International Journal of Mathematical, Engineering and Management Sciences
Vol. 8, No. 6, 1083-1112, 2023
https://doi.org/10.33889/IJMEMS.2023.8.6.062

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

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(Received on May 5, 2023; Accepted on August 20, 2023)

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 modeling 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 changing and dynamic business environment, the ability to adapt quickly to shifting demand patterns is critical for the success of any enterprise. With the growth of e-commerce and online shopping, warehouses and distribution centers have become key components of supply chains. To meet the demands of this changing landscape, businesses are turning to automated systems to improve productivity, accuracy, and flexibility. One such technology that has gained increasing attention in recent years is the SBSRS (Carlo and Vis, 2012; Marchet et al., 2013).

SBSRS is an automated warehousing system that uses robotic shuttles to move products between storage locations and picking stations (see Figure 1). It is a high-throughput system that is widely used in mini-load retailer warehouses to improve the efficiency and accuracy of product picking and storage operations (Carlo and Vis, 2012). In a traditional SBSRS design, each tier of an aisle is dedicated to a single shuttle that travels between that tier and a lift station, where totes are transferred to their destination bays. However, this non-flexible design leads to low average shuttle utilization, as shuttles are often idle while waiting for lift access. This might contribute to inefficiency in the system from both cost and sustainability perspectives.

To address this issue, a more flexible SBSRS design has been developed, where fewer shuttles can travel between multiple tiers within an aisle (Arslan and Ekren, 2022; Ekren and Arslan, 2022; Ekren et al., 2023). Figure 2 shows the new flexible SBSRS. In Figure 2, an additional lifting mechanism, shown as Lift 2, is installed on the opposite side of the aisle to facilitate the transfer of shuttles between tiers. This flexible SBSRS design has the potential to increase shuttle utilization and improve system performance, but it also introduces new challenges for priority assignment and transaction processing. In particular, the increased flexibility of the system makes it more difficult to determine the optimal way of processing transactions.

This paper aims to address the following research question (RQ): How can the implementation of PARs to process transactions and real-time data tracking techniques improve the performance metrics: the AFT, MFT, etc., in a flexible SBSRS design? To address that RQ, PARs for processing transactions in a flexible SBSRS design applying real-time data and information tracking are developed. A simulation model using an agent-based approach is employed to evaluate the pre-developed PARs performance, where shuttles are treated as intelligent agents that can sense their environment and make advantageous decision in processing transactions. Specifically, in developing the PARs, the focus is on improving multi-objective performance metrics, including the AFT, MFT, and SD of a transaction in the system. Studying not only the AFT but also the MFT and the SD of flow times in a transaction processing system can provide several benefits. Firstly, the MFT represents the longest time it takes for a transaction to complete in the system. This metric might be particularly important in situations where there are time constraints for delivery or processing. For example, in e-commerce, customers may expect their orders to be delivered within a certain timeframe and exceeding that timeframe can result in dissatisfied customers and potentially lost business. Therefore, optimizing the MFT can ensure that the system meets the required service level agreements and customer expectations.

Secondly, the SD can provide insights into the variability and consistency of the system's performance. A low SD indicates that the system is operating consistently, while a high SD indicates that there is significant variability in the system's performance. Hence, decreasing SD in process time would help improve the overall system performance and customer satisfaction.

Additionally, considering multiple performance metrics (AFT, MFT, and SD) simultaneously provides a more comprehensive evaluation of the system's performance. By optimizing for multiple metrics, the system can achieve a balance between performance goals and trade-offs. For example, optimizing only for AFT can result in a system that prioritizes fast transaction processing but may sacrifice consistency or the ability to meet time constraints. Therefore, considering multiple performance metrics can help ensure that the system is optimized for all relevant factors by providing a more comprehensive evaluation of the system's performance.

The significance of this study lies in two folds. First, a multi-objective performance improvement procedure for flexible SBS/RS is presented for the first time. Second, a real-time data and information utilization procedure under agent-based modelling resulting in increased performance in the system is proposed. The outcome of this study provides insights and guidance for warehouse managers and researchers interested in improving the performance of SBSRS and other automated warehousing systems. In addition, the proposed PARs in the paper have the potential to bring several benefits to warehouse operations, resulting in cost savings, increased efficiency, and improved customer satisfaction.

In the remainder of this article, a detailed review of the literature on SBSRS systems and related research on transaction processing and scheduling policies is presented. Then, the methodology for developing and

testing PARs for a flexible SBSRS design is given. Finally, the results of the conducted experiments are compared.

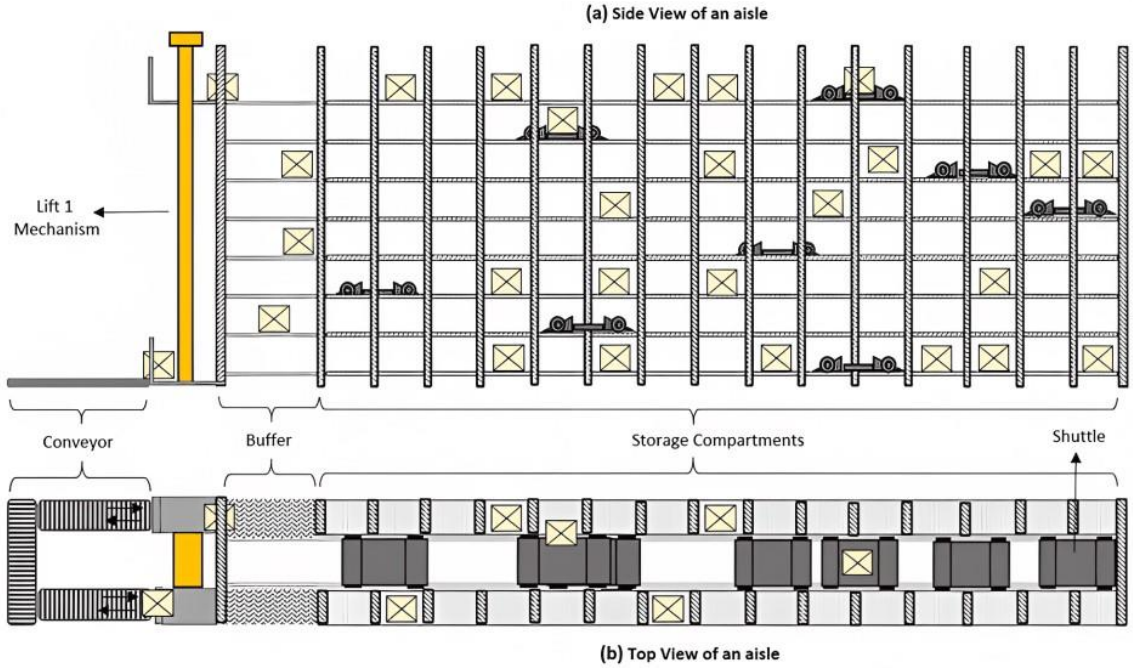


Figure 1. Non-flexible SBSRS design configuration.

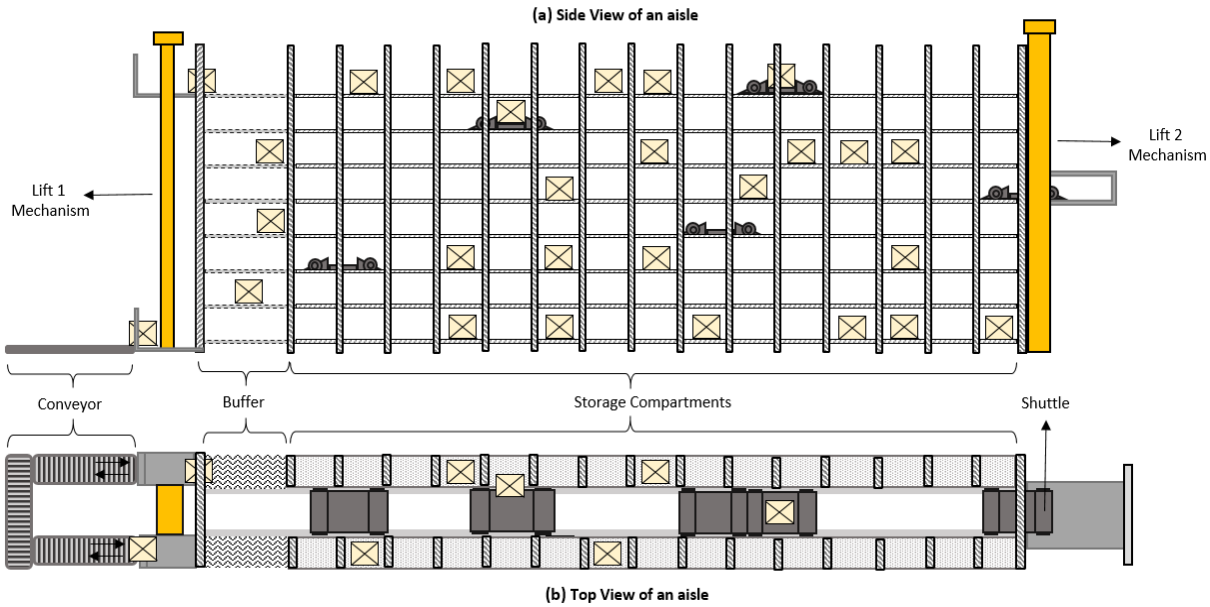


Figure 2. Flexible SBSRS design configuration.

2. Literature Review

This section delves into the literature survey focusing on non-flexible and flexible SBS/RS designs in warehouse automation.

2.1 Non-Flexible SBSRS Works in Literature

An early study on simulation modelling of various automated warehouse design scenarios is presented by Ekren and Heragu (2011). Heragu et al. (2011) present analytical modelling approaches for crane-based AS-RSs and AVS-RSs. They apply the models in a tool called MPA for the system analysis. Ekren and Heragu (2012) perform comparison of two different AS-RS designs: crane-based AS-RS and AVS-RS. Ekren et al. (2013, 2014) proposes semi-open queuing network models by utilizing their closed queuing network algorithms (Ekren and Heragu, 2010).

A first study is presented on non-flexible SBSRS by Marchet et al. (2012), where they propose open-queuing network models to predict significant system outputs (e.g., average waiting and AFT of a transaction). Later, Marchet et al. (2013) propose simulation models presenting design trade-offs in non-flexible SBSRS designs. They compare several design performance metrics which also include the system investment costs of those designs. Their results show that a decreased number of aisles assures better performance metrics in the system. Roy et al. (2014) investigated a queueing network model that incorporates vehicle blocking effects in an AVS-RS. The study reveals that the possibility of blocking leads to a decrease in system efficiency. Additionally, the authors demonstrate that the number of storage bays does not impact blocking delays, but the configuration of tiers has a substantial effect on the occurrence of blocking.

A different design version of the non-flexible SBSRS with two non-passing lifting mechanisms is studied by Carlo and Vis (2012). They present a heuristic-based solution for operation rule of lifts in that design.

Wang et al. (2015) focus on the optimization of task scheduling in a non-flexible SBSRS using a genetic algorithm (GA) optimization procedure. They introduce a non-dominated sorting GA to tackle the multi-objective optimization problem. In the same years, Lerher et al. (2015a) present the advantage of non-flexible SBSRS by its throughput rate performance metric. They compare the system performance under different warehousing design scenarios. Lerher et al. (2015b) present closed-form representations of travel of shuttles/lifts (S/L) in a non-flexible SBSRS. They experiment several design scenarios such as velocity profiles of S/L and scheduling of transactions. Ekren et al. (2015) present storage policies in non-flexible SBSRS designs whose result show that class-based storge policy performs better in the system. Lerher (2016) focuses on SBSRS with double-deep storage compartments. By the double-deep storage bay design, efficient utilization of floor space is possible.

