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AGENT-BASED SIMULATION MODELLING FOR DESIGN OF A SMART SBS/RS

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ABSTRACT

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In this thesis, we aim to study a tier-to-tier shuttle-based storage and retrieval (SBS/RS) design developed as alternatively to tier-captive SBS/RS design to overcome its negativeness. SBS/RS is an automated warehousing technology widely utilized in mini-load warehouses. Since there is a dedicated shuttle in each tier of an aisle in tier-captive SBS/RS, the average utilization of shuttles are very low compared to lifting mechanism located as a single server at each aisle. In an effort to decrease the number of shuttles in the system, we propose that novel tier-to-tier SBS/RS where there are few shuttles aisle than the number of tiers in a dedicated aisle so that those shuttles can travel between tiers. By the decreased number of shuttles, it is expected to highly utilize those shuttles. However, this time the throughput rate of the system may decrease compared to the tier-captive SBS/RS under the same warehouse design. For that, we also focus on smart operating policies in that tier-to-tier SBS/RS to improve its performance. We utilize simulation modelling approach for modelling approach.

This thesis mainly focuses on three research questions: i) is there an alternative SBS/RS design to tier-captive SBS/RS design where the utilization of shuttles are balanced with lifts? ii) in the porposed novel tier-to-tier SBS/RS, is there a system design meeting the desired system performance metrics with a low total investment cost? iii) what is the best priority assignment rule for transactions scheduling in queues to improve multi-objective performance metrics in the system? We provide solutions to all those questions. Finally, we define a novel tier-to-tier SBS/RS design and show that this design can be utilized as an alternative to classical SBS/RS considering cost, time and energy performances. We also complete a factor analysis to identify

significant factors affecting the performance of tier-to-tier SBS/RS, statistically. Moreover, to improve the performance of this novel design, we apply priority assignment rules by tracking real-time data in the system.

Key Words: SBS/RS, tier-to-tier SBS/RS, automated warehousing, automated storage and retrieval system

ÖZ

AJAN TABANLI SIMÜLASYON İLE AKILLI BİR OTOMATİK ARAÇLI DEPO TASARIMI

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Ocak 2021

Bu tezde katlara adanmış otomatik araçlı depolama ve çekme sistemlerinin olumsuzluklarının üstesinden gelebilecek kattan kata otomatik araçlı depolama ve çekme sisteminin (SBS/RS) tasarlanması hedeflenmektedir. Otomatik araçlı depolama sistemleri küçük yük depolarında oldukça yaygın kullanılan bir teknolojidir. Her kata bir aracın adanmış otomatik araçlı depolama sisteminde her katta bir araç olduğundan, her koridorda bir adet bulunan asansör mekanizmasına göre oldukça düşük kullanım oranına sahiptir. Sistemdeki otomatik araç sayısını azaltmak için bir koridordaki araç sayısının kat sayısından daha az olduğu yani araçların katlar arasında dolaşmasına izin verildiği yeni kattan kata otomatik araçlı depolama ve çekme sistemi tasarımı sunulmaktadır. Araç sayısının düşürülmesiyle araçların daha yüksek faydalı kullanım oranlarına sahip olması beklenmektedir. Bununla birlikte, sistemin çıktı oranı kata adanmış otomatik araçlı sisteme göre daha düşük olacaktır. Bu yüzden, sistem performansını iyileştirmek için kattan kata depolama ve çekme sistemi için akıllı operasyon politikalarına odaklanılmıştır. Bunu yapmak için de simülasyon modelleme yaklaşımı kullanılmıştır.

Bu tez esas olarak üç araştırma sorusuna odaklanmaktadır: i) mekiklerin kullanımının asansörlerle dengelendiği her aracın bir kata adanmış SBS/RS tasarımına alternatif bir SBS/RS tasarımı var mı? ii) Söz konusu yeni kattan kata SBS/RS'nde, düşük bir toplam yatırım maliyeti ile istenen sistem performans ölçütlerini karşılayan bir sistem tasarımı var mı? iii) sistemdeki çok amaçlı performans ölçütlerini iyileştirmek için kuyruklarda işlem planlaması için en iyi öncelik atama kuralı nedir? Bütün bu soruların yanıtı bu tez ile araştırılmıştır.

Son olarak, maliyet, zaman ve enerji bakımından klasik SBS/RS tasarımlarına alternatif olabilecek yeni bir kattan kata SBS/RS tasarımı önerilmiştir. Bu tasarımın performansını etkileyen faktörler istatistiksel olarak analiz edilmiş ve sistem performansını geliştirmek için gerçek zamanlı veri kullanılarak çeşitli öncelik atama kuralları uygulanmıştır.

Anahtar Kelimeler: SBS/RS, otomatik depolama sistemi, otomatik depolama ve çekme sistemleri

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First of all, I would like to thank my supervisor Banu Y. EKREN for her guidance and patience during this study.

I would like to express my enduring love to my parents, who are always supportive, loving and caring to me in every possible way in my life.

Melis KÜÇÜKYAŞAR
İzmir, 2021

TEXT OF OATH

I declare and honestly confirm that my study, titled "AGENT BASED SIMULATION MODELING FOR DESIGN OF A SMART" and presented as a Master's Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions. I declare, to the best of my knowledge and belief, that all content and ideas drawn directly or indirectly from external sources are indicated in the text and listed in the list of references.

