Transaction Processing Policies in a Flexible Shuttle-Based Storage and Retrieval System by Real-Time Data Tracking under Agent-Based Modelling

[1]Madhu Krishna N,[2]Chinna Ponnu Y, [3]Muthu Kumar. L
[1,2,3]Department Electrical and Electronics Engineering
[1,2,3]Easwari Engineering College, Chennai, India .

Abstract
This study investigates priority assignment rules (PARs) for transaction processing in automated warehouses featuring a shuttle-based storage and retrieval system (SBSRS). By incorporating real-time data tracking through agent-based modeling, the research explores the unique aspect of the SBSRS design, which involves flexible travel of robotic order picker shuttles between tiers. The paper proposes PARs under agent-based modelling to enhance multi-objective performance metrics, including average flow time (AFT), maximum flow time (MFT), outlier transaction AFT, and standard deviations of flow times (SD) within the system. Experimental evaluations are conducted with various warehouse designs, comparing the results against commonly used static scheduling rules. The findings demonstrate that real-time tracking policies significantly improve system performance. Specifically, prioritizing the processing of outliers based on transaction waiting time enhances MFT, SD, and other performance metrics, while minimizing adverse effects on AFT. Certain rules exhibit notable improvements in MFT and SD, while others achieve the lowest AFT values among all experiments. This paper contributes to the existing literature by presenting a multi-objective performance improvement procedure and highlighting the advantages of real-time data tracking-based scheduling policies in automated warehousing systems.
Keywords: SBSRS, Shuttle-based, Automated warehousing, Storage and retrieval system, Shuttle-based storage and retrieval system.

1. Introduction

In today's rapidly evolving business environment, automated systems in warehousing are critical for meeting increasing customer demands, especially with the rise of e-commerce. One such system that has garnered significant attention is the **Shuttle-Based Storage and Retrieval System (SBSRS)**, an automated warehousing system that utilizes robotic shuttles for high-efficiency picking and storing of products. SBSRS is primarily deployed in mini-load retailer warehouses to streamline operations and improve system performance.

The traditional SBSRS features shuttles operating on fixed tiers, leading to lower utilization of shuttles due to the non-flexible design, which may contribute to inefficiencies in cost and sustainability. To address this, a more **flexible SBSRS design** has been developed where shuttles can traverse multiple tiers, facilitated by additional lift mechanisms. While this flexible design potentially increases shuttle utilization, it introduces new challenges in transaction processing and shuttle scheduling.

This study addresses these challenges by investigating the impact of **Priority Assignment Rules (PARs)** and real-time data tracking in optimizing transaction processing for flexible SBSRS designs. By using **agent-based modeling**, we aim to evaluate multi-objective performance metrics, including **Average Flow Time (AFT)**, **Maximum Flow Time (MFT)**, and the **Standard Deviation (SD)** of flow times, to provide a more comprehensive view of the system's efficiency.

2. Literature Review

2.1 Non-Flexible SBSRS Research

Non-flexible SBSRS designs have been extensively studied, with early research focusing on the performance of automated systems like crane-based and autonomous vehicle storage and retrieval systems (Ekren & Heragu, 2011;

Heragu et al., 2011). Simulation models have been developed to compare design performance and cost efficiency, showing that fewer aisles generally result in better system performance (Marchet et al., 2013).
Further research explored optimization of task scheduling using genetic algorithms (Wang et al., 2015) and investigating vehicle blocking effects (Roy et al., 2014). The impact of non-flexible designs on energy consumption and system efficiency has also been modeled analytically and via simulation (Ekren et al., 2018; Eder, 2019).

2.2 Flexible SBSRS Research

Compared to non-flexible SBSRS designs, the literature on flexible SBSRS is more limited. Flexible SBSRS, where fewer shuttles operate across multiple tiers, was first studied by Ha and Chae (2018). More recent studies explored optimization strategies using machine learning methods (Ekren & Arslan, 2022), simulation-based design evaluation (Ekren et al., 2023), and shuttle scheduling using heuristic approaches (Yang et al., 2023).

2.3 Agent-Based Modeling in Automated Warehousing

Agent-based modeling has been widely applied in automated warehousing to simulate dynamic decision-making scenarios. Early studies showed that this approach effectively modeled complex systems with high variability (Guller & Hegmanns, 2014). More recent works applied reinforcement learning to transaction scheduling in SBSRS (Arslan & Ekren, 2022). This study extends agent-based modeling to real-time data tracking and multi-objective optimization of transaction processing in a flexible SBSRS design.