In their study, Tappia et al. (2015) compare the performance of a crane-based Automated Storage and Retrieval System (AS-RS) with an autonomous vehicle-based Storage and Retrieval System (AVS-RS). The results of their analysis reveal that the AVS-RS exhibits superior performance over the AS-RS, particularly in terms of environmental impact. In a separate investigation, Tappia et al. (2016) propose a queuing model for predicting crucial system outputs of a non-flexible SBSRS. This model offers valuable insights into the performance characteristics of the system. Zou et al. (2016) explore a fork-join queueing approach to model a non-flexible SBSRS. Their model incorporated the simultaneous movement of shuttles and lifts within the system. The validity of these models was verified through simulation modeling.

Ekren (2017) proposes simulation models to evaluate several system outputs under different design options in a non-flexible SBSRS. Ekren et al. (2018) presents the development of a tool that provides a closed-form solution for estimating the mean and variance of cycle time for S/L. Additionally, the tool can predict the

average energy consumption and regeneration amount associated with a transaction within the system. Ekren et al. (2018) proposes closed-form mathematical solutions for estimating the mean and variance of travel time of S/L in non-flexible SBSRSs. Later, by using those algorithms, Ekren and Akpunar (2021) present open queuing network models by a user-friendly software tool, which can produce critical outputs from an SBSRS warehouse design. Zhao et al. (2018) study scheduling of lifts in a non-flexible SBSRS. Because the lifts become bottleneck in the system, they consider acceleration and deceleration of lifts as design parameters to minimize the make span of travels. They propose a function to predict the lift route and a scheduling genetic algorithm.

More recently, Eder (2019) employs an open queueing network model with restricted capacity to predict critical system outputs of a non-flexible SBSRS. This work provides further insights into the system's behavior under varying conditions. A recent non-flexible SBS/RS is studied by Ekren (2020) where they present factorial analysis in identifying significant design factors. The findings highlight the significant influence of the number of aisles on the system's performance. In a separate study, Ekren (2021) delves into a multi-objective optimization procedure specifically designed for the non-flexible SBSRS. The research focuses on two crucial system outputs: minimizing AFT and reducing energy consumption per transaction.

2.2 Flexible SBSRS Works in Literature

Limited literature exists on flexible SBSRS than non-flexible SBSRS. The first work is conducted by Ha and Chae (2018) where to prevent collision of shuttles, they define a free-balancing procedure. In that design, there is a single lifting system performing transfer of totes/shuttles between tiers. Later, Ha and Chae (2019) study models to find out the number of shuttles in a flexible SBSRS. Zhao et al. (2019) present an integer mathematical model optimizing the system's efficiency by reducing idle time for lifts and the time that shuttles spend waiting. They utilize simulation modelling approach for the optimization procedure.

Recent work is completed by Ekren and Arslan (2022) by applying a machine learning method to schedule transactions in a flexible SBSRS. However, due to the long training time of agents, this approach might prove costly for companies in application.

In their research, Küçükyaşar et al. (2020) conduct a performance comparison between non-flexible and flexible SBSRSs. They estimate system investment cost, cycle time, and energy consumption as performance metrics. The findings indicate that certain design configurations in flexible SBSRSs outperform non-flexible SBSRSs.

Meanwhile, He et al. (2022) investigate a multi-objective model with the goal of minimizing various factors in an industry setting. Their objectives include reducing the maximum ending time of autonomous vehicles, minimizing the total idle time of these vehicles, minimizing the total tardiness of jobs, and reducing the energy consumption of vehicles.

Ekren et al. (2023) study simulation-based optimal design in a flexible SBSRS. They consider multiple performance metrics from the systems also, including energy consumption.

Yang et al. (2023) presents a study focused on shuttle transfer and retrieval request scheduling in a deep-lane storage system that integrates both forklifts and shuttles. The primary objective is to minimize the makespan. They propose a mathematical optimization model to formally establish the problem's classification as NP-hard. Later, they solve the problem by using a two-stage heuristic.

2.3 Agent-Based Works in Literature

In this section, relevant papers in agent-based modelling and related automated warehousing are reviewed. Guller and Hegmanns (2014) introduce a multi-agent model for non-flexible SBSRS to predict some performance outputs from the system. The findings indicate that the order structure has a significant impact on system efficiency. In addition, they show that agent-based modelling provides a powerful approach in modelling such complex systems. Güller et al. (2018) determine the performance of a cellular transport system by an agent-based simulation model under different system factors. They predict the AFT and average utilization of shuttles under different number of vehicles and throughput rate scenarios in the system.

Recently, Ekren and Arslan (2022) and Arslan and Ekren (2022) have studied reinforcement and deep-Q learning modelling approaches in flexile SBSRSs, respectively. Turhanlar et al. (2022) study flexible SBSRS for aisle-to-aisle design, where agent-based modelling is developed to prevent collision and deadlocks in the system. Chen et al. (2023) study an SBSRS with two load capacity for lifts that can be processed independently. To tackle the scheduling problem of transactions, a mixed-integer programming model is formulated. To efficiently compute near-optimal solutions, a decomposition-based adaptive large neighborhood search heuristic is employed. This heuristic approach enables quick computation and aids in finding solutions that are close to the optimal solution. Different from the existing works, flexible SBSRS working under multiple dynamic decision-making rules for efficient operation of transactions under multi-objectives is studied. The modelling details and experimental results are explained in the following sections.

3. Methodology

This section delves into the modelling approach utilized to tackle the problem at hand concerning the flexible SBSRS. Given the intricate nature of the system, which permits shuttles to travel flexibly across tiers, a simulation modelling approach has been adopted to investigate the optimal PARs. It is worth noting that the flexibility of the studied system allows for the adjustment of the number of shuttles to cater to the specific needs of the warehouse. Within this section, we provide an outline of the system and simulation model assumptions, along with the development of the PARs, shedding light on their significance and implications.

3.1 System Definition and Assumptions of the Flexible SBSRS

In the flexible SBSRS under study, each tier does not house a single shuttle. Instead, the system allows for a reduced number of shuttles to travel between multiple tiers while maintaining the flexibility of shuttle travel between tiers. To facilitate the transfer of loads (totes) between tiers or the I/O point, Lift 1 (shown in Figure 2) is employed in the system. The shuttles are confined to their respective aisles and cannot switch between aisles. This flexible design aims to achieve higher average shuttle utilization by balancing it with the average utilization of lifts, thereby reducing redundant shuttle capacity in the system. However, the reduced number of shuttles may result in increased shuttle travel time.

To address this drawback, various PARs are examined to determine the most effective rule for selecting transactions from queues. The goal is to minimize the AFT and MFT of transactions, as well as the AFT of outliers and the SD of flow times. Figure 2 depicts the configuration of the flexible SBSRS being studied. Each tier consists of two storage sides where shuttles can store loads on either side, with a capacity of one tote per bay. The system utilizes two lifting mechanisms: Lift 1, for transferring totes, and Lift 2, for transferring shuttles between tiers. An incoming transaction demand can be either a storage or retrieval request. Lift 1 has separate tote lifting capacities on its left and right sides, while each shuttle has the capacity to handle a single tote. Additional simulation assumptions are summarized below:

- Storage/retrieval demand arrives/ends at the I/O point in its aisle address.
- In cases where the load address is located on the first tier, Lift 1 remains unused.
- Two buffer locations are situated on each side of every tier.
- The capacity of each buffer area is six totes.
- Lift 1 deposits the storage tote at one of the buffer sides based on the utilized lifting table. Shuttles randomly deposit the tote at a buffer location.
- The arrival rate of storage/retrieval transactions follows a Poisson distribution with identical means.
- The study incorporates a random storage policy.
- The dwell points of S/L are defined as the final points where they conclude their respective tasks.
- To prevent shuttle collisions, only one shuttle is permitted within a tier. The working rule is explained in the flow charts section below.
- Both shuttles and lifts have an acceleration and deceleration rate of 2 m/sec^2. The maximum velocity achievable by both shuttles and lifts is 2 m/sec.
- The spacing between adjacent bays and tiers is set at 0.5 m and 0.35 m, respectively, as documented in the studies by Lerher et al. (2015b); Lerher (2016); Ekren et al. (2018) and Ekren (2020).
- The physical configuration of the storage area consists of 15 tiers in each aisle and 25 bays on each side of a tier.
- There are five shuttles in each aisle.

For the modeling approach, a single aisle is simulated, as all aisles are assumed to be identical. To perform a steady-state analysis, the models are run for a total of 45 days, including a warm-up period of 15 days. To ensure robustness, the simulations are repeated five times. Furthermore, a common variance reduction technique is implemented during the simulation runs.

3.2 Description of the Simulation Model

An SBSRS is a complex system that involves multiple resource devices, such as lifts and shuttles, for its time-efficient management. Thus, two separate queues for lifts and shuttles exist in the system for those resources whose efficient management is essential to improving the overall system's performance. However, in this study, the flexible SBSRS is equipped with two distinct lifting mechanisms, one of which is specifically designed to facilitate the flexible movement of shuttles. To develop an efficient queuing management mechanism, real-time data and information tracking-based operating policies are developed for dynamic decision-making. To develop these decision-making rules, an agent-based simulation modeling approach is employed, as analytical models may not be suitable for modeling dynamic decision-making approaches. In these models, lifts, shuttles, and demands are represented as intelligent agents capable of sensing and monitoring real-time data and information from their environment. These agents interact with each other to make intelligent decisions based on the gathered information. The commercial simulation software ARENA 16.0 is used for the model development. The system's performance is evaluated based on several metrics, such as the AFT and average MFT of a transaction, the average utilization of a shuttle/lift, throughput rate, SD of flow times, and AFT of outlier transactions.

The progress in digitization technologies has paved the way for the development of robotic systems capable of sensing and tracking real-time data and information within their surroundings. This advancement has led to the creation of an agent-based management system that can dynamically make decisions by assessing real-time data and information. In this particular study, shuttles, Lift 1, Lift 2, and transactions are considered as agents with the ability to sense, track, and evaluate real-time data and information from their environment. This includes information such as the current tier and bay location of S/L, remaining time to

destination points, as well as the current types of transactions and their respective desired address information. The attributes and behavior of these agents are illustrated in Figures 3-6 for demand, shuttle, Lift 1, and Lift 2 agents, respectively.

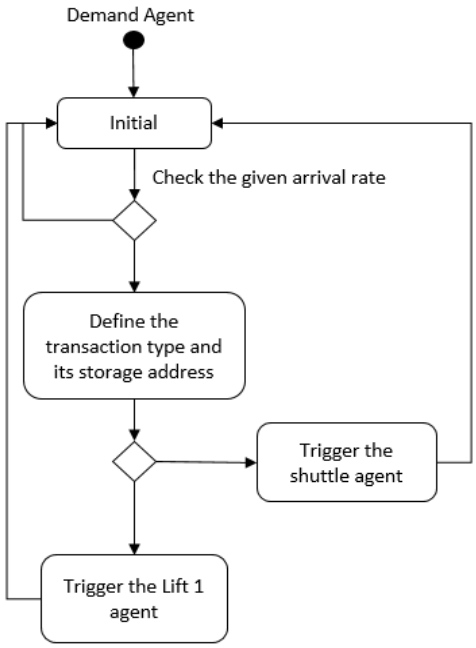


Figure 3. State transition model of demand agent.