Melis KÜÇÜKYAŞAR
Signature
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February 1, 2021

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SYMBOLS AND ABBREVIATIONS

ABBREVIATIONS:

SBS/RS	Shuttle-based Storage and Retrieval System
AVS/RS	Autonomous Vehicle Storage and Retrieval System
AS/RS	Automated Storage and Retrieval System
OQN	Open Queuing Network
MPA	Manufacturing System Performance Analyzer
FIFO	First-in-First-Out
SPT	Shortest Process Time
I/O Point	Input/Output Point
PAR	Priority Assignment Rule
DC	Dual Command
DC&SPT	Combination of Dual Command and Shortest Process Time Rules
PT/WT	Process Time/Waiting Time
RTOTR	Real-Time Outlier Tracking Rule

SYMBOLS:

T	Number of Tiers
B	Number of Bays
A	Number of Aisles
W	Warehouse Capacity
TC	Total İnvestment Cost
E	Energy Consumption per Transaction
R	Ratio
C	Coefficient
C_1	Cost of a Shuttle

C_2	Cost of Lift 1
C_3	Cost of Lift 2
C_4	Cost of a Bay
C_5	Cost of Space
S	The footprint of the Warehouse
n_s	Number of Shuttles in an Aisle
L_W	Length of the Warehouse
W_W	Width of the warehouse
d	Distance Between Two Adjacent Bays
l_b	Length of a Buffer Area
l_c	Length of Conveyor Area
l_1	Length of Lift 1 Mechanism
l_2	Length of Lift 2 mechanism
w	Width of a Rack
w_a	Width of an Aisle
t	Average Flow Time per Transaction
t_{out}	Average flow Time per Outlier transaction
t_{max}	Average Maximum Flow Time
t_{ind}	Maximum Flow Time Realized Among All Replications
s	The Standard Deviation of Transactions
s_{out}	The Standard Deviation of Outlier Transaction
N	The Average Number of Outlier Transactions
U_s	Average Utilization of Shuttles
U_{L1}	Average Utilization of Lift 1
U_{L2}	Average Utilization of Lift 2
λ	Average Throughput Rate

CP_1	Critical Point 1
CP_2	Critical Point

CHAPTER 1

INTRODUCTION

One of the recent biggest challenges facing the modern industry is the necessity to adapt today's fast changing competitive environment. Therefore, business models are seeking for methods to be flexible to keep up with this rapid changes. Automation has become a very significant investment through becoming flexible and productive target. Not only automation, but also smart algorithms integrated in those technologies helping to work with efficiently would also be required to reach those targets.

The age of digitalization that has come with the Industry 4.0 developments find its implementations in warehouses as well. Warehouses are significant in supply chains. The main purposes of warehouses are to store items temporarily in order to reduce the negative effects of demand variability as well as to be responsive to customer orders.

Shuttle based storage and retrieval system (SBS/RS) is one of robotic technology-based solutions for automated warehouses that are widely used in mini-load warehouses. With the recent e-commerce trend, order profile has changed towards more variability with low volume. Towards that changes Grand View Research (2019) predicts that the material handling equipment market size including automated storage and retrieval system equipment will grow by 6.8% from 2019 to 2025.

In this thesis, we focus on design of a novel automated warehouse robotic technology design to overcoming the negative aspects of previous tier-captive SBS/RS design. We also develop smart operating policies for that proposed system resulting with multi-objective performance improvements.

SBS/RS is initially introduced as tier-captive SBS/RS by Marchet et. al (2012) and Carlo and Vis (2012). Figure 1.1 shows the physical configuration of a tier-captive SBS/RS drawn for a single aisle. In this system, each tier has a dedicated shuttle traveling within an aisle. Therefore, the number of shuttles is the same as the number of tiers in an aisle in the system. Shuttles perform horizontal travel to pickup the totes from their storage addresses or to store them at the designated storage addresses. There is a lifting mechanism that is located in front of each aisle providing vertical travel for loads (i.e., totes) to change their tiers. We refer this lifting mechanism as Lift 1 in Figure 1.1. In each aisle, it is assummed that there is a single input/output (I/O) location where transaction requests starts or ends. In another word, Lift 1 transfers the totes from/to I/O points to/from the buffer area at each tier. At each tier there are two buffer areas located either left and right sides connected with the lifting mechanism. Totes wait there temporarily until they are picked up either by lifts or shuttles.

There are two main transaction types in the system: storage and retrieval transactions. For the storage process, first the lift travels to the I/O point to pick up the tote. Then, the tote is dropped off at one of the buffer locations at the target tier. Shuttle picks up this tote to store it at the target storage compartment (i.e., bay). For the retrieval process, first, the shuttle picks up the tote from its bay address and drops off it at one of buffer locations at that tier. Last, the lift travels to that tier and picks up the tote from the buffer location to drop off it at the I/O point.

