Aisle-to-aisle Design for SBS/RS under Smart Deadlock Control Policies

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Abstract
Recent increase in e-commerce, warehouse operations have become one of the most significant issues. Recent customer profile requests fast delivery time with flexible options in purchasing. Automated warehousing technologies are widely utilized in warehouses to provide fast solutions for those demand profiles. Shuttle-based storage and retrieval system (SBS/RS) is an automated warehousing technology assuring fast transaction process in warehouses. In this work, we study a special design for SBS/RS where automated vehicles (i.e., shuttles) are more flexible in their travel pattern so that the system would not require a dedicated shuttle in each tier resulting with decreased number of shuttles compared to a dedicated one (i.e., each zone with a single shuttle) in the system. We compare these two system designs, flexible and dedicated ones, by using an agent-based simulation modelling approach. The proposed flexible design is developed on deadlock and collision prevention algorithms evaluating real time information. The performance of the system is compared by their average flow time per transaction, maximum flow time of a transaction, throughput rate and utilization of shuttles, etc. The results show that by integrating smart collision and deadlock prevention algorithms, the proposed flexible aisle-to-aisle SBS/RS works better than the dedicated system design.

Keywords
Aisle-to-aisle SBS/RS, Deadlock prevention, Agent-based simulation, Shuttle-based storage and retrieval system (SBS/RS) and Flexibility.

1. Introduction
Flexibility in warehouse operations and smart operations management are among the fundamental necessities in today's supply chains. Applications providing fast processing time, cost reduction, and flexibility in warehouses are critical in automated warehouse systems. SBS/RS is one of autonomous vehicle-based warehousing technologies mainly utilized for large distribution centers that require high throughput rate per unit time and, provides efficiency in warehouse operations.

Figure 1 shows a traditional SBS/RS design (e.g., tier-captive SBS/RS). In this design, there is an autonomous vehicle (i.e., shuttle) performing storage and retrieval process within a dedicated aisle. In each aisle, there is a lifting mechanism carrying loads (i.e., totes) between tiers. In this traditional design, since there is a dedicated shuttle in each tier of an aisle, average utilization of shuttles are mostly very low compared to average utilization of lifts. In an effort to increase the utilization of shuttles, we propose an alternative design for this system, where shuttles can travel between multiple aisles within a tier so that there can be decreased number of shuttles in the system compared to the
tier-captive SBS/RS. This new design would also contribute both decreased initial investment cost as well as increased utilization of shuttles in the system.

The novel flexible system design, proposed in this paper is referred as aisle-to-aisle SBS/RS where shuttles are flexible in their travel pattern so that they can change their aisles during their travel (Figure 2). Namely, in this design, there can be several shuttles running within the same aisles so that collision and deadlock prevention algorithms should be integrated in the operating policy.

Figure 1. SBS/RS design with dedicated shuttles

Figure 2 shows the physical configuration of the proposed flexible aisle-to-aisle SBS/RS. To integrate smart collision and deadlock prevention algorithms, in the layout, we consider extra gaps between certain numbers of bays so that the shuttles can escape, make decisions, and wait at those places for efficiently operating. We detail the smart operating rules in Section 3.

Figure 2. The physical configuration of the flexible aisle-to-aisle SBS/RS
1.1 Objective of the Study

The objectives of the study can be summarized to be:

- searching an alternative novel design to the tier-captive SBS/RS where shuttles can also be highly utilized by the decreased number of shuttles, while also the system provides fast process time for transactions.
- for the proposed novel flexible SBS/RS where shuttles can travel between multiple aisles, searching for a good collision and deadlock prevention policy resulting with decreased average flow time per transaction and maximum flow time of transactions as well as increased throughput rate.

Through those objectives, we develop our solution approaches summarized in Section 3.