Figure 3 presents the attributes of the demand agent, which is responsible for generating transactions based on the specified arrival rate and distributions. When a retrieval transaction needs to be processed, the corresponding shuttle agent is activated as the first step. However, if the location is not on the first tier, the first Lift 1 agent in the corresponding aisle is activated instead. The shuttle agent then proceeds to drop off the retrieval transaction at the designated buffer location and pick up any storage transactions awaiting there. Simultaneously, the Lift 1 agent retrieves the retrieval transaction from the buffer location and transports it to the I/O point. For storage transactions, Lift 1 drops them off at the buffer location of the corresponding tier address.

Figure 4 shows the behavior of shuttle agents based on retrieval and storage processes separately. The working principle of shuttle agents during the retrieval and storage processes is depicted in Figure 4. When an available shuttle agent is triggered, it first evaluates the waiting transactions based on the defined PAR. If another shuttle agent is already active at the selected transaction's tier address, the current shuttle agent ignores it and selects another advantageous transaction from its queue. Once a transaction is selected, the process flow is determined based on the transaction type (see Figure 4(a) or 4(b)). In the case where Lift 2 is required for the process, the shuttle creates a duplicate entity that enters the queue for Lift 2. Simultaneously, the shuttle proceeds towards the Lift 2 location to reach the corresponding tier. In the case of a retrieval process, the shuttle moves to the retrieval address to collect the tote. Subsequently, it transports the tote to an available buffer location for storage. During the storage process, the shuttle travels to the buffer location with the intention of retrieving the tote. In cases where the tote has not yet arrived at the buffer location, the shuttle remains in a waiting state until Lift 1 brings the tote to the buffer location. Once

the load is present at the buffer location, the shuttle picks it up, and both the shuttle and the load proceed to the assigned storage address.

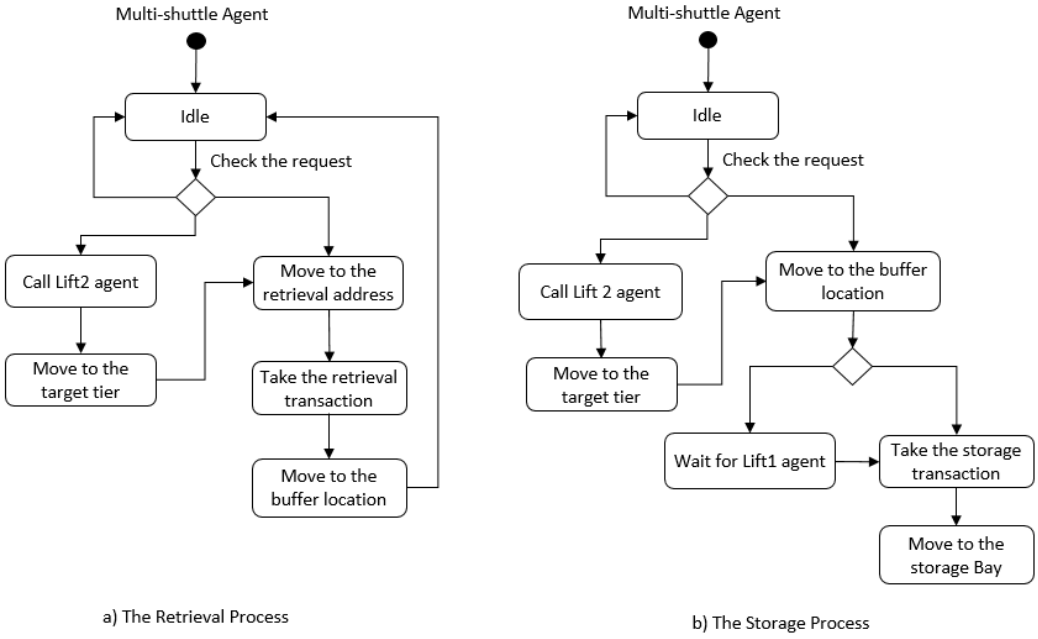


Figure 4. State transition model of multi-shuttle agent.

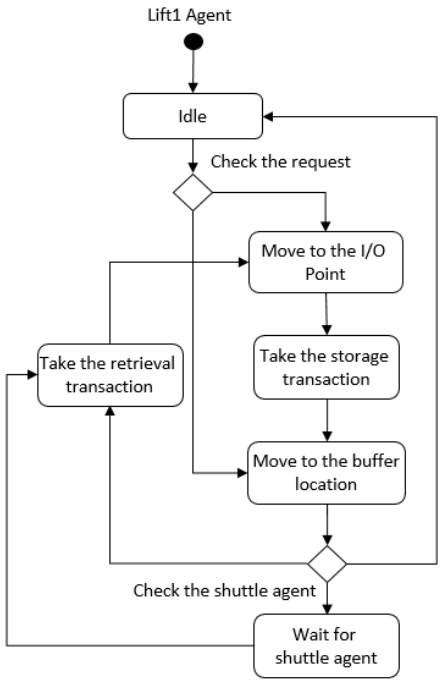


Figure 5. State transitions for Lift 1 agent.

The working principle of Lift 1 agent is depicted in Figure 5. Lift 1 agent is activated by either a storage transaction entity or a shuttle agent upon completion of a retrieval process. When a retrieval transaction needs to be processed, Lift 1 is directed to the buffer tier address in order to retrieve the tote. If the tote is not yet present at the buffer location when Lift 1 arrives, it waits until the tote arrives. Once the tote is available, Lift 1 picks it up and transports it to the designated I/O point. On the other hand, in the case of a storage transaction, Lift 1 directly moves to the I/O point to retrieve the tote. Subsequently, Lift 1 travels with the tote to the storage tier.

The Lift 1 agent in our system uses the DC&SPT rule as its preferred method of following the PAR. This rule combines the dual command (DC) and shortest process time (SPT) rules to improve efficiency in the system. Further details on this rule are provided in the following section. The simulation runs have shown that the DC&SPT rule outperforms the SPT or DC rules alone by up to 5%. As a result, DC&SPT PAR rule is implemented for the Lift 1 agent in the system simulation.

The working principle of the Lift 2 agent is presented in Figure 6. The agent is triggered by a request from a shuttle agent and begins to travel to the Lift 2 location. Once there, the agent and the shuttle together travel to the destination tier.

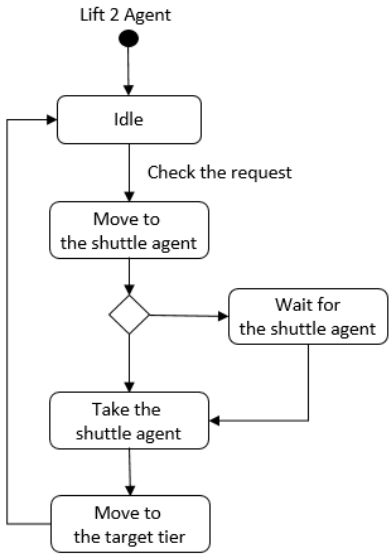


Figure 6. State transitions for Lift 2 agent.

The simulation flow charts for the shuttle, Lift 1 and Lift 2 agents are depicted in Figures 7-9, respectively. The models are rigorously verified and validated through debugging and system animation, as well as by comparing the model outputs with the literature. Figure 10 presents a snapshot from the animated simulation model.

To develop efficient queuing management mechanisms in the flexible SBSRS, we employ a real-time data and information tracking-based operating policy. This involves treating the lifts, shuttles, and transactions as intelligent agents with the ability to perceive, monitor, and assess real-time data and information from their surroundings. By employing the agent-based simulation modeling approach, we define the attributes and behaviors of these agents, enabling them to make intelligent decisions utilizing real-time information

such as tier and bay locations, remaining time to reach destination points, transaction types, and desired address information. The simulation is conducted using commercial software (ARENA 16.0), and performance is evaluated based on several metrics, including average and maximum flow times of transactions, average utilization of S/L, throughput rate, standard deviations of flow times, and average flow time of outlier transactions.

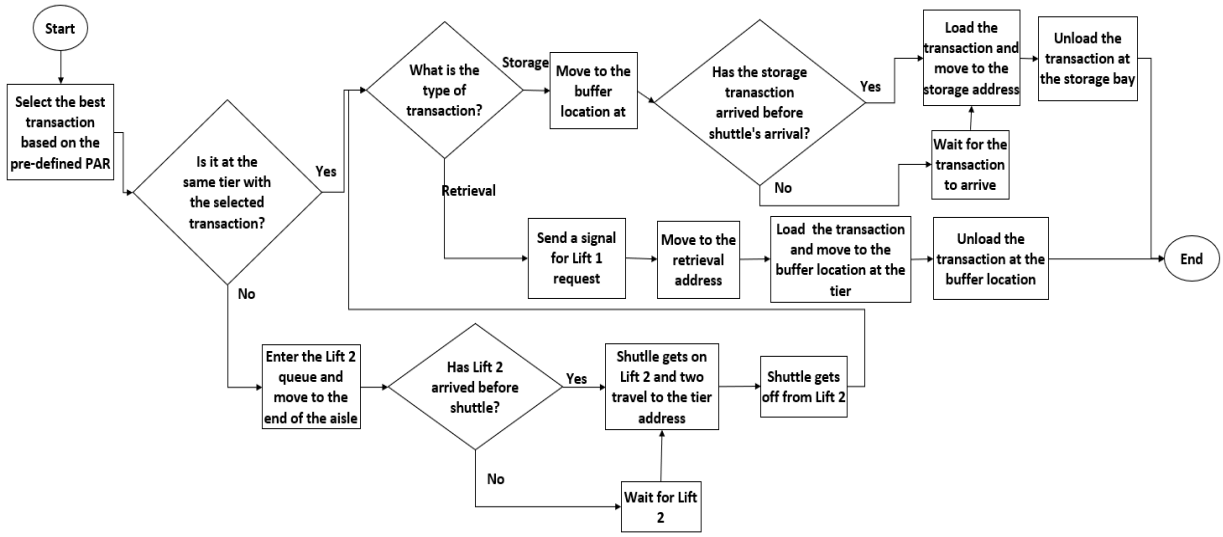


Figure 7. Flow chart for shuttle agent.