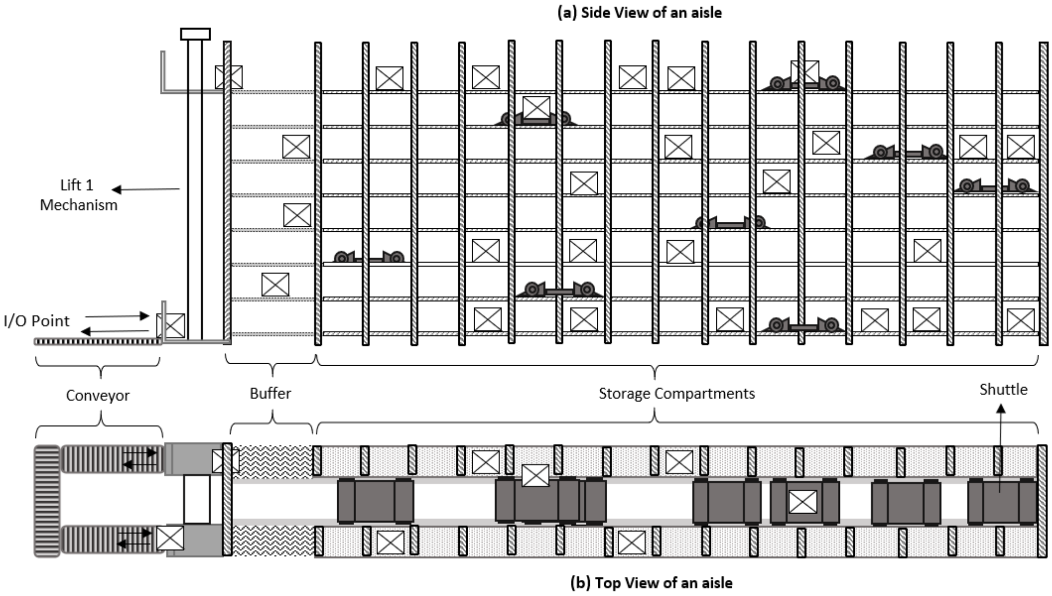


Figure 1. 1. The physical Configuration of tier-captive SBS/RS

In tier-captive SBS/RS, lift usually become bottleneck. This is because while there is a single lifting mechanism in each aisle, there are shuttles as many as number of tiers. Therefore, average utiliation of shuttles are very low compared to lifts in those systems (e.g., average utilizations of shuttles are roughly 40%, when lifts' are roughly 85%). The newly proposed tier-to-tier SBS/RS provides an opportunity to balance those utilization levels by decreasing the number of shuttles in the system which might also help for decreasing initial investment cost of those systems.

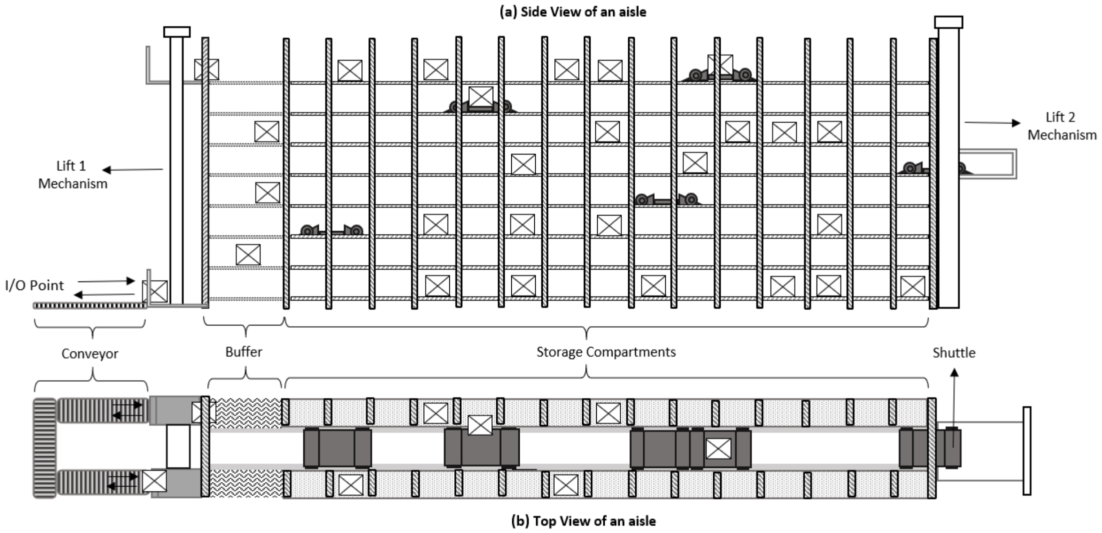


Figure 1. 2. The physical configuration of tier-to-tier SBS/RS design

Figure 1.2 shows the proposed tier-to-tier SBS/RS developed as an alternative design to tier-captive SBS/RS. Upper figure shows the top view, while the lower one shows the side view of this design. In this system design, shuttles are not tier-captive meaning that they can travel between tiers. By the decreased number of shuttles we allow shuttles travel between tiers by a separate lifting mechanism located at other end side of each aisle. We refer this lifting mechanism as Lift 2 in Figure 1.2. Once again, Lift 2 is dedicated for travel of shuttles between tiers.

There are three main research questions in this thesis. These are summarized as follows;

RQ1: Is there any alternative SBS/RS design to tier-captive SBS/RS design where the utilization of shuttles are balanced with lifts?

RQ2: In the porposed novel tier-to-tier SBS/RS, is there a system design meeting the desired system performance metrics with a lower total investment cost than tier-captive SBS/RS? What are the significant design factors affecting performance of this tier-to-tier SBS/RS design?

RQ3: Is there a good priority assignment rule for waiting jobs in queues that can improve the multiple objectives of flow time related performance metrics: average flow time per transaction, maximum flow time and standard deviation of flow times, average flow time of outliers, etc.?

To investigate those three questions, for RQ1 we propose a tier-to-tier SBS/RS design. For RQ2, we compare tier-to-tier designs with tier-captive designs in terms of throughput rate, average energy consumption per transaction, and total investment cost under different physical configurations. Also, we conduct an experimental design to identify the factors affecting the system performance such as average flow time per transaction, average energy consumption per transaction under different physical configurations. For RQ3, we propose several priority assignment policies for waiting jobs in queues in tier-to-tier SBS/RS by tracking real-time information and data. Then, we compare their performance results.

For the modelling purpose, we use simulation implemented in the commercial software Arena 16.0. The following subsections provide background about SBS/RSs.