3. Methodology

3.1 System Definition and Assumptions

In the flexible SBSRS design, shuttles are not restricted to a single tier but can move between tiers using a secondary lift (Lift 2). The system assumptions are as follows:

- **Shuttles** operate in designated aisles, with a capacity of one tote per bay.
- **Lifting Mechanisms**: Lift 1 is used for tote transport, while Lift 2 moves shuttles between tiers.
- **Transactions** arrive following a Poisson distribution, with random storage and retrieval demands.
- **Simulation Parameters**: The system configuration includes 15 tiers per aisle, 25 bays on each side, and five shuttles per aisle.

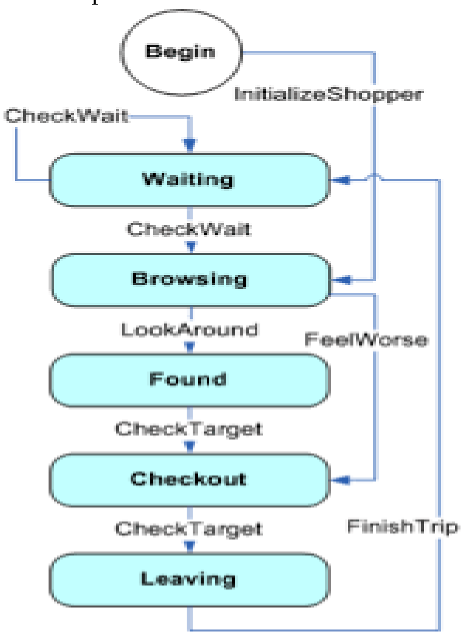

Figure1: Agent State Transition Diagram | Download Scientific Diagram

3.2 Agent-Based Modeling

The study uses agent-based simulation to evaluate system performance under different PARs. Shuttles, lifts, and transactions are modeled as intelligent agents, capable of sensing and reacting to real-time information. This approach allows for dynamic decision-making in transaction processing based on real-time data.

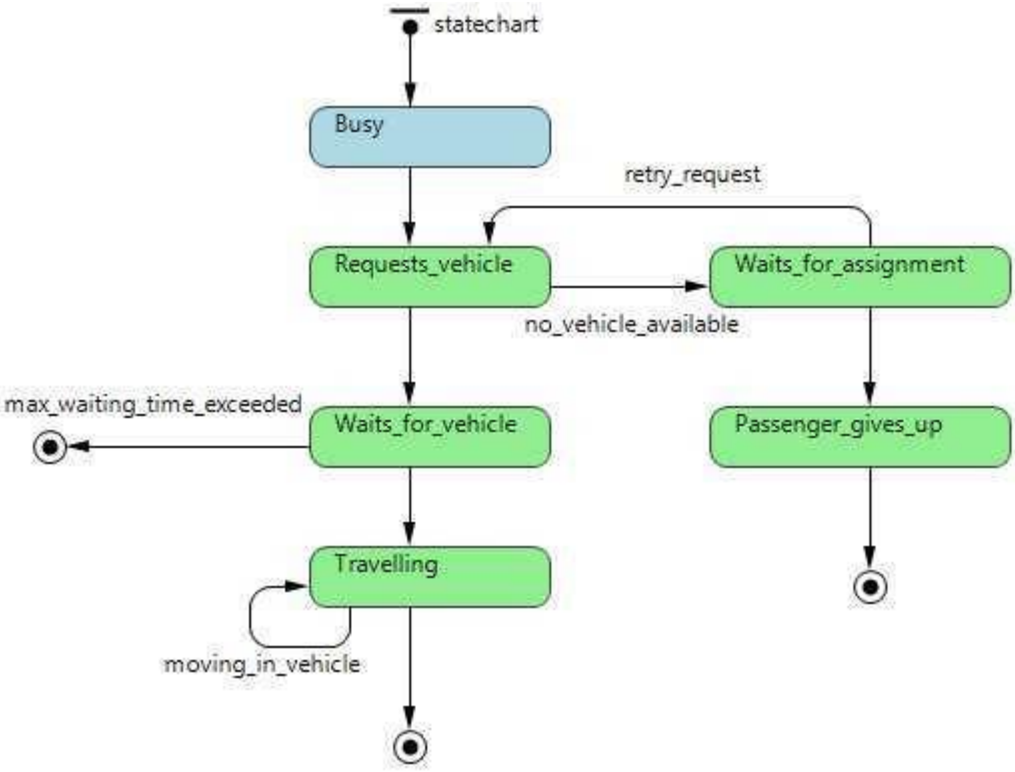

Figure 2. State transition model of multi-shuttle agent.