2. Literature Review

The existing publications about SBS/RS generally focus on tier-captive SBS/RS where there is a dedicated shuttle in an aisle of a dedicated tier. Different from that system design, there are some recent works on tier-to-tier SBS/RS where shuttles can only move between tiers within an aisle (Kucukyasar et al., 2021; Ha and Chae, 2018). In this section, first we discuss studies on tier-captive SBS/RS constituting the basic studies on SBS/RS. Then, we discuss the existing tier-to-tier studies. Last, the studies on collision prevention methods related with the aisle-to-aisle working principle that is the subject of this paper is given.

The first study on SBS/RS is carried out by Carlo and Vis (2012). They focus on scheduling of two non-passing lifts in traditional SBS/RS. Two functions for candidate solutions are introduced and heuristic solutions are developed to solve the problem. Marchet et al. (2012) present an analytical model for tier-captive SBS/RS by utilizing an open queuing network modeling approach to estimate some system performance measures. For the model validation, they compare the results with their simulation results. Later, Marchet et al. (2013) examine tier-captive SBS/RS design trade-offs using simulation. Ekren et al. (2015) evaluate throughput of tier-captive SBS/RS considering a class-based storage policy for totes where the tier location of each class is predefined based on request possibility. Their study results with decreased cycle time by finding out appropriate rack configuration. Ekren (2017) examine the design of a traditional tier-captive SBS/RS by a simulation-based modelling approach. She assesses performance metrics based on designs by drawing several graphs under a wide variety of design concepts. Ekren et al. (2018) study a tool for mean and variance estimation of travel time of lifts and shuttles per transaction in a tier-captive SBS/RS. The proposed tool enables the estimation of the energy-related performance metrics based on several design parameters. Ekren and Akpunar (2021) propose an open queuing network-based model for some critical performance metrics from an SBS/RS. Recently, Ekren (2021a, 2021b) conduct an experimental design study and multi-objective optimization procedure for the tier-captive SBS/RS design by taking the optimization of the performance metrics average cycle time and energy consumption per transaction into consideration simultaneously.

Ha and Chae (2018) analyze the free balancing effect in SBS/RS by comparing basic system controls. According to the results of their simulation analysis, the use of free balancing enables a reduction in the burden on elevators in the tier-to-tier SBS/RS which improves the system performance and provides more productive operation in the system. Ha and Chae (2019) propose a decision model for a tier-to-tier SBS/RS to specify the number of shuttles. They indicate that the model proposed can provide the appropriate number of shuttle values for the required throughput rate. Recently, Kuçukyasar et al. (2021) compare the performance of tier-captive and tier-to-tier SBS/RS by considering cycle time, energy consumption, and investment cost. Their results show that tier-to-tier system configurations resulting in lower cost and higher performance could be obtained under a well-designed configuration.

Collision prevention policies have been mostly studied in AGV (automated guided vehicle) systems rather than SBS/RSs. Hsueh (2010) develop a design in which loads can be exchanged between AGVs (EX-AGV). The simulation results show that the proposed system provides efficient and robust performance. Cozzentino et al. (2011) present an agent-based simulation model to make decisions for warehouse management system. A conservative policy which is based on reserving the path assigned to each AGV is applied in their model in order to avoid collisions between AGVs. Note that since a single floor design of our current study can be considered as an AGV system running at the ground floor, the proposed models in this paper can also be used for AGV systems.

Roy et al. (2013) develop protocols for three types of vehicle blocking warehouses with autonomous vehicles. It is indicated that delays caused by blocking cause a significant increase (10-20%) in the transaction cycle time by their numerical studies. One of the most relevant studies to this proposed study is about SBS/RS with aisle-changing shuttle
carriers conducted by Lerher (2018). He proposes analytical travel time models and performance comparison of the analytical models with simulation model resulted in 1.14% reduction in deviations. The models demonstrate good performance results for designing the SBS/RS with aisle changing shuttles. Hence, it has the potential of being a practical tool for professionals in early decision-making stages. Lienert and Fottner (2017) present a model applying time window routing method to move shuttles safely as another of the studies most relevant to this proposed study. They focus on tier-to-tier and aisle-to-aisle system configurations.