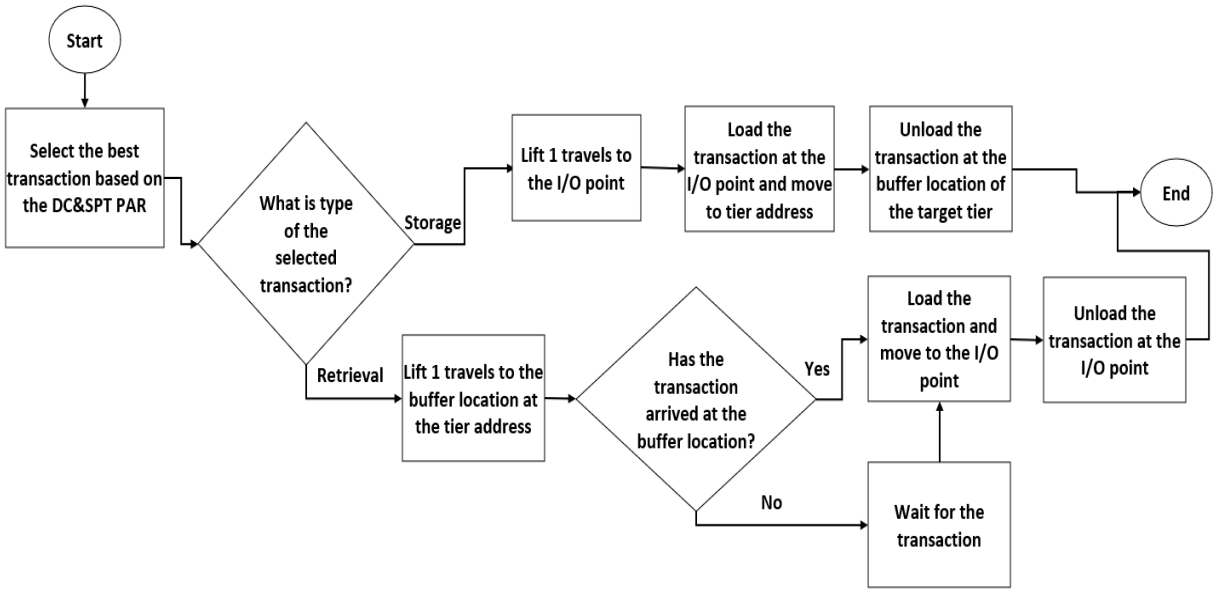


Figure 8. Flow chart for Lift 1 agent.

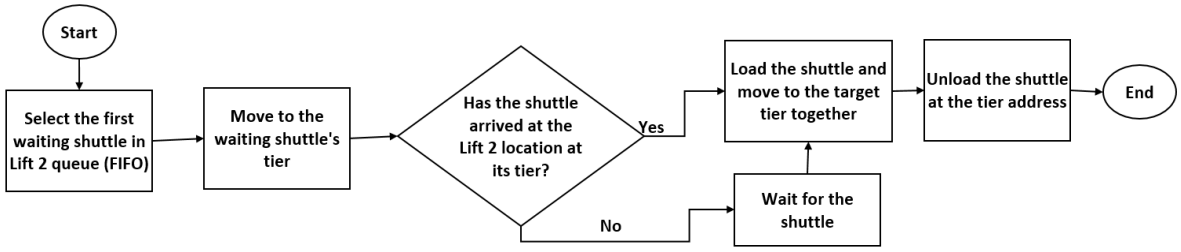


Figure 9. Flow chart for Lift 2 agent.

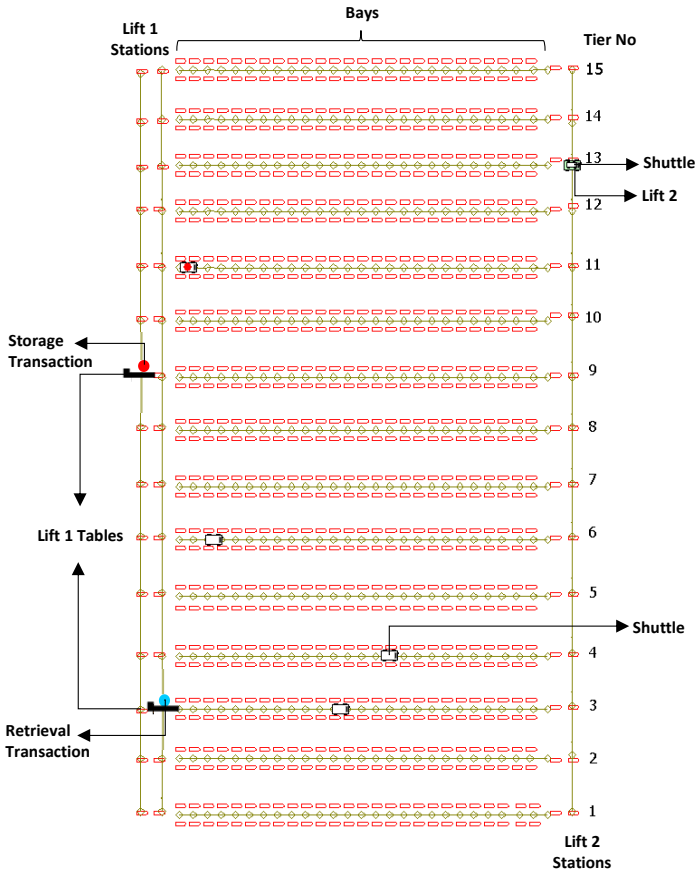


Figure 10. A snapshot from the agent-based simulation model.

3.3 Design Scenarios and System Outputs

The flow time is a crucial performance metric in the studied system, which measures the time a transaction spends in the system until it is completed. This includes the waiting times in shuttle/lift queues. In this work, a novel approach where there is not only a goal to minimize the AFT of a transaction but also minimize the MFT and improve outlier transaction-related performance metrics is proposed. AFT quantifies the mean duration that a transaction remains within the system until its disposed. It provides a general indication of the overall efficiency of the system. By minimizing AFT, the priority assignment rules aim to reduce the

average processing time for transactions, leading to improved system performance. MFT is the maximum time a transaction remains within the system until its disposed. It focuses on outliers or transactions with exceptionally long flow times. Minimizing MFT is also crucial in meeting the increasing demand for shorter response times in competitive supply chain environments, particularly in the context of e-commerce. By reducing MFT, the priority assignment rules ensure that transactions are processed within acceptable time frames, avoiding delays and customer dissatisfaction. Failure to meet these tight response times may result in customer orders not being shipped on their planned delivery times. Therefore, in the proposed control approach, agents collaborate to process tasks and find solutions not only for reduced flow time but also reduced maximum flow times.

Although the SPT rule may lead to a decrease in AFT per item, it may increase the MFT of an item. To address this issue, PARs are developed considering tracking real-time data and information on long waiting times for transactions. Further details on the developed rules are provided in the following sub-sections.

Table 1 presents the notations and units of measurement for all output metrics observed in the system. AFT denotes the average flow time of a transaction, while T_{out} represents the AFT for the outliers in five replications (i.e., the AFT of N transactions). Outlier flow time values are assumed to be those where the flow time of transactions is greater than $T + 3 \bullet S$, where S is the standard deviation of flow time during replications. T_{max} represents the average MFT obtained from the five replications, while T_{ind} denotes the MFT value observed among the five replications. Since outlier flow times are also taken into account, their standard deviation value is defined as S_{out}.

In the simulation model, real-time flow times of transactions are monitored to ensure that the MFT in the system is not increased. To achieve this, transactions with an estimated flow time greater than the critical point, $T + 3 \bullet S$, which indicates that they are outliers, may be given priority in processing. If there are multiple transactions under this condition, the pre-defined PAR determines the order of priority. Details of the priority assignment rules can be found in section 3.3.5.

Table 1. System outputs.

Notation	System output	Unit
T	AFT of a transaction	sec.
T_{out}	AFT of outlier transactions	sec.
T_{max}	Average MFT	sec.
T_{ind}	MFT realized among all replications	sec.
S	SD of flow time of transactions	sec.
S_{out}	SD of flow time of outlier transactions	sec.
N	Average number of outlier transactions	
U_s	Average utilization per shuttle	%
U_{L1}	Average utilization per Lift 1	%
U_{L2}	Average utilization per Lift 2	%
λ	Average throughput rate	transactions/month

The simulation models include three types of queues: shuttles, Lift 1, and Lift 2. To establish PARs for transactions waiting in these queues, two PARs are pre-defined for the shuttle queue, and several variations are created based on them. After some initial trials, it is observed that the SPT&DC PAR is effective for the Lift 1 queue, while the FIFO PAR works well for the Lift 2 queue. The details on the PARs implemented for the shuttle, Lift 1, and Lift 2 queues, as well as their operational principles, are presented in the following subsections.

3.3.1 First-In-First-Out PAR Rule

The first-in-first-out (FIFO) rule prioritizes tasks in a queue based on their arrival times, giving priority to the first task that arrived at the queue. This rule is implemented for the waiting tasks in the Lift 2 queue, which is the server that provides vertical travel for shuttles between tiers. When a shuttle needs to change its current tier, it sends a request signal to Lift 2. Since the shuttle's travel time to the target destination tier would not change once Lift 2 is seized by the shuttle, minimizing the waiting time for processing by Lift 2 would likely result in a decreased flow time output. Following numerous what-if analyses, it has been noted that the FIF) rule performs admirably for the Lift 2 server. Therefore, the FIFO rule is fixed as the primary PAR for the Lift 2 queue. By minimizing the waiting time for processing by Lift 2, the FIFO rule aims to decrease the flow time output. This PAR can be effective in scenarios where the shuttle needs to change tiers.

3.3.2 Shortest Process Time Sequencing Rule

The priority of a transaction is determined by the Shortest Process Time (SPT) rule, which assigns priority to the transaction with the shortest estimated travel time. This is determined by calculating the estimated process times for all the transactions waiting in their respective queues, using real-time distance information provided by the environment. Agents use this information to calculate time metrics based on distance and velocity. By considering real-time distance information and velocity, this rule enables efficient allocation of resources and minimizes the overall flow time. It takes into account the dynamic nature of the system, allowing for adaptive decision-making based on real-time data.

In order to accurately predict the travel time of transactions that are in the shuttle queue, the forecast takes into consideration the travel times of both Lift 1 and Lift 2. The demand agent calculates the horizontal and vertical travel times for shuttles, and also factors in the estimated waiting time in the Lift 2 queue. Once the travel time is estimated for each demand, the shuttle agent selects the transaction with the shortest travel time.

It should be noted that the SPT rule aims to reduce AFT. However, while AFT decreases, the MFT may tend to increase. This emphasizes the importance of considering both AFT and MFT when evaluating system performance.

3.3.3 Dual Command (DC) & SPT Sequencing Rule

The DC rule involves processing storage and retrieval transactions in a specific order. For Lift 1, the dwell point is always the first tier for retrieval processes and any tier for storage processes. To reduce the process time of Lift 1, it may be beneficial to process these two types of transactions consecutively. This is because a storage process begins at the I/O point, while a retrieval process ends there. Combining these transaction types could potentially decrease travel time. As there is no such pattern for the shuttle that requires changing its current tier, that rule is only applied to the Lift 1 queue.

When using a combination of the DC and SPT rules, Lift 1 selects transactions in the order of storage, retrieval, storage, and so on, while also assigning priority to the transaction with the shortest estimated

travel time. By consecutively processing storage and retrieval transactions for Lift 1, it reduces travel time and potentially decreases the overall process time. This PAR is based on the observation that combining these transaction types can optimize flow time.

3.3.4 Process Time (PT)/ Waiting Time (WT) Rule

When running the models using the aforementioned rules, it has been observed that although the AFT per transaction decreases over time with the SPT PAR, the MFT of a transaction tends to increase. This is likely due to the fact that the SPT rule assigns priority to transactions with the shortest estimated travel time, resulting in transactions with longer travel times potentially waiting longer in the queue, leading to increased maximum flow time in the system. In other words, since the SPT rule may prioritize a newly arriving task in the queue, this can increase the MFT of a transaction by prolonging the waiting time of other transactions in the system.

Companies may choose to adopt a customer-oriented approach to supply network management, which can limit their ability to implement short response time strategies. With the growing trend of responsive supply networks, companies often make promises to their customers regarding delivery times, and therefore, minimizing the maximum flow time becomes an important performance metric for supply chain management. To achieve comprehensive customer satisfaction, designing systems with a multi-objective optimization approach can be beneficial. As such, it is aimed to identify a rule that considers both the minimization of AFT and MFT system outputs simultaneously. Hence, the Priority assignment rule based on Process Time (PT) and Waiting Time (WT) is chosen to balance the trade-off between AFT and MFT. This rule aims to minimize not only AFT but also MFT by incorporating the waiting times of transactions.