1.1. Tier-Captive SBS/RSs

This existing literature is mostly related to tier-captive SBS/RS. Remember that, tier-captive designs have a dedicated shuttle in each tier of an aisle (see Figure 1.1). Because of this reason, average utilization of shuttles is very low compared to average utilization of lifts. However, these systems provide increased throughput rate outputs. One of the initial works in tier-captive SBS/RS is proposed by Marchet et. al. (2012). They develop an analytical model to predict significant performance metrics such as average waiting and cycle time of transactions in the system. They also validate the proposed open queuing network model by using the simulation modeling approach. After this study, Marchet et. al. (2013) introduce a study about design trade-offs for tier-captive SBS/RS. They analyze several performance metrics also including the initial investment cost of these designs by using simulation modeling. They obtain that a decreasing number of aisles ensures better performance metrics.

Another initial work in tier-captive SBS/RS is realized by Carlo and Vis (2012) for a different system design with two non-passing lifting mechanism. They use a heuristic-based solution for scheduling of those lifts.

Lerher et al. (2015a) study on the advantage of the tier-captive SBS/RS by obsering the throughput rate performance metric from the system. They investigate that performance metric under different physical configuration and velocity values of lifts and shuttles.

Lehrer et al. (2015b, 2016) study analytical models for travel time modelling in tier-captive SBS/RS. They consider many design scenarios developed on velocity profiles of shuttles and lifts and, single and dual command scheduling of transactions. They validate the models by their simulation results. Then, Lerher (2016) studies an SBS/RS with double-deep racks. The results show that this design provides more efficient utilized floor space.

Ekren et al. (2015) propose application of class-based storage policy in SBS/RS. They show the effectiveness of that policy by modelling it in ARENA 14.0 simulation software. The results of this study show that a class-based storage policy is applicable for SBS/RS resulted in a good performance.

Ekren and Heragu (2011) state the advantages of simulation modeling in analyzing many different experiments in automated warehouse systems. Ekren (2017) presents a simulation-based design approach to give several performance outputs considering different design configurations in a tier-captive SBS/RS. Ekren et al. (2018) provide a closed-form solution to predict the mean, variance of travel time of lifts and shuttles per transaction. That tool can also predict the mean consumption of energy and the mean regeneration of energy per transaction.

Wang et al. (2015) provide a mathematical optimization procedure for scheduling of tasks in SBS/RS. They present a multi-objective optimization problem developed on non-dominated sorting genetic algorithm. Tappia et al. (2016) present a queuing network model to estimate some critical performance metrics from a tier-captive SBS/RS. Zou et al. (2016) propose a fork-join queueing network model to estimate performance metrics from a tier-captive SBS/RS. By that, they could implement a parallel movement of shuttles and lifts in transaction travels. The validity of models is tested by simulation models. One of the recent works is by Eder (2019) where he proposes a model developed analytically to estimate some critical performance metrics from a tier-captive SBS/RS. He employs an open queueing network model with capacity constraint.

Ekren and Heragu (2012) compare the performance of two autonomous storage and retrieval system designs: crane-based AS/RS and AVS/RS. Ekren et al. (2013, 2014) model an AVS/RS by semi-open queuing network approach by utilizing their pre-developed extended algorithm (Ekren and Heragu, 2010b). Heragu et al. (2011) study crane-based AS/RS and AVS/RS for comparison purpose. They utilize a tool referred as manufacturing system performance analyzer (MPA), for the performance analysis of OQNs.

Zhao et al. (2018) study the scheduling of two non-passing lifts on a common rail SBS/RS. Because lifts are the bottleneck in the system, they consider acceleration and deceleration of lifts as design parameters to minimize the makespan of travels. They propose a function to predict the lift route and a scheduling genetic algorithm.

Ekren (2020a) presents a recent study on tier-captive SBS/RS from a statistical point of view. This study provides the factors that affect the system performance of tier-captive SBS/RS by using statistical experimental design. Results show that increased number of aisle affects the system performance significantly. The other recent worn on this system provided by Ekren (2020b). The study argues on a multi-objective optimization solution considering sverage cycle time and energy consumption per transaction for tier-captive SBS/RS.

1.2. Tier-to-Tier SBS/RSs

The number of works related tier-to-tier SBS/RS. Ha and Chae (2018a) study firstly, on that design. One of the most important part of their study is based on preventing collision of shuttles by defining a free-balancing approach. Against our study, they use a single lifting mechanism to carry loads and shuttles. After that work, Ha and Chae (2018b) focus on the number of shuttles in a tier-to-tier SBS/RS. They develop a model to determine the optimal number of shuttles considering velocity profiles, and physical configuration of a tier-to-tier SBS/RS.

Another study elaborates to minimize waiting times of shuttles, and idle time of lifts by Zhao et al. (2019) They develop an integer programming model for a tier-to-tier SBS/RS by using simulation modeling approach for the optimization procedure.

Very recent work is by Küçükyaşar et al. (2020a) studying performance comparison of tier-captive and tier-to-tier SBS/RSs under different warehouse design configurations. For the performance metrics, initial investment cost, flow time, and energy consumption performance metrics are considered. The results suggest that there could be better designs in tier-to-tier SBS/RS than tier-captive SBS/RS resulting in decreased investment costs and increased performance metrics. Küçükyaşar et al. (2020b) also show that the factors that affect the performance metrics of the tier-to-tier SBS/RS under different rack configuration. The results show that increasing the velocity profile and the number of tiers, decreasing the number of aisles cause to increase of average energy consumption in the system.

1.3. Agent-Based Modelling in Automated Warehouses

The simulation approach is mostly developed on those methods; discrete-event, continuous-event, and agent-based approaches. Agent-based simulation approach differs from the others with defined components in the model. This approach can be used in different fields such as sociology, biology, and engineering.