There are few numbers of papers in the literature studying collision avoidance and shuttles crossing between aisles. In this work, in an effort to decrease the number of shuttles invested for the system and increase the average utilization of shuttles in the system, we propose an aisle-to-aisle SBS/RS where shuttles can travel between multiple aisles within a tier. Due to that flexible travel pattern of multiple shuttles in a tier, collision and deadlock prevention algorithms should be developed not to cause any undesirable long delays and collisions. For that, we treat the shuttles as agents in the system, which are able to track real time information from the environment of system. We explain the agent-based modelling approach in below section.

3. Method
The advantages of the agent-based modeling approach are utilized due to the complexity of the proposed system and requirement of autonomous decision-making of the shuttles. The agent-based simulation modeling is found to be an appropriate approach, as it is suitable for modeling and analyzing complex and smart systems. Intelligent capabilities of agents allow the system work effectively by using real-time information. ARENA 16.0 commercial software was used to simulate the system.

The agents defined in the model are shuttles and demand agents. The agent that makes the final decision as a result of communications in the system is the shuttle agent. There are multiple agents in the system which are able to communicate with each other and track real time information from the environment. Agent interactions are shown in Figure 3. All agents interact with the environment for information transfer. Shuttle agents are in two-way communication with each other and with demand agents. Real-time information on system status is provided by all agents and all can evaluate this information. The use of this communication in decision making is called the bidding strategy required in agent-based simulation. Shuttle decisions are determined as a result of this bidding process. The behavior of the agents is determined by the predefined operating rules. Continuous communication in the system and revised decisions in this direction are designed for the system to work in the most efficient way. Each shuttle's decision or each state change in the system affects the decision of all other shuttles.

![Figure 3. Agent interactions](image)

The notation used for system parameters and performance metrics are shown in Table 1.
Table 1. The notation used

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{max}$</td>
<td>The maximum speed that a shuttle can reach in long travel distance</td>
<td>m/s</td>
</tr>
<tr>
<td>$a_v$</td>
<td>Acceleration value of shuttle</td>
<td>m/s$^2$</td>
</tr>
<tr>
<td>$d_v$</td>
<td>Deceleration value of shuttle</td>
<td>m/s$^2$</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Mean arrival rate of transactions</td>
<td>transactions/month</td>
</tr>
<tr>
<td>$T_{avg}$</td>
<td>Average flow time of transactions</td>
<td>s/transaction</td>
</tr>
<tr>
<td>$T_{max}$</td>
<td>Maximum flow time of transactions</td>
<td>sec.</td>
</tr>
<tr>
<td>$U_{avg}$</td>
<td>Average shuttle utilization</td>
<td>%</td>
</tr>
<tr>
<td>$W_{avg}$</td>
<td>Ratio of average waiting time to average flow time of transaction</td>
<td>%</td>
</tr>
<tr>
<td>$SD$</td>
<td>Standard deviation of flow time of transactions</td>
<td>sec.</td>
</tr>
</tbody>
</table>

The operating procedure of the flexible system is based on the decisions made by the shuttles. The source of these decisions is pre-defined set of rules which are determined to prevent collisions and contribute to the efficient operation of the system. In order to ensure collision control, shuttles move between the points referred as “decision points” where they stop and make decisions at those points to decide where to move. Namely, shuttles decide their next destination points at those points which are located at the end of each aisle. However, if two adjacent decision points are empty which are on the path of shuttle, then shuttle travels to that second “decision point” without stopping.

The procedure how shuttle agent selects the proper transaction is as follows. Once a shuttle becomes available, that shuttle assigns priority to the waiting transactions in these orders: first, it assigns the priority to the ones waiting more than current average waiting time of all transactions; second, among those long waiting transactions, it considers the ones whose address path has the least traffic density; last it gives the priority to the one with the closest distance to shuttle’s current location. By this selection rule, we aim to decrease the variability of transactions’ process times, also resulting with decreased maximum flow time of transactions in the system. With the recent customer oriented supply chain requirements, companies tend to decrease their response time for customers. Hence, decreasing the maximum flow time of transactions would also be an important output to be improved.