Our proposed approach involves calculating a ratio (R) using (1) to determine priority for transactions waiting in the shuttle queue. This ratio takes into account both low process time and long waiting time when assigning priority to transactions, ensuring a fair and efficient system.

$$R = \frac{process\ time}{waiting\ time} \tag{1}$$

When compared to the SPT rule, using this rule may result in increased AFT but decreased MFT.

3.3.5 Real-Time Outlier Tracking Rule (RTOTR)

A significant contribution of this paper is the introduction of a PAR rule that utilizes real-time data and information to track the flow time of waiting transactions. This rule determines whether to assign priority to a transaction based on the already implemented pre-defined PAR. This approach, called Real-time outlier tracking rule (RTOTR), can be implemented on either the SPT or PT/WT rules. For example, if SPT is used as the PAR for transactions in the shuttle queue, the priority is given to a transaction that meets the pre-defined RTOTR criteria. The algorithmic steps of this approach are detailed below:

(i) During the simulation run, such as in a steady-state, re-calculate the AFT and SD after a transaction is processed.
(ii) Calculate the critical point, CP_1 by (2), which identifies transactions waiting in the queue with estimated flow times higher than CP_1 as outliers.
(iii) Calculate the average flow time of outliers (T_{out}) and standard deviation (S_{out}) during the simulation runs.
(iv) Using (3), calculate the critical point (CP_2) where transactions with flow times larger than CP_2 are considered outliers of outliers. The coefficient C in the equation is determined through experimental work to find the optimal value.

(v) In order to reduce T_{max} and T_{ind}, priority should be given to the transactions in shuttle queue with the shortest travel time (SPT), if their estimated flow times exceed CP_2.

In below, the algorithmic flow of the developed RTOTR under the SPT rule is given.

$CP_1 = T + 3 \bullet S$ (2)

$CP_2 = T_{out} + C \bullet S_{out}$ (3)

$i = 1$
$while\ i\ \leq$ number of transactions in queue
$if\ estimated\ flow\ time_i\ >\ CP_2$
$Assign\ attribute\ as\ label\ =\ 1$
$i = i + 1$
$else$
$i = i + 1$
end
end
$search\ i\ for\ min(estimated\ flow\ time_i)\ where\ label\ =\ 1$
$if\ i\ =\ 0$
$search\ i\ for\ min(estimated\ flow\ time_i)$
end
$select\ i^{th}\ transaction\ in\ queue$
end

Consequently, the RTOTR approach determines whether to assign priority to a transaction based on its existence in outlier in terms of time. By considering outliers and dynamically updating critical points, this rule enhances decision-making and can improve the performance metrics, including AFT, MFT, and standard deviations. Namely, by dynamically adjusting priority based on the real-time presence of outliers in terms of flow times, we aim to achieve a balance between reducing outlier-related metrics (Tout, Sout) and minimizing potential negative impacts on AFT and MFT.

The experiments are conducted to observe how the pre-defined performance metrics are affected under the defined PARs, as summarized in the following section.

4. Experimental Study, Results and Discussion

It should be noted that DC&SPT and FIFO PARs are applied for transactions waiting in Lift 1 and Lift 2 queues, respectively. However, the most challenging decision is which transaction to process first among the ones waiting in the shuttle queue. This is because the process starts with the selection of a suitable transaction by an available shuttle. The experimental design tables for the PARs of transactions are presented in Table 2 and Table 3 for the cases when there is no RTOTR and when RTOTR is considered, respectively.

Table 2. Experimental design for PAR when no RTOTR.

Design no	Initial PAR
1	SPT
2	PT/WT

Table 2 shows the application of either SPT or PT/WT as PAR for the transactions waiting in the shuttle queue.

Table 3. Experimental design for PAR under RTOTR.

Initial PAR	*C* Value	CP_1 - CP_2 Update
SPT	1	Static - Static
PT/WT	2	Static - Dynamic
	3	Dynamic - Dynamic

Table 3 illustrates the application of RTOTR on SPT or PT/WT rules with the coefficient *C* used for calculating CP_2 as shown in (2). The coefficient for CP_1 calculation is always 3 as shown in Section 3.3.5. The last column shows whether the *T*, *S*, and T_{out}, S_{out} values are updated during the simulation runs, as assigning priority to outliers may cause these values to dynamically change. Different combinations of static and dynamic updating are experimented with to observe their effects on performance metrics. For instance, the last combination, dynamic-dynamic, means that the values of CP_1 and CP_2 are dynamically updated during the simulation runs. Note that *T*, *S*, and T_{out}, S_{out} are real outputs from the system. When a static policy is considered, CP_1 or CP_2 calculation is not updated during the simulation run, and Design 1 and Design 2 results are used for (1) and (2) calculations.

It should be noted that the implementation of RTOTR aims to enhance several performance metrics, including T_{max}, T_{out}, *S*, and S_{out}, while minimizing any negative impact on *T*. Table 4 presents the results of five simulation replications and their corresponding confidence intervals. It is important to mention that most companies prefer highly utilized resources. To reflect this preference, the arrival rates are set to achieve a bottleneck server utilization of approximately 99% in the scenario with the worst *T* value. Then, this scenario is used for all experiments. Specifically, an exponential distribution for transaction arrivals with a mean inter-arrival time of 2.6 seconds is considered in the simulations.

Dot plots are drawn to represent the flow time values of all five replications in Table 4. Figure 11 represents the results for Design 1, which uses SPT as the PAR, while Figure 12 shows the results for Design 2, which uses PT/WT as the PAR (see Table 3). RTOTR is not used in either design. In each figure, part "a" displays the flow times of all transactions in the five replications, while part "b" displays the flow times of outliers in the five replications. Please note that T_{max} represents the average MFT obtained from the five replications, while T_{ind} represents the MFT value observed across all five replcations. The performance metrics *S* and S_{out} represent the standard deviations for the flow time and the flow time of outliers, respectively.

Table 4. Experimental results for five independent replications.

Design No.	Initial PAR	CP_1 - CP_2 Update	*C* Value	*T* (sec.)	*S*	T_{out} (sec.)	S_{out}	T_{max} (sec.)	U_{L1}	U_{L2}	U_S	*N*	λ (per month)
1	SPT	n.a.	n.a.	31.90±0.06	21.11±0.09	126.05±0.44	32.06±0.47	453.87±41.06	86%±0.05%	91%±0.03%	97%±0.05%	20881±140	997281±1206
2	PT/WT			40.87±0.17	15.60±0.08	95.96±0.59	9.75±0.89	209.49±46.35	87%±0.07%	92%±0.05%	99%±0.04%	4218±87	997214±1139

Table 4 continued…

3	SPT	Static - Static	1	31.98±0.08	20.69±0.10	121.10±0.50	21.77±0.07	219.40±31.19	86%±0.07%	91%±0.05%	97%±0.03%	22583±126	997271±1104
4			2	31.94±0.05	20.92±0.07	124.06±0.36	26.82±0.13	233.07±24.44	86%±0.07%	91%±0.06%	97%±0.04%	21616±128	997303±1168
5			3	31.92±0.07	21.02±0.12	125.09±0.70	29.4±0.41	278.63±52.13	86%±0.04%	91%±0.04%	97%±0.05%	21239±155	997312±1174
6	SPT	Static - Dynamic	1	32.18±0.08	20.48±0.07	116.2±0.30	15.1±0.51	231.50±29.72	86%±0.05%	91%±0.06%	97%±0.04%	24502±232	997247±1219
7			2	31.96±0.04	20.81±0.05	122.58±0.22	24.06±0.22	234.14±19.63	86%±0.06%	91%±0.05%	97%±0.03%	22142±123	997283±1261
8			3	31.91±0.06	20.99±0.05	124.92±0.29	28.79±0.38	260.94±35.64	86%±0.05%	91%±0.06%	97%±0.04%	21365±147	997235±1156
9	SPT	Dynamic - Dynamic	1	32.24±0.08	20.48±0.09	115.39±1.09	14.06±1.04	212.84±19.54	86%±0.04%	91%±0.05%	97%±0.04%	24931±408	997318±1172
10			2	31.99±0.07	20.82±0.05	122.57±0.29	23.86±0.46	246.06±52.32	86%±0.06%	91%±0.03%	97%±0.06%	22153±132	997297±1160
11			3	31.91±0.06	20.96±0.12	124.71±1.13	28.55±0.77	246.56±13.13	86%±0.06%	91%±0.04%	97%±0.05%	21322±244	997294±1209
12	PT/WT	Static - Static	1	41.10±0.30	16.17±0.65	108.36±8.31	17.68±5.29	241.94±51.21	87%±0.04%	92%±0.03%	99%±0.03%	5788±1828	997253±1194
13			2	40.92±0.12	15.62±0.05	96.15±0.25	9.64±0.44	200.40±16.00	86%±0.06%	92%±0.04%	99%±0.04%	4234±119	997275±1241
14			3	40.87±0.11	15.61±0.07	96.18±0.70	10.17±1.17	209.96±34.52	87%±0.07%	92%±0.02%	99%±0.03%	4207±117	997170±1337
15	PT/WT	Static - Dynamic	1	41.05±0.26	16.33±1.32	118.28±40.59	29.3±28.32	260.28±68.94	87%±0.05%	92%±0.02%	99%±0.05%	4553±442	997238±1179
16			2	40.92±0.09	15.62±0.06	96.19±0.35	9.84±0.75	207.6±34.62	87%±0.07%	92%±0.04%	99%±0.02%	4197±159	997293±1232
17			3	40.88±0.09	15.62±0.04	96.10±0.35	9.92±0.59	214.94±36.07	87%±0.07%	92%±0.04%	99%±0.05%	4236±111	997278±1296
18	PT/WT	Dynamic - Dynamic	1	40.98±0.21	15.97±0.56	107.24±17.19	21.61±17.17	241.15±54.93	87%±0.06%	92%±0.05%	99%±0.04%	4528±277	997221±1219
19			2	40.90±0.12	15.62±0.06	96.10±0.53	9.83±0.82	211.44±10.32	87%±0.07%	92%±0.01%	99%±0.03%	4273±160	997251±1165
20			3	40.90±0.10	15.61±0.08	96.10±1.00	10.37±2.21	224.50±44.17	86%±0.07%	92%±0.03%	99%±0.03%	4219±183	997223±1164

Note: n.a. refers not applicable

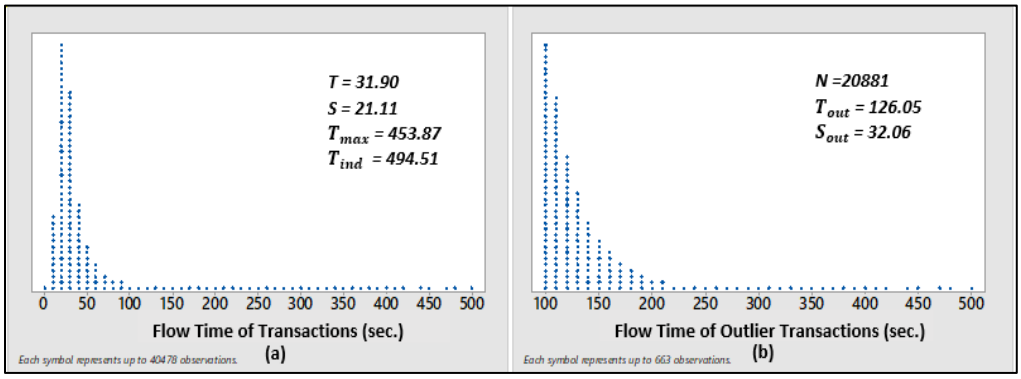


Figure 11. (a) Dot plots for flow times of transactions for Design 1, (b) Dot plots for flow times of outlier transactions for Design 1.