In agent-based modeling, of a set of agents is defined according to aim of the modelling system. Agents are modelled as autonomous and self-directed. The most important feature of agents is deciding independently in a dynamic and changing environment.

In this modelling approach, agent's behaviors are the critical point. They act by using the information coming from environments and the other agents.

Guller and Hegmanns (2014) introduce a detailed multi-agent simulation model for SBS/RS to evaluate the performance of the system. The results show that the order structure has a significant impact on performance of the system. In addition, they propose that agent-based simulation approach is a powerful tool in modelling complex multi-shuttle systems. Güller et al. (2018) study performance of a transport system by utilizing agent-based simulation approach under different factors. They estimate the cycle time and utilization of shuttles as performance metrics by expeimenting the number of vehicles and throughput rate in the system.

Although the most related work is by Güller and Hegmanns (2014), they just focus on how the logic of multi-agent model can be designed in an SBS/RS. They do not consider smart dynamic scheduling policies in the system. Differently, we propose both a novel SBS/RS design as well as a dynamic decision making models by evaluating real time information from the environment. Specifically, in real time tracking approach, this thesis studies priority assignment policies for tasks waiting in queues. The modelling details are given in the following sections.

CHAPTER 2

A PERFORMANCE COMPARISON WORK FOR TIER-CAPTIVE AND TIER-TO-TIER SBS/RS DESIGNS

In this chapter, we aim to present a performance comparison work on tier captive SBS/RS and tier-to-tier SBS/RS. First, we provide a comparative study between tier-to-tier and tier-captive SBS/RSs to explore whether or not there might be a good design for tier-to-tier SBS/RS that could be an alternative design to tier-captive SBS/RS. For that we experiment different physical configurations from the systems designs and observe their cost, throughput rate, and energy consumption performance metrics. Second, by focusing on tier-to-tier SBS/RS, we experiment more system designs to observe time and energy related performance metrics.

2.1. System Description and Model Assumptions

Here, we introduce the tier-to-tier SBS/RS design that we focus on. As mentioned, in this novel system design, shuttles are able to travel between tiers. However, they cannot leave their dedicated aisles. Namely, the number of shuttles is lower than the number of tiers in an aisle against the tier-captive designs. Here, Lift 2 is dedicated for travel of shuttles between tiers. Lift 2 has a single shuttle capacity. Besides, the other lifting mechanism referred as Lift 1, is positioned at front of each aisle is dedicated for travel of totes. Lift 1 has two lifting tables that are able to work independently. There are two sides equipped with storage compartments in each aisle. These storage compartments can hold a single tote.

Shuttles, Lift 1, and Lift 2 can work simultaneously. In this system, transaction demands trigger the servers (i.e., Lift 1, Lift 2 or shuttle). Namely, when a transaction arrives in the system, first it checks the shuttle locations and selects one of them, randomly. Then, this transaction also calls Lift 1 and Lift 2 simultaneously based on its requirement. If any of those servers are busy at that time, then the transaction entity enters the queue of that server. Initially, Lift 1 and Lift 2 follow first-in-fist-out (FIFO) priority assignment rule. The reason for checking the shuttles' location is that there is the possibility of collision between shuttles. To prevent collision between shuttles, a single shuttle is allowed to travel in a single tier. Therefore, it is first checked whether or not there is a shuttle in the target tier. If so, the transaction selects that shuttle. Otherwise, the transaction selects a shuttle, randomly.

The other assumptions that we consider in this initial work are:

1. Arriving storage transactions in the warehouse are assumed to appear at I/O points. Besides, arriving retrieval transactions in the system are assumed to end at the I/O point of regarding aisle.

2. Storage transactions flow is from I/O point to a buffer location at the target tier. It is exact opposite for retrieval transactions.

3. There are two buffers locations that are located at both sides at each tier. Each side has three totes capacity.

4. Shuttle picks up storage transactions from the buffer locations to drop off them in storage compartments. It picks up retrieval transactions from storage compartments to drop off them in buffer locations.

5. Lift 1 picks up the storage transaction from the I/O point and it drops off it at a buffer location at the regarding tier. It picks up the retrieval transaction from a buffer location and drops off it at the I/O point in the regarding aisle. Note that, Lift 1 is not utilized if the transaction request is at the first tier.

6. Dwell point of servers is determined to be the last point where they complete their process.

Simulation model details are explained in the following section.

2.2. Simulation Modelling of the System

In this thesis, the studied systems are modeled by simulation, by using the commercial software, ARENA 16.00. The flow chart of the defined tier-to-tier SBS/RS is shown in Figure 2.1. The verification and the validation of the simulation models are done by debugging the codes and animating the model. Besides, we compare the outputs obtained by the simulation models with the system experts and literature papers (Ha and Chae, 2018a). In Figure 2.2, an animation screen shot figure is given for the studied tier-to-tier SBS/RS. That system warehouse has 15 tiers and 50 bays in a tier. Red ball and blue ball represent the storage and retrieval transactions, respectively.

Figure 2.1 shows the flow chart of the considered simulation model for process of storage and retrieval transactions. Arrival transaction initialize the model. First it checks the availability of the buffer area at the target tier. Note that, a transaction arrives at the system with the attributes of storage/retrieval address and transaction type. If the buffers at the regarding tier are, then it waits until it becomes available. Later, the transaction checks whether there is a shuttle at the same tier or heading to that tier. If there is not, it selects a shuttle randomly. If it requires Lift 1 or Lift 2, it also enters their queues simultaneously, by duplicating itself. When the shuttle arrives at the target tier, it picks up the transaction from the buffer/storage compartment and drops off it to the storage compartment/buffer by the type of transaction.