3.3 Priority Assignment Rules (PARs)

Various PARs are tested to determine the optimal transaction processing method for minimizing AFT, MFT, and SD of flow times. These include:

- **First-In-First-Out (FIFO)**: Prioritizes tasks based on their arrival time.
- **Shortest Process Time (SPT)**: Selects transactions with the shortest estimated process time.
- **Dual Command & SPT**: Combines storage and retrieval processes to minimize travel time.
- **Real-Time Outlier Tracking Rule (RTOTR)**: Tracks real-time flow times and assigns priority to transactions that exceed a critical point, dynamically updating the system during simulation runs.

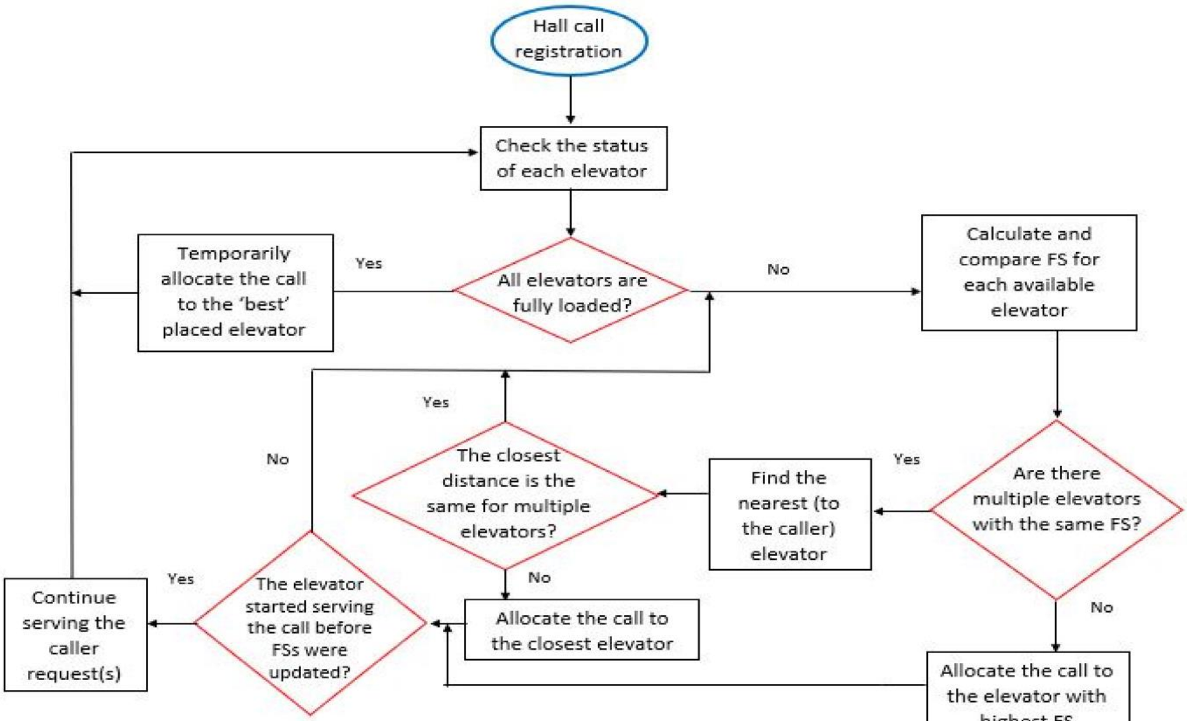

Figure 3. Flowchart of conventional nearest car (NC) algorithm.

4. Results and Discussion

4.1 Experimental Setup

The simulation was run for 45 days, with a warm-up period of 15 days. Performance metrics such as AFT, MFT, and SD were collected across different warehouse configurations and PAR scenarios. The results show that the RTOTR-based scheduling rules significantly reduced outlier transaction processing times and minimized variability in the system.

4.2 Performance Comparison

Among the different PARs, the **SPT rule** achieved the lowest AFT, while the **PT/WT rule** effectively minimized MFT. The introduction of RTOTR led to substantial improvements in system performance, particularly in reducing outlier transaction times without adversely affecting AFT.