Based on the data presented in Figure 11, the SPT rule yielded the following results: T = 31.90 sec, T_{ind} = 494.51 sec, and T_{max} = 453.87 sec. In order to identify outliers, the CP_1 value is calculated by adding three times the standard deviation to the T value, resulting in a CP_1 of 95.24 sec (refer to equation (1)). Any flow times exceeding 95.24 sec are considered outliers. It is important to note that the objective is to reduce the values of T_{out}, T_{max}, T_{ind}, S, and S_{out} while minimizing any significant increase in the T value. To achieve this, the RTOTR approach described in Section 3.3.5 is implemented. Figure 11b comprises a total of 20,881 data points.

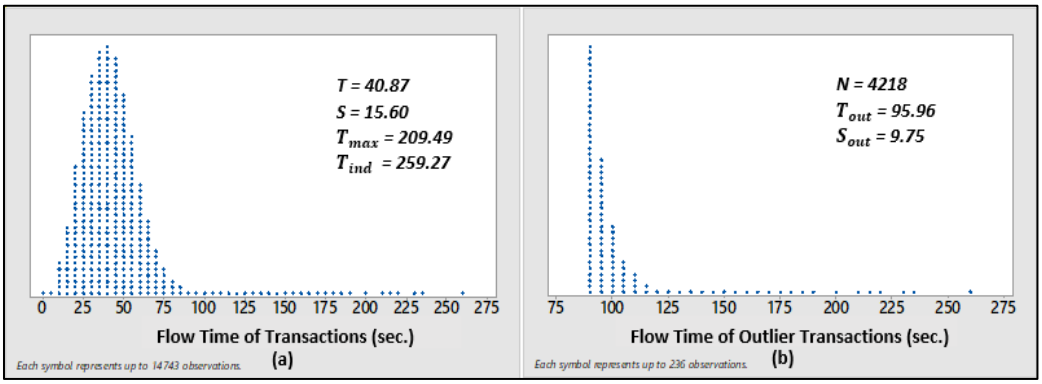


Figure 12. (a) Dot plots for flow times of transactions for Design 2, (b) Dot plots for flow times of outlier transactions for Design 2.

The data presented in Figure 12 shows that the PT/WT rule produces the following values: T = 40.87 sec, T_{ind} = 259.27 sec, and T_{max} = 209.49 sec. Using equation (1), the CP_1 value for outliers can be calculated as 87.67 sec. based on the PT/WT rule (e.g., 40.87 + 3 * 15.60 = 87.67 sec).

When comparing Figure 11 with Figure 12, it is evident that the PT/WT PAR has the potential to decrease the values of T_{out}, T_{max}, T_{ind}, S, and S_{out}. However, reducing these performance metrics may lead to an increase in the T. Nevertheless, a reduction in the S value can be considered a positive contribution to the overall flow times in the PT/WT PAR.

It is important to note that as the value of C increases (e.g., C = 3), CP_2 also increases. Upon analyzing the results of all experiments in Table 4, it is observed that Design 9 and Design 13 demonstrate favorable outcomes from a multi-objective perspective. The dot plots of these experiments are presented in Figure 13 and Figure 14.

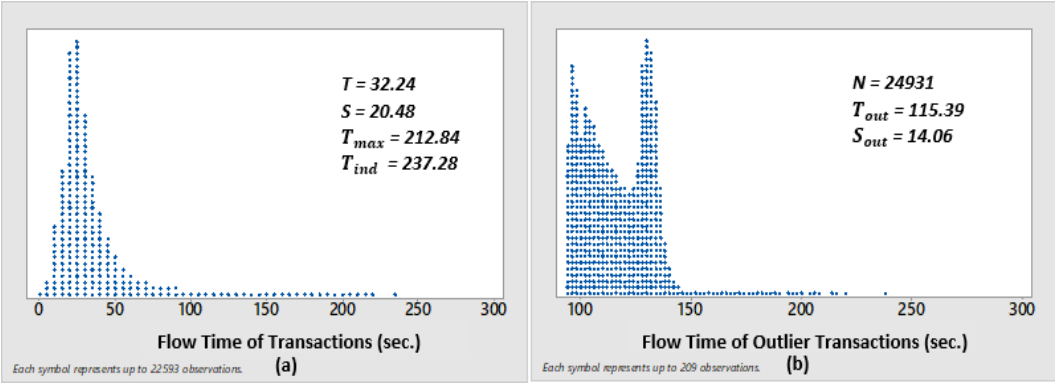


Figure 13. (a) Dot plots for flow times of transactions for Design 9, (b) Dot plots for flow times of outlier transactions for Design 9.

Figure 13 displays the dot plots representing the outcomes of Design 9. This design incorporates the SPT PAR with dynamic CP_2 calculation using C = 1. In this approach, the SPT rule is applied, and if multiple transactions are identified as outliers with estimated travel times exceeding CP_2, the SPT rule is utilized for those specific cases. Both CP_1 and CP_2 values are dynamically updated during simulation runs.

In comparison to Design 1, where only the SPT rule is implemented, Design 9 demonstrates significant reductions in T_{max}, T_{ind}, and S_{out}. Although there is a slight increase in the T value, it is not deemed substantial. Neglecting the negligible increase in T_{max}, Design 9 may be considered the most favorable outcome among all the experiments conducted.

Upon comparing the outcomes of Design 9 and Design 2, it is evident that the T value in Design 9 outperforms that of Design 2. Although Design 2 yields the best results for the performance metrics N, T_{out}, and S_{out} among all the experiments conducted, it also leads to an increase in the T value. Therefore, considering a multi-objective perspective, Design 2 can be regarded as the optimal design.

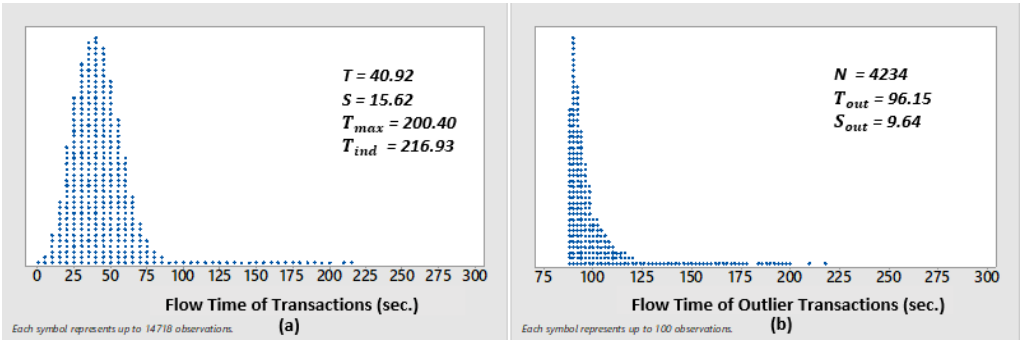


Figure 14. (a) Dot plots for flow times of transactions for Design 13, (b) Dot plots for flow times of outlier transactions for Design 13.

Figure 14 displays the dot plots showcasing the results obtained from Design 13. In this design, the PT/WT PAR is implemented with static RTOTR. The CP_1 and CP_2 values are calculated based on the T and T_{out} values of Design 2, which does not incorporate the RTOTR PAR. This implies that once the CP_1 and CP_2 values are determined, they remain constant throughout the simulation period. The value of C in this design is set to 2.

Among all the experiments conducted, Design 13 demonstrates the best performance, exhibiting the lowest values for T_{out}, T_{max}, T_{ind}, and S_{out} performance metrics. This policy may be favored when the minimization of T_{max} is of utmost importance.

The Appendix section includes dot plots that provide a comprehensive summary of the results obtained from all the experiments. These simulations highlight the substantial improvement achieved in multiple performance metrics through real-time tracking of data and information decision-making. The outcomes reveal that specific designs surpass others in terms of various performance metrics, thereby offering valuable insights for decision-making in enhancing system efficiency.

5. Conclusion

The objective of this paper is to investigate a flexible design for an SBSRS that deviates from the conventional non-flexible approach by incorporating fewer shuttles and eliminating the need for a dedicated lift for tier changes. PARs are proposed to enhance the processing of transactions and improve various performance metrics, including average and maximum flow time. In today's competitive supply chain environment, reducing the maximum flow time is crucial as customers expect faster order response times.

The proposed approaches are developed based on real-time tracking of flow times and environmental information, resulting in significant enhancements across different performance metrics. Notably, Design 9 exhibits favorable performance results from a multi-objective perspective. This specific design, utilizing the SPT rule with dynamic RTOTR, consistently demonstrated the optimal balance between multiple performance metrics. The Appendix contains all the experiment results, allowing practitioners to select the approach that best suits their specific requirements.

In conclusion, this study highlights the benefits of a flexible SBSRS design with improved performance metrics achieved through the implementation of priority assignment rules. The findings emphasize the importance of real-time tracking and decision-making based on flow times and environmental information. By adopting the appropriate approach, practitioners can enhance the efficiency of their systems and meet customer demands effectively. In terms of practical applicability, our research findings hold relevance in real-world contexts. For instance, our study underscores how the optimization of multi-objective performance metrics, including average and maximum flow times as well as outlier management, has a direct impact on customer satisfaction. The reduction in MFT aligns with customer expectations for quicker response times, especially in the context of e-commerce. We delve into the significance of dynamic decision-making strategies, as exemplified by the introduction of our Real-Time Outlier Tracking (RTOTR) approach. This strategy augments adaptability within the system, allowing it to intelligently manage outlier transactions and maintain consistent performance. Looking ahead, we explore various avenues for future research, including different PAR variations, the influence of velocity profiles on system performance, and extending the application of our approach to diverse warehousing designs. The conclusion is summarized from three perspectives, as below:

Implications to Theory and Practice

The theoretical contributions of this study are made to the existing literature on flexible SBSRS. The findings of this study also have important managerial implications for practitioners in the field of automated warehousing systems, especially from the perspective of cost savings, increased efficiency, and improved customer satisfaction. The proposed PARs based on real-time data tracking provide valuable insights into optimizing transaction processing in flexible SBSRS. Managers can leverage these findings to enhance system performance by reducing average and maximum flow times, minimizing the impact of outlier transactions, and reducing the standard deviations of flow times. Specifically, the identified policy, Design 9, demonstrates promising results in terms of multi-objective performance metrics. Therefore, practitioners can consider adopting Design 9 as a guideline for decision-making processes in similar flexible SBSRS designs.

Key Lessons Learned

The importance of considering both AFT and MFT as performance metrics and the need for a multi-objective optimization approach in supply chain management are the significant key lessons learned from the work. In addition, the significance of real-time data tracking and information-based decision-making in enhancing system efficiency and improving performance metrics, as well as the value of dynamic decision-making and the potential of different PARs in optimizing transaction processing, are other important lessons learned from this work.