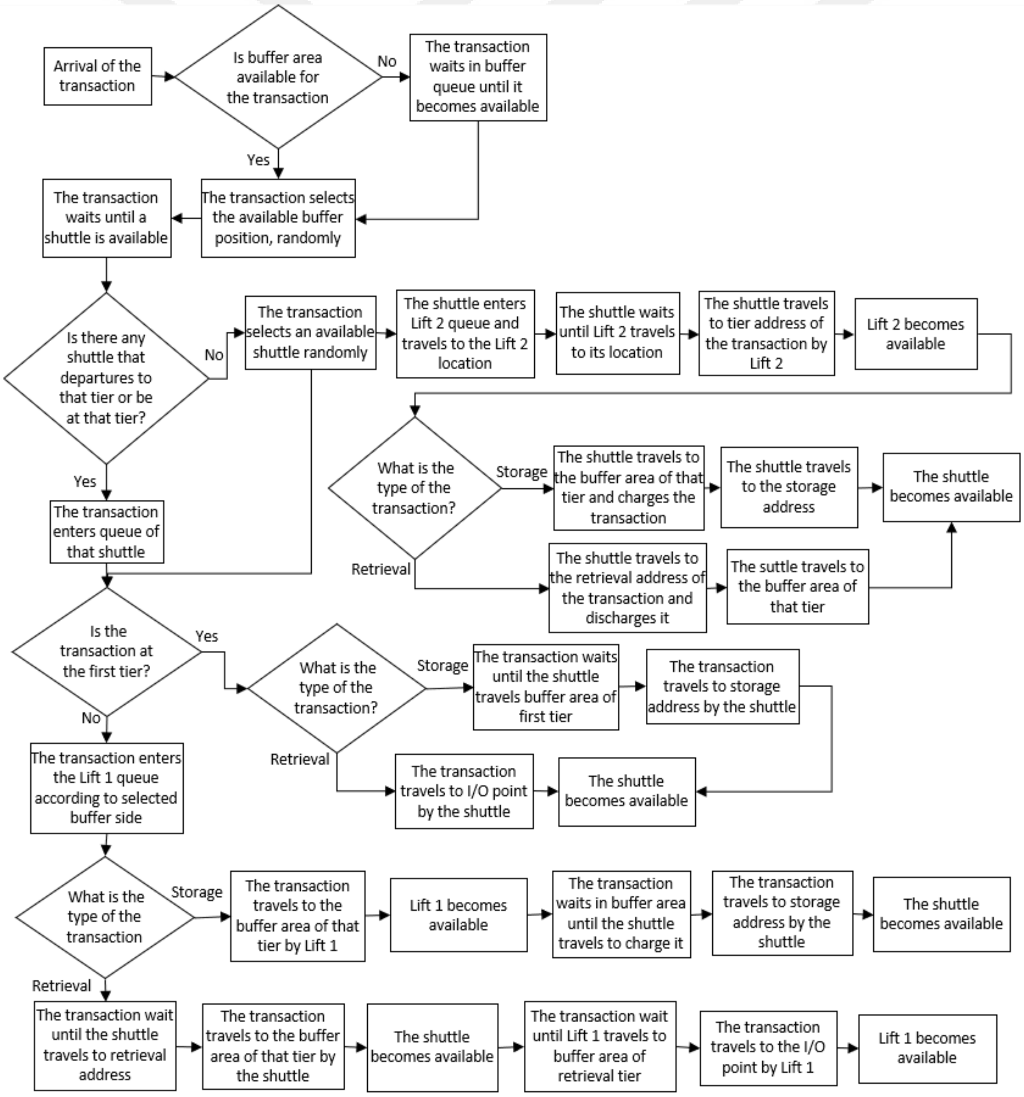


Figure 2.1. Flow chart for the storage and retrieval transactions.

Lift 1, Lift 2, and shuttles may wait any of each other at the meeting points. For instance, Lift 1 may wait for a loaded shuttle until it arrives at the buffer location to pick up the retrieval transaction. Another example, a shuttle may wait for Lift 2 at the end of the tier until Lift 2 arrives there.