5. Conclusion

This study presents a flexible SBSRS design and evaluates various PARs for transaction processing using real-time data tracking under an agent-based modeling framework. The results demonstrate that real-time tracking policies, such as RTOTR, provide significant improvements in system performance, particularly for outlier transactions. By optimizing multiple performance metrics simultaneously, the proposed PARs offer a comprehensive solution for improving automated warehousing systems.

References

1. Arslan, B., & Ekren, B.Y. (2022). Transaction selection policy in tier-to-tier SBSRS by using deep Q-learning. *International Journal of Production Research*.
2. Carlo, H.J., & Vis, I.F.A. (2012). Sequencing dynamic storage systems with multiple lifts and shuttles. *International Journal of Production Economics*.
3. Chen, R., Yang, J., Yu, Y., & Guo, X. (2023). Retrieval request scheduling in a shuttle-based storage and retrieval system with two lifts. *Transportation Research Part E*.
4. Ekren, B.Y., & Heragu, S.S. (2011). Simulation-based performance analysis of autonomous vehicle storage and retrieval system. *Simulation Modeling Practice and Theory*.
5. Arslan, B., & Ekren, B.Y. (2022). Transaction selection policy in tier-to-tier SBSRS by using deep Q-learning. *International Journal of Production Research*. https://doi.org/10.1080/00207543.2022.2148767. (In press).
6. Carlo, H.J., & Vis, I.F.A. (2012). Sequencing dynamic storage systems with multiple lifts and shuttles. *International Journal of Production Economics*, 140(2), 844-853. https://doi.org/10.1016/j.ijpe.2012.06.035.
7. Chen, R., Yang, J., Yu, Y., & Guo, X. (2023). Retrieval request scheduling in a shuttle-based storage and retrieval system with two lifts. *Transportation Research Part E: Logistics and Transportation Review*, 174, 103117. https://doi.org/10.1016/j.tre.2023.103117.
8. Eder, M. (2019). An analytical approach for a performance calculation of shuttle-based storage and retrieval systems. *Production & Manufacturing Research*, 7(1), 255-270. https://doi.org/10.1080/21693277.2019.1619102.