Limitations of this Research

Note that this study focuses on a specific type of SBSRS and that further research is needed to test and evaluate different PARs and consider various warehousing designs. There would also be a need for sensitivity analysis with respect to the velocity profiles of shuttles and lifts.

The real-time data and information tracking-based dynamic decision-making application introduced in this study also opens avenues for further research and exploration. Future research endeavours can focus on testing and evaluating different PARs, considering various warehouse designs, and analyzing sensitivity to the velocity profiles of shuttles and lifts. This would provide deeper insights into the performance optimization potential of different approaches and enable practitioners to choose the most suitable strategies based on their specific requirements and operational contexts.

Conflict of Interest

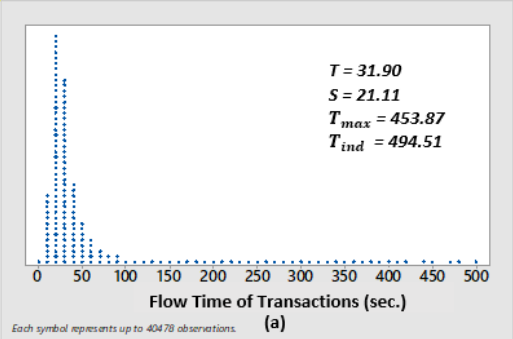
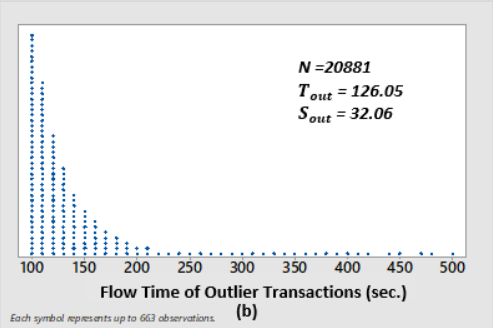
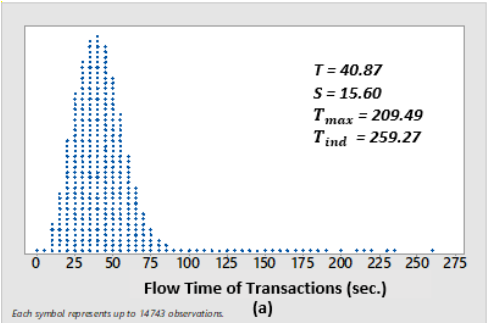
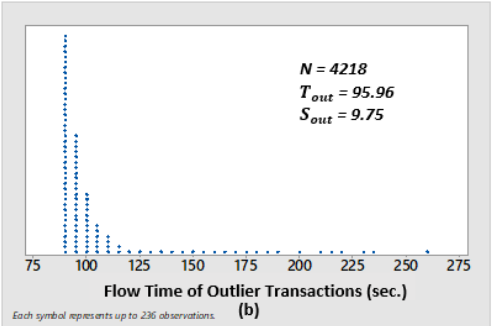
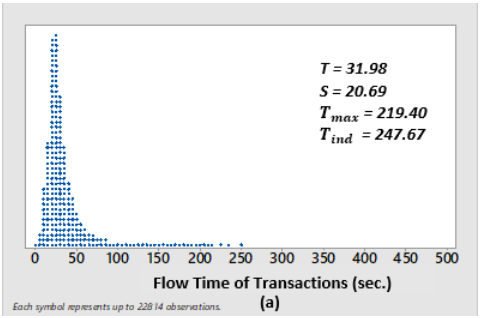
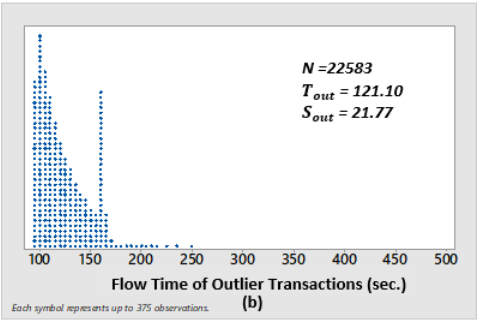
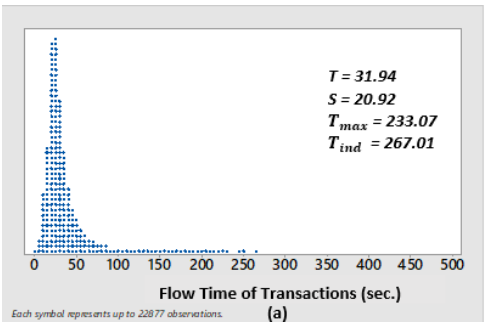
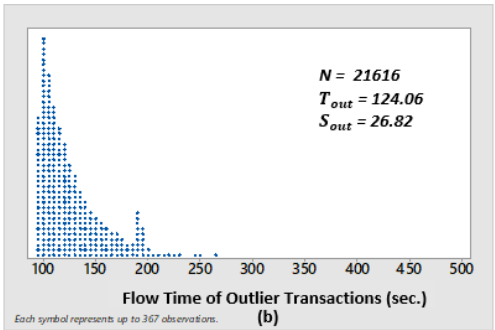
The authors confirm that there is no conflict of interest to declare for this publication.

Acknowledgements

This study was supported by the Scientific and Technological Research Council of Turkey: TÜBİTAK [grant number: 118M180].

Appendix

A1. Dot Plots of all experiments (Design 1- Design 20)

Design No.	Dot plots for flow times of transactions	Dot plots for flow times of outlier transactions
1.		
2.		
3.		
4.		

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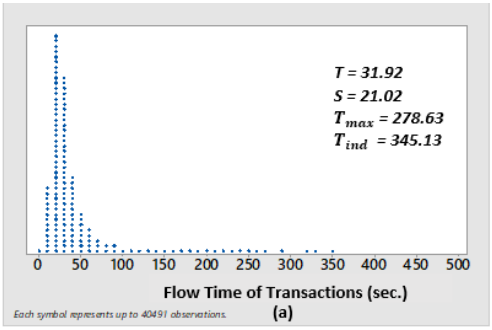
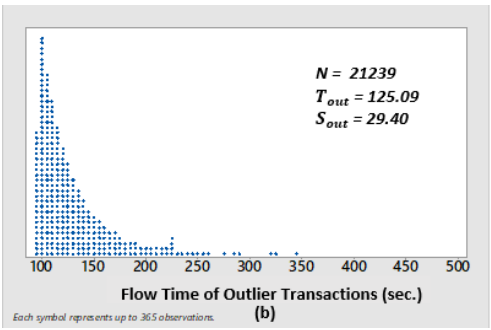
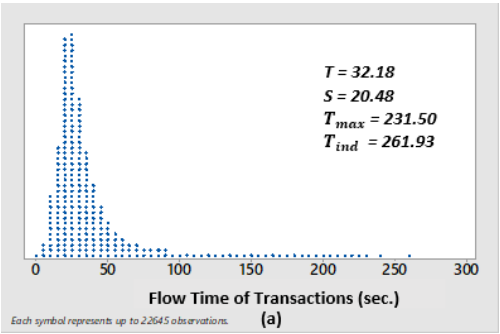
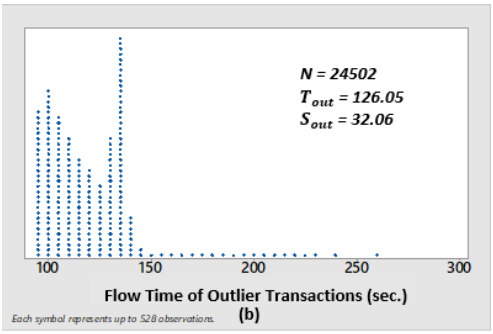
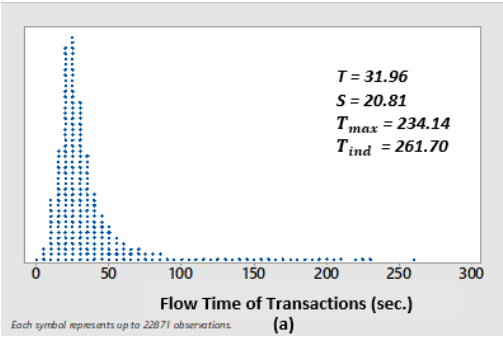
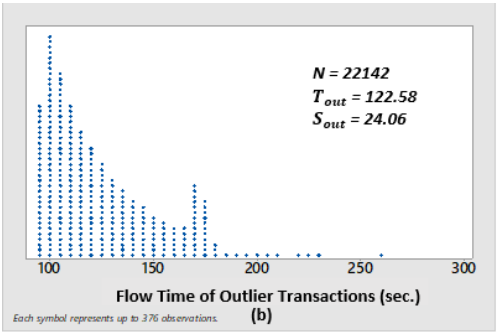
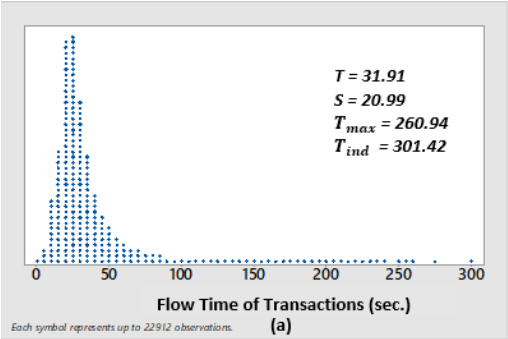
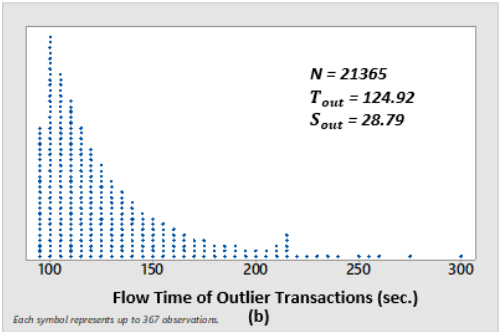
5.		
6.		
7.		
8.		