Note that the dwell point of a shuttle could be either a decision point or the bay/buffer address of the transaction. There are two types of transactions arriving to the system: storage and retrieval. Storage transactions arrive to a buffer location, randomly. Shuttle picks up the tote at the buffer location if it is a storage transaction. Then, it drops off the transaction at the storage address. If the transaction is a retrieval process, then shuttle picks up the tote at the bay address and drops off it at the buffer location through transaction’s aisle location.

While making a decision on the direction at a decision point, if the shuttle is to direct an aisle when there is another shuttle waiting in that aisle, then the shuttle which is to make decision creates an alternative route not to cause a deadlock. If there is no feasible alternative route, then the shuttle waits until the other one completes its process in that aisle. Shuttle’s dwell point policy is the point of closest “decision point” to its last process location. If another shuttle is to arrive to that decision point when an idle shuttle is waiting there, then that idle shuttle travels to the “waiting point” next to its location. Its travel is triggered by a traveling shuttle by sending a signal to that idle shuttle. This triggering policy plays a significant role in straight traffic flow without any collision.

The shuttle at the waiting point waits there until it seizes a transaction. After selecting a transaction, it travels to the closest decision point to decide which decision point/aisle/buffer to direct. Note that “waiting points” are located at the right side of each “decision point”. Another significant location for shuttles, “escape point” is also defined located connected with “waiting point”. When a shuttle intends to pass through a “waiting point” and the “decision point” next to it, and if both are busy, then the shuttles being at the “waiting point” and the “decision point” are triggered to travel to the closest “escape point” and the other closest “decision point”, respectively. The shuttle at the escape point goes back to the “waiting point” immediately after the traffic jam is over. By those rules, no deadlock and no collision takes place in the system.

Note that, when there are four or more shuttles in the system, there may be an infinite loop fully blocking the system. This case is traced by shuttles in real time. If this happens, then a shuttle changes its direction to break the cycle and continues its way when the loop is broken.
If two or more shuttles are idle when a transaction arrives, then the shuttle closest to the transaction address is assigned to the arriving job.

The assumptions considered in the simulation model are summarized as follows:

- Mean arrival rate for storage and retrieval transactions follows Poisson distribution. The mean values are adjusted such that, we obtain 95% average utilization value for shuttles (see Table 2).
- Arriving storage or retrieval addresses are specified randomly.
- The required tote loading and unloading time onto/from the shuttle is assumed to be 3 seconds.
- The maximum velocity that shuttles can reach is assumed to be 2 m/sec or 3 m/sec based on the pre-defined design. The acceleration and deceleration values for velocity are 1-3 m/sec² based on the experiment.
- 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 the warehouse capacity is 3,600 bays for each tier including 12 aisles and 150 bays with double side.
- There are four number of shuttles in the system.
- The simulation run length is one month with one week warm-up period decided by the eye-ball technique.
- The model is run for five independent replications.
- The system performance metrics are considered to be: average flow time per transaction, maximum flow time of transactions, ratio of waiting time to flow time, total number of transactions processed during the simulation run, and standard deviation of transaction flow times.
- Shuttles do not breakdown during the simulation run.
Verification and validation of the simulation model are done by debugging the model by animating the system as well as by the help of an expert working on design and analyses of those systems practically. Figure 4 shows a snapshot from the animated simulation model.