9. Ekren, B.Y. (2017). Graph-based solution for performance evaluation of shuttle-based storage and retrieval system. *International Journal of Production Research*, 55(21), 6516-6526. https://doi.org/10.1080/00207543.2016.1203076.
10. Ekren, B.Y. (2020). A simulation-based experimental design for SBS/RS warehouse design by considering energy-related metrics. *Simulation Modelling Practice and Theory*, 98, 101991. https://doi.org/10.1016/j.simpat.2019.101991.
11. Ekren, B.Y. (2021). A multi-objective optimisation study for the design of an AVS/RS warehouse. *International Journal of Production Research*, 59(4), 1107-1126. https://doi.org/10.1080/00207543.2020.1720927.
12. Ekren, B.Y., & Akpunar, A. (2021). An open queuing network-based tool for performance estimations in a shuttle-based storage and retrieval system. *Applied Mathematical Modelling*, 89(2), 1678-1695. https://doi.org/10.1016/j.apm.2020.07.055.
13. Ekren, B.Y., & Arslan, B. (2022). A reinforcement learning approach for transaction scheduling in a shuttle-based storage and retrieval system. *International Transactions in Operational Research*, 1-22. https://doi.org/10.1111/itor.13135. (In press).
14. Ekren, B.Y., & Heragu, S.S. (2010). Approximate analysis of load-dependent generally distributed queuing networks with low service time variability. *European Journal of Operational Research*, 205(2), 381-389. https://doi.org/10.1016/j.ejor.2010.01.022.
15. Ekren, B.Y., & Heragu, S.S. (2011). Simulation-based performance analysis of autonomous vehicle storage and retrieval system. *Simulation Modeling Practice and Theory*, 19(7), 1640-1650. https://doi.org/10.1016/j.simpat.2011.02.008.
16. Ekren, B.Y., & Heragu, S.S. (2012). Performance comparison of two material handling systems: AVS/RS and AS/RS. *International Journal of Production Research*, 50(15), 4061-4074. https://doi.org/10.1080/00207543.2011.588627.
17. Ekren, B.Y., Akpunar, A., Sari, Z., & Lerher, T. (2018). A tool for time, variance and energy-related performance estimations in a shuttle-based storage and retrieval system. *Applied Mathematical Modelling*, 63, 109-127. https://doi.org/10.1016/j.apm.2018.06.037.
18. Ekren, B.Y., Heragu, S.S., Krishnamurthy, A., & Malmborg, C.J. (2013). An approximate solution for semi-open queuing network model of autonomous vehicle storage and retrieval system. *IEEE Transactions on Automation Science and Engineering*, 10(1), 205-215. https://doi.org/10.1109/tase.2012.2200676.
19. Ekren, B.Y., Heragu, S.S., Krishnamurthy, A., & Malmborg, C.J. (2014). Matrix-geometric solution for semi-open queuing network model of autonomous vehicle storage and retrieval system. *Computers & Industrial Engineering*, 68, 78-86. https://doi.org/10.1016/j.cie.2013.12.002.
20. Ekren, B.Y., Kaya, B., & Küçükyaşar, M. (2023). Shuttle-based storage and retrieval systems designs from multi-objective perspectives: Total investment cost, throughput rate, and sustainability. *Sustainability*, 15(1), 762. https://doi.org/10.3390/su15010762.
21. Ekren, B.Y., Sari, Z., & Lerher, T. (2015). Warehouse design under class-based storage policy of shuttle-based storage and retrieval system. *IFAC-PapersOnLine*, 48(3), 1152-1154.
22. Güller, M., & Hegmanns, T. (2014). Simulation-based performance analysis of a miniload multishuttle order picking system. *Procedia CIRP*, 17, 475-480.
23. Güller, M., Karakaya, E., Uygun, Y., & Hegmanns, T. (2018). Simulation-based performance evaluation of the cellular transport system. *Journal of Simulation*, 12(3), 225-237. https://doi.org/10.1057/s41273-017-0061-1.
24. Ha, Y., & Chae, J. (2018). Free balancing for a shuttle-based storage and retrieval system. *Simulation Modelling Practice and Theory*, 82, 12-31. https://doi.org/10.1016/j.simpat.2017.12.006.
25. Ha, Y., & Chae, J. (2019). A decision model to determine the number of shuttles in a tier-to-tier SBS/RS. *International Journal of Production Research*, 57(4), 963-984. https://doi.org/10.1080/00207543.2018.1476787.
26. He, L., Chiong, R., & Li, W. (2022). Energy-efficient open-shop scheduling with multiple automated guided vehicles and deteriorating jobs. *Journal of Industrial Information Integration*, 30, 100387. https://doi.org/10.1016/j.jii.2022.100387.
27. Heragu, S.S., Cai, X., Krishnamurthy, A., & Malmborg, C.J. (2011). Analytical models for analysis of automated warehouse material handling systems. *International Journal of Production Research*, 49(22), 6833-6861. https://doi.org/10.1080/00207543.2010.518994.
28. Küçükyaşar, M., Ekren, B.Y., & Lerher, T. (2020). Cost and performance comparison for tier-captive and tier-to-tier SBS/RS warehouse configurations. *International Transactions in Operational Research*, 28(4), 1847-1863. https://doi.org/10.1111/itor.12864.
29. Lehrer, T., Ekren, B.Y., Sari, Z., & Rosi, B. (2015a). Simulation analysis of shuttle-based storage and retrieval systems. *International Journal of Simulation Modelling*, 14(1), 48-59.
30. Lerher, T. (2016). Travel time model for double-deep shuttle-based storage and retrieval systems. *International Journal of Production Research*, 54(9), 2519-2540. https://doi.org/10.1080/00207543.2015.1061717.
31. Lerher, T., Ekren, B.Y., Dukic, G., & Rosi, B. (2015b). Travel time model for shuttle-based storage and retrieval systems. *The International Journal of Advanced Manufacturing Technology*, 78(9-12), 1705-1725. https://doi.org/10.1007/s00170-014-6726-2.
32. Marchet, G., Melacini, M., Perotti, S., & Tappia, E. (2012). Analytical model to estimate performances of autonomous vehicle storage and retrieval systems for product totes. *International Journal of Production Research*, 50(24), 7134-7148.
33. Marchet, G., Melacini, M., Perotti, S., & Tappia, E. (2013). Development of a framework for the design of autonomous vehicle storage and retrieval systems.
34. Ekren, B.Y., & Akpunar, A. (2021). An open queuing network-based tool for performance estimations in a shuttle-based storage and retrieval system. *Applied Mathematical Modelling*.