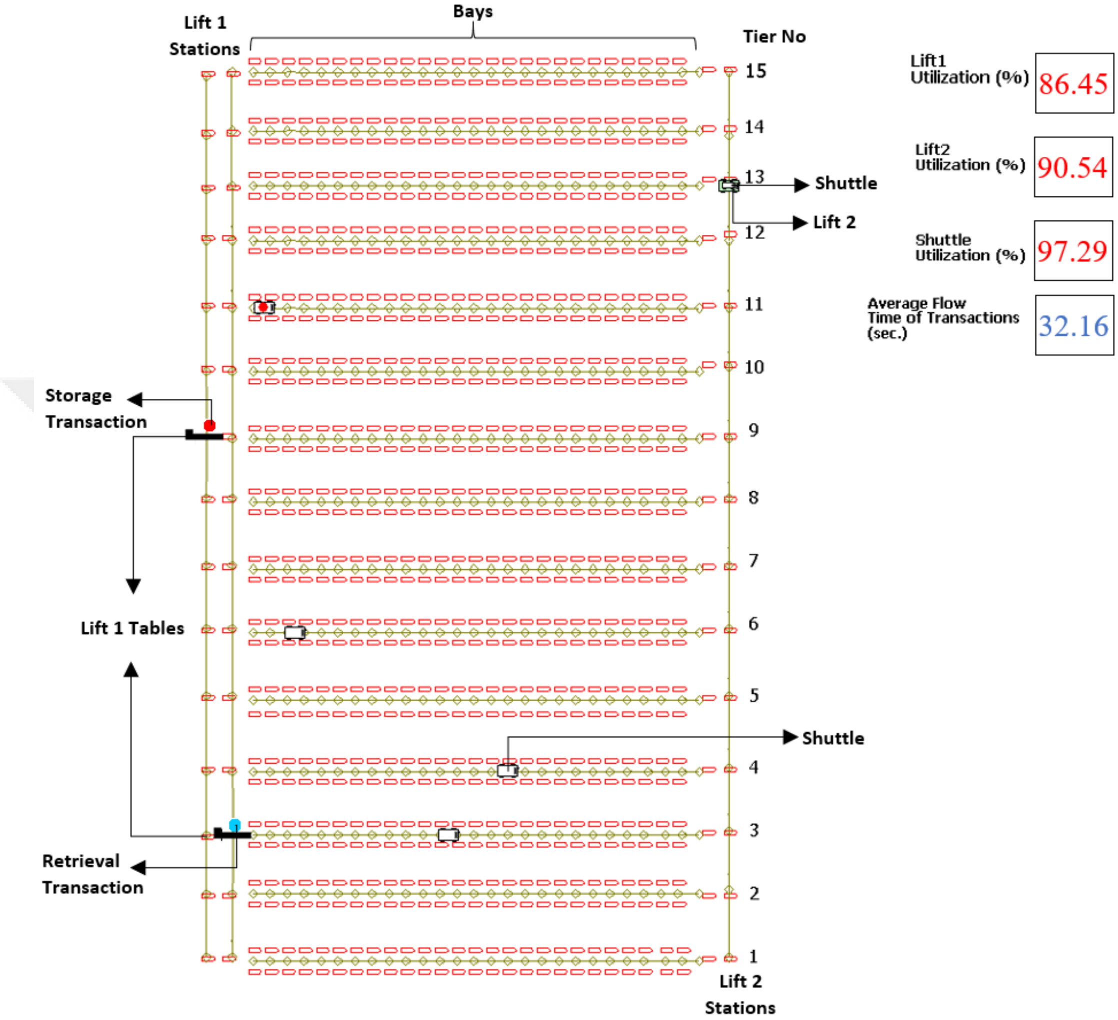


Figure 2.2. A screenshot from the animation of the simulation model

The other assumptions considered in the simulation model are listed as follows:

1. Acceleration and deceleration values, maximum velocity are considered for shuttles and lifting mechanisms.

2. Mean arrival rates for storage and retrieval transactions are equals and generated by using Poisson distribution.

3. Random storage policy is used for determining transactions’ storage or retrieval addresses.

Some parameters for metrics, velocities, and weights are considered as follows;

1. The distance between two adjacent bays is equal and 0.5 m in each tier. Distance between buffers is also assumed as the same. The distance between two adjacent tiers is 0.35 m. (Lerher et al., 2015a, 2015b; Ekren, 2018, 2020a).

2. The acceleration and deceleration values of lifts and shuttles are assumed to be 2 m/sec^2 and the maximum velocity of them is considered as 2 m/s.

3. Shuttle, Lift 1, Lift 2, and tote's weights are assumed as 40 kg, 60 kg, 60 kg, and 20 kg, respectively (Lerher et al., 2015a, 2015b; Ekren, 2018, 2020a).

The simulation time is determined as 40 days with 10 days warm-up period. To determine this period, we use the eye-ball technique by checking whether or not the average flow time per transaction reaches the steady-state condition. The simulation models are run for 5 replications.

2.3. Cost and Performance Comparison for Tier-to-Tier and Tier-Captive SBS/RSs

In the previous part, tier-to-tier SBS/RS design is described. In this part, we compare tier-to-tier design and tier-captive design. Therefore, firs we define assumptions of the tier-captive design.

In our study, tier-captive design differs from tier-to-tier design only based on the number of shuttles. Namely, tier-captive design has a shuttle in each tier of an aisle. Therefore, Lift 2 is not necessary for this design. The other assumptions are valid for this system as well.

In this section, we aim to present that there are tier-to-tier designs that can provide the performance of tier-captive designs in terms of time, energy consumption, and even provide more advantages in terms of cost. To perform our aim, we define different warehouse configurations that have the same warehouse capacity. Details of the scenarios are given in the following sub-section. Performance metrics are considered as throughput rate, energy consumption per transaction, and total investment cost.

2.3.1. Design Scenarios and Performance Metrics

In this section, design scenarios and performance metrics are detailed to provide cost and performance comparisons for tier-to-tier and tier-captive designs. Table 2.1 shows the design scenarios.

Table 2. 1. The racking designs for the SBS/RSs

Design No	Number of Tiers (*T*)	Number of Bays (*B*)	Number of Aisles (*A*)	Warehouse Capacity (*W*)
1	25	60	8	12,000
2	20	50	12	12,000
3	15	40	20	12,000
4	10	40	30	12,000

We define firstly 4 different tier (T) levels for the physical configuration of the warehouse and then we increase the number of aisles (A) while T decreases. Because we know that increased A provides an increased throughput rate with the study of Ekren (2020a). Therefore, we adjust the number of bays in each tier (B) so that fix the desired warehouse capacity (W). Note that W is calculated as $T\ x\ B\ x\ A$. Namely, B is defined as the number of storage compartments (i.e., bays) in each tier in an aisle.