4. Data Collection

For the system input data definition, we utilize experts’ insights and information who also provided data for parameter definitions such as distance metrics, shuttle velocity, acceleration, deceleration values, etc. Theoretically, since the maximum velocity that a shuttle can reach horizontally ($V_{max}$) can take values up to 4 m/sec (Lerher 2018), $V_{max}$ takes the values 2 m/sec or 3 m/sec based on the velocity profiles of the designs. The other input data, required to determine the loading and unloading time onto/from the shuttle and the bay width, are determined based on the previous papers in the literature that work SBS/RS. According to that loading and unloading times are assumed to be 3 sec. (Ha and Chae 2019). Distance between two adjacent bays are assumed to be 0.5 m. (Ning et al. 2016, Ha and Chae 2019, Eder 2019). Mean arrival rate for storage and retrieval transactions ($\lambda$) follows Poisson distribution, this information is obtained from literature papers (Roy et al. 2013, Marchet et al. 2013, Ning et al. 2016, Ha and Chae 2019, Eder 2019, Wu et al. 2020). The following section summarizes the results of the simulation run.
5. Results and Discussion

5.1 Numerical Results
Remember that we aim to compare the performance of two system designs, flexible, aisle-to-aisle SBS/RS and dedicated, tier-captive, SBS/RS, performances. Figure 5 shows the studied dedicated SBS/RS for single zone with three aisles. Note that there is a single shuttle in the zone. In that design, shuttles travel to buffer location to pick up/drop off the load. In the dedicated system, we assume that a single shuttle is dedicated to pre-defined number of aisles so that this shuttle can solely travel between those aisles. Since there is a single shuttle travelling in the system, no collision is possible in the dedicated SBS/RS. To make a fair comparison, we keep the number of aisles and shuttles same for the systems designs. For instance, if there are 12 aisles in the flexible aisle-to-aisle SBS/RS with four shuttles, then, in the dedicated SBS/RS, a single shuttle is dedicated to three (12/4) aisles. Table 2 and Table 3 show the experimental results for flexible aisle-to-aisle SBS/RS and dedicated SBS/RS, respectively. According to that, we conduct experiments for two levels of maximum velocity that shuttles can reach and three levels of acceleration/deceleration values.

![Figure 5. Dedicated SBS/RS with three numbers of aisles](image)

Flexible and dedicated systems are compared under several performance criteria whose values are shown in Tables 2 and 3, respectively. Once again, the experiments’ arrival rates are adjusted so that we run the systems under 95% utilization levels of shuttles. However, note that to make a fair comparison, we run the two systems under the same arrival rate scenarios.

<table>
<thead>
<tr>
<th>Design</th>
<th>Velocity Scenario</th>
<th>Performance Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>#</td>
<td>$V_{max}$, $aV$, $dV$</td>
<td>$\lambda$, $U_{avg}$, $T_{avg}$, $T_{max}$, $W_{avg}$, $SD$</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>176,520± 420, 0.947± 6\times 10^{-4}</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>204,260± 319, 0.948± 4\times 10^{-4}</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>221,710± 355, 0.946± 8\times 10^{-3}</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>196,570± 295, 0.947± 4\times 10^{-4}</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>259,560± 399, 0.951± 9\times 10^{-4}</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>270,350± 433, 0.951± 1\times 10^{-3}</td>
</tr>
</tbody>
</table>
Table 3. Simulation results for the dedicated system

<table>
<thead>
<tr>
<th>Design</th>
<th>Velocity Scenario</th>
<th>Performance Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>#</td>
<td>Vₘₐₓ, aᵥ, dᵥ</td>
<td>λ</td>
</tr>
<tr>
<td>1</td>
<td>176,316± 324</td>
<td>0.773± 7*10⁻⁴</td>
</tr>
<tr>
<td>2</td>
<td>204,000± 350</td>
<td>0.829± 4*10⁻³</td>
</tr>
<tr>
<td>3</td>
<td>221,524± 364</td>
<td>0.859± 4*10⁻³</td>
</tr>
<tr>
<td>4</td>
<td>196,324± 321</td>
<td>0.694± 4*10⁻³</td>
</tr>
<tr>
<td>5</td>
<td>259,648± 292</td>
<td>0.796± 2*10⁻³</td>
</tr>
<tr>
<td>6</td>
<td>270,560± 351</td>
<td>0.812± 3*10⁻³</td>
</tr>
</tbody>
</table>

