relatively a little bit better than the SPT rule in each number of shuttle scenario. However, by improving the bidding rules as a future work could improve the system performance.

Discussion and Conclusion

In this paper, in an effort to reduce initial investment cost and increase the average utilization of shuttles in SBS/RS, we propose a novel tier-captive aisle-to-aisle SBS/RS design in which multiple shuttles can run within multiple aisles and a dedicated tier. The proposed system is designed for the use of industrial warehouses requiring an increased throughput rate with decreased investment cost compared to traditional SBS/RS. Since this system considers travel of shuttles between aisles within a single tier, the management of collision and deadlock of shuttles may become a significant issue. In order to prevent collisions and deadlock of shuttles, we study agent-based modeling to find out a good control policy. We define the agent's behaviors and rules and try them for three different number of shuttle scenarios by simulating the system. To be able to compare the effectiveness of the proposed agent-based working system, we also compare its results with two static alternative transaction selection procedures: FCFS and SPT.

The results are evaluated in terms of the average flow time of a transaction, the ratio of waiting time within average flow time, and the total number of transactions processed in two months. It is observed that the proposed bidding procedure works better; however, it could be improved more.

As a future work, it would worth studying more intelligent agent-based control policies for the proposed system. Also, it might be beneficial to compare the proposed tier-captive aisle-to-aisle design with alternative designs of SBS/RS (e.g., traditional tier-captive designs, solely tier-to-tier designs, etc.).

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