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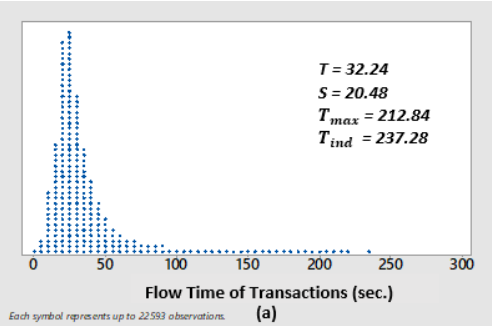
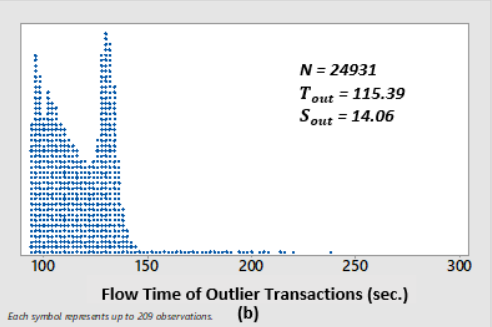
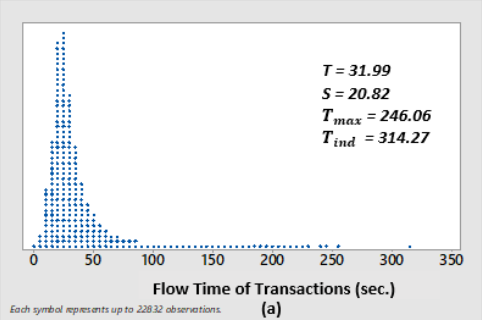
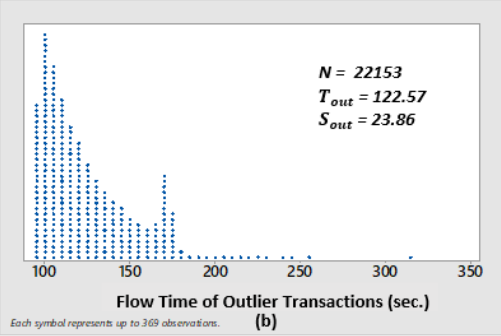
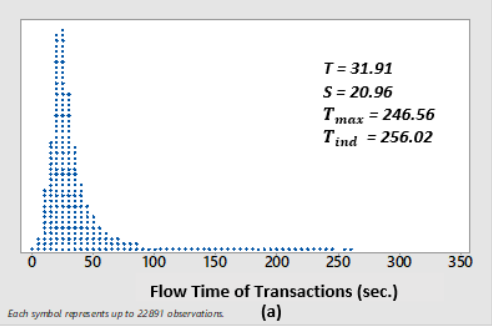
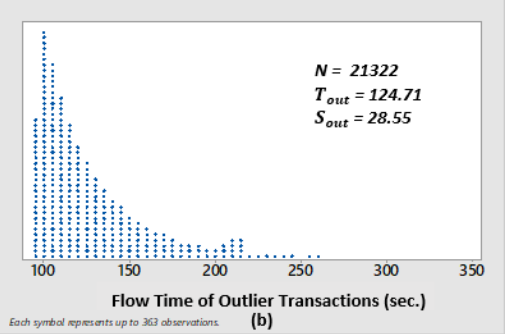
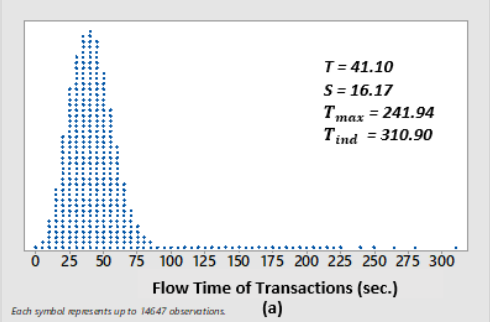
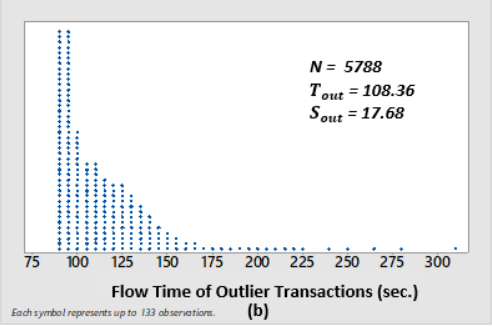
9.		
10.		
11.		
12.		

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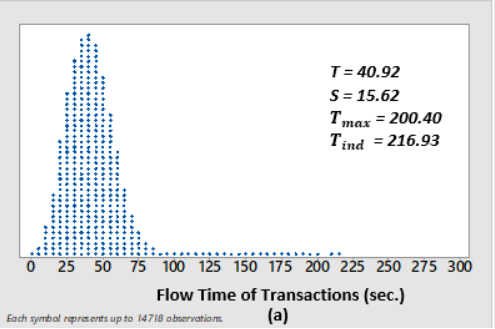
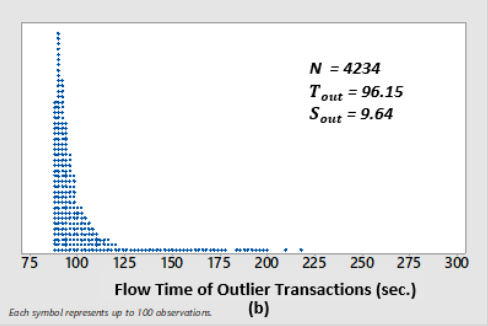
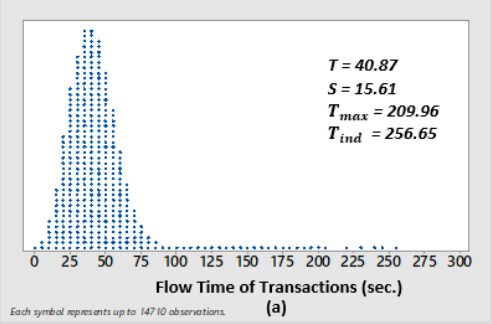
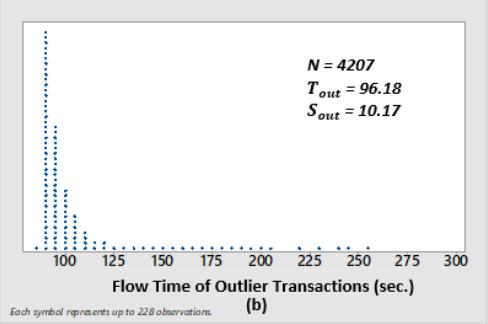
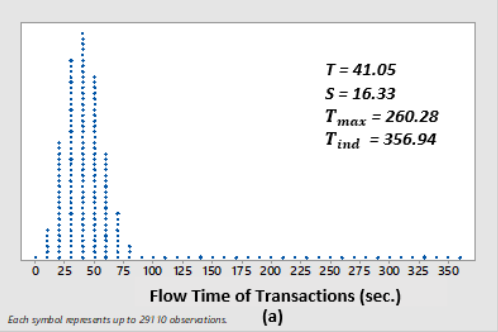
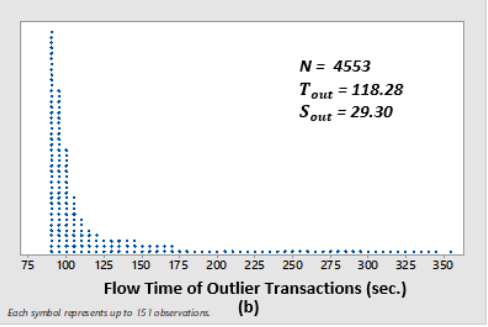
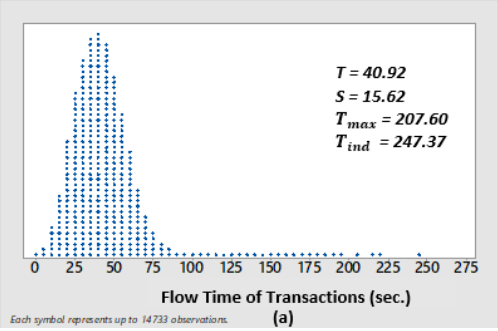
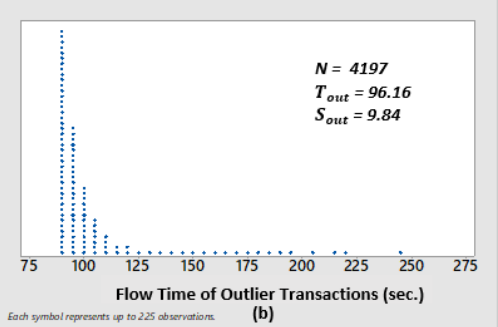
13.		
14.		
15.		
16.		

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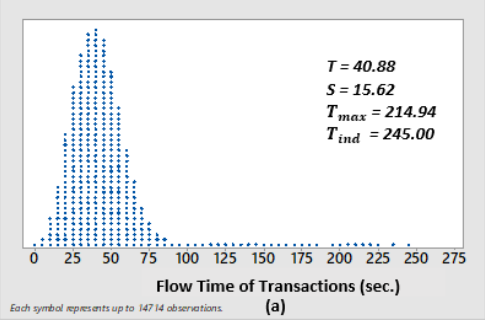
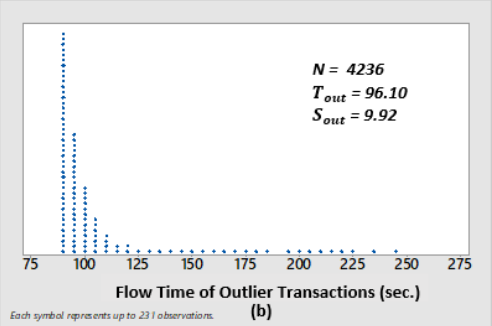
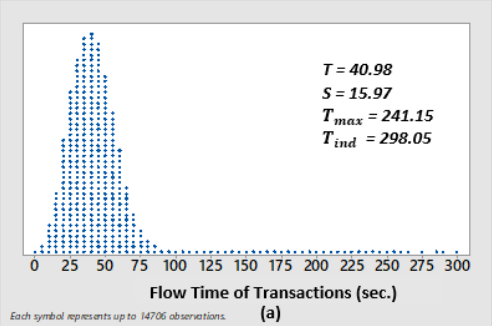
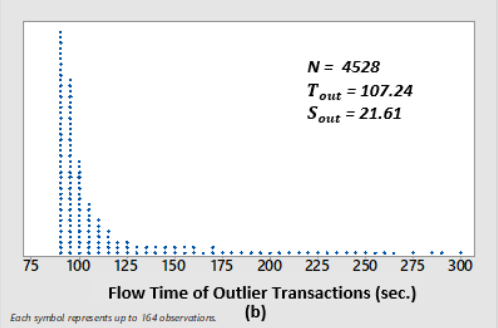
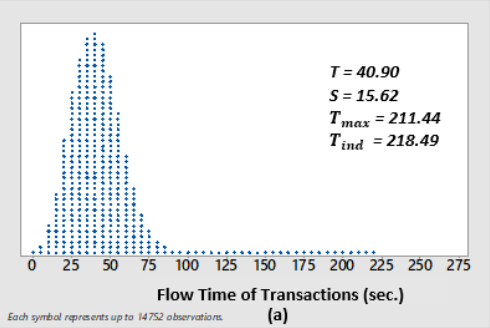
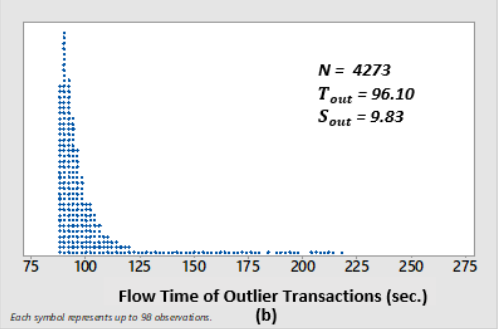
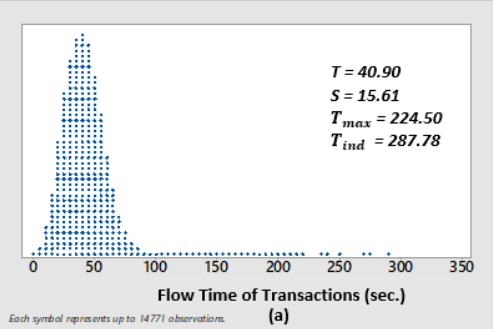
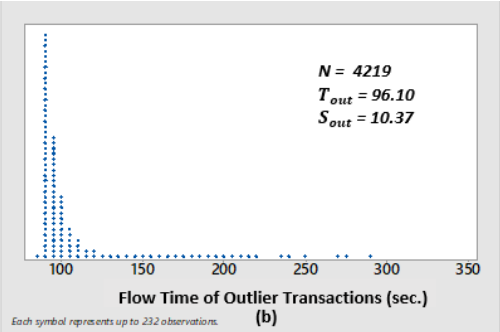
17.		
18.		
19.		
20.		

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