According to Table 2 and Table 3 results, the performance metrics usually outperform in flexible SBS/RS compared to the dedicated one. Besides, the maximum flow time of transactions and the standard deviation of the flow times are always lower in flexible aisle-to-aisle SBS/RS than the dedicated system. Looking at the ratio of average waiting time to average flow time of transaction (Wₐᵥ), it is seen that flexible aisle-to-aisle SBS/RS is again always better than the dedicated system design. As a result, it is observed that around at least 15% improvement can be managed by a flexible SBS/RS design, which can be improved more by integrating more intelligent operating rules in the system.

5.2 Graphical Results

The average flow time values of transactions for both systems depending on the velocity are shown in Figure 6. The lowest average flow time value and mostly the better average flow time values are observed in the flexible aisle-to-aisle SBS/RS. Increase in the acceleration and deceleration values make the flexible aisle-to-aisle SBS/RS work better than the dedicated SBS/RS. Dedicated SBS/RS could be preferable in high velocity and the low acceleration and deceleration scenarios. However, flexible aisle-to-aisle SBS/RS is found to be more efficient than the dedicated SBS/RS due to its potential not only reducing average flow time of a transaction but also the maximum flow time of transactions. Figure 7 shows Tₘₐₓ and SD versus Vₘₐₓ, aᵥ, dᵥ graph.
From Figure 7, it is observed that the flexible aisle-to-aisle SBS/RS is advantageous in terms of maximum flow time of transactions and standard deviation of flow times in any velocity scenario.

5.3 Validation
Verification and validation was of the simulation model is done by debugging and tracing the model by animating the models. Comparison of the models of flexible and dedicated SBS/RS shows the consistency of values of performance metrics. Comparison with a known result could not be made because of that there was no real system.

In addition, degenerate tests are applied to test the correctness of the developed model. For example, when the arrival rate of the transactions is increased in the system, the utilization and waiting time levels tend to increase. Also, when we decrease the \( V_{\text{max}} \) values of shuttles the \( T_{\text{avg}} \) values tend to increase. After all those tests, we run the experimented models.

Internal validity was tested by observing variability between replications, which makes the system questionable if they are high. To see this, the half-width values of the simulation results in the numerical results part are checked.

6. Conclusion
In this work, we propose a novel aisle-to-aisle SBS/RS design where multiple shuttles can travel between aisles within a tier. Our aim is to compare the performance of this novel system performance with a dedicated design one. The main motivation of proposing a flexible SBS/RS is by enabling more flexible travel of shuttles, the transaction process rate would increase and hence, with less number of shuttles we could obtain the same performance in the dedicated SBS/RS.

We simulate the two system designs where the flexible SBS/RS is modelled by an agent-based modelling approach where shuttles and orders are defined to be agents interacting with each other. We compare the two system designs under different velocity profiles of shuttles. The results show that the proposed flexible travel of shuttles between aisles provide better performance metric results in terms of average flow time per transaction, maximum flow time of transactions, throughput rate outputs than the dedicated system design. Hence, more smart algorithms in operating of those shuttles could be developed to increase this novel system performance.

As future works, more experiments on those two design by also including warehouse rack designs could be considered. Besides, different layouts and decision making rules for that flexible system design could also be developed and tested.
References


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Biographies

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Banu Y. Ekren is a full time academic in the department of Industrial Engineering, at Yasar University in Izmir, Turkey. She got her Ph.D., from University of Louisville in the Dept. of Industrial Engineering, in Kentucky, USA. Her research focuses on future of education, warehousing, stochastic and simulation modelling, modelling supply chains, simulation-based optimization, and design and analysis of automated warehousing. Banu Y. Ekren holds associate professor position at her university and teaches simulation, stochastic modelling and facility planning and logistics courses at undergraduate level. She has several journal and book chapter publications.

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