The defined designs in Table 2.1 are implemented for both tier-captive and tier-to-tier designs. Namely, all designs are simulated with a dedicated shuttle in each tier of an aisle and a different number of shuttles in a dedicated aisle such as 3, 4, 5, and 6. The lifting mechanism becomes bottleneck in the tier-captive designs because of excess amount of shuttles. However shuttle is generally bottleneck in tier-to-tier system because of decreased number of it. To make a convincing analysis, we run the pre-defined design scenarios at 95% utilization of bottleneck server in the system. To perform that, we adjust the arrival rates accordingly. Thus, we mainly compare tier-to-tier designs and tier-captive designs by the throughput rate performance metrics.

The performance metrics are determined as total investment cost (TC), throughput rate per month in each aisle (λ), and energy consumption per transaction (E) where there is an energy regeneration mechanism in the system. Due to the slowing down of shuttles and lift mechanisms, energy is regenerated and subtracted from the total energy consumption because slowing down of the lifts and shuttles causes to regenerate energy. Namely, E shows the net energy consumption per transaction. Formulas of energy consumptions and regenerations of shuttles and lifts are taken from Ekren et al. (2018).

To calculate the initial investment cost, we include total cost of shuttles, lifts, storage compartments and space area costs in the total cost function. To build the *TC* function, the parameters in Table 2.2 are used (Lerher and Potrѐ, 2006; Marchet et al., 2013).

Table 2. 2. Parameters for the total investment cost (*TC*) function

Parameters	**Definition**	**Unit**	**Value**
C_1	Cost of shuttle	€/shuttle	20,000
C_2	Cost of Lift 1	€/Lift 1	50,000
C_3	Cost of Lift 2	€/Lift 2	75,000
C_4	Cost of a bay	€/bay	30
C_5	Cost of space	€/m^2	50
S	The footprint of the warehouse	m^2	
n_s	Number of shuttles in an aisle		
L_W	Length of the warehouse	m	
W_W	Width of the warehouse	m	
d	Distance between two adjacent bays	m	
l_b	Length of a buffer area	m	
l_c	Length of conveyor area	m	
l_1	Length of Lift 1 mechanism	m	
l_2	Length of Lift 2 mechanism	m	
w	Width of a rack	m	
w_a	Width of an aisle	m	

In order to calculate S, first we compute L_W by (1). Then, we compute W_W by (2). As a result, S is calculated by (3).

$$L_w = d \cdot \left(\frac{B}{2}\right) + l_b + l_c + l_1 + l_2 \tag{1}$$

$$W_w = (2 \cdot w + w_a) \cdot A \tag{2}$$

$$S = L_w \cdot W_w \tag{3}$$

The total cost functions of tier-captive and tier-to-tier SBS/RS designs are given by (4) and (5), respectively.

$$TC = (C_1 \cdot T + C_2) \cdot A + (C_4 \cdot T \cdot B \cdot A) + (S \cdot C_5) \tag{4}$$

$$TC = (C_1 \cdot n_s + C_2 + C_3) \cdot A + (C_4 \cdot T \cdot B \cdot A) + (S \cdot C_5) \tag{5}$$

2.3.2. Simulation Results

Note that, the design scenarios in Table 2.1 are run for the arrival rate that is providing 95% utilization value for the bottleneck server in the system. Accordingly, Table 2.3 shows the results of those designs. Remember that, pre-defined design scenarios are run as tier-captive and tier-to-tier with different number of shuttle (n_s) level such as 3, 4, 5, and 6. The first four designs are tier-captive SBS/RS and the rest of them are tier-to-tier SBS/RS with different levels of n_s. In Table 2.3, the simulation results are given at 95% confident intervals.

Table 2. 3. Simulation results for the conducted experiments

	Scenario	T	B	A	n_s	λ	E	Total Cost
Tier-captive	1	25	60	8	25	864,066	2.38E-03 ± 8.94E-07	€ 4,776,128
	2	20	50	12	20	997,154	2.03E-03 ± 1.39E-06	€ 5,781,042
	3	15	40	20	15	1,178,190	1.66E-03 ± 8.56E-07	€ 7,389,820
	4	10	40	30	10	1,296,131	1.25E-03 ± 4.50E-07	€ 7,904,730
Tier-to-tier	5	25	60	8	3	392,926	4.07E-03 ± 5.64E-06	€ 1,856,128
	6	25	60	8	4	498,736	4.03E-03 ± 5.73E-06	€ 2,016,128
	7	25	60	8	5	602,944	3.94E-03 ± 2.96E-06	€ 2,176,128
	8	25	60	8	6	682,391	3.89E-03 ± 2.21E-06	€ 2,336,128
	9	20	50	12	3	462,974	3.48E-03 ± 5.70E-06	€ 2,601,042
	10	20	50	12	4	602,944	3.39E-03 ± 3.34E-06	€ 2,841,042
	11	20	50	12	5	720,021	3.33E-03 ± 1.21E-06	€ 3,081,042
	12	20	50	12	6	836,219	3.22E-03 ± 3.75E-06	€ 3,321,042
	13	15	40	20	3	575,957	2.78E-03 ± 4.42E-06	€ 4,089,820
	14	15	40	20	4	751,185	2.70E-03 ± 1.92E-06	€ 4,489,820
	15	15	40	20	5	909,568	2.61E-03 ± 2.67E-06	€ 4,889,820
	16	15	40	20	6	1,058,067	2.50E-03 ± 2.52E-06	€ 5,289,820
	17	10	40	30	3	632,458	1.98E-03 ± 2.26E-06	€ 5,954,730
	18	10	40	30	4	864,076	1.86E-03 ± 1.13E-06	€ 6,554,730
	19	10	40	30	5	1,058,068	1.77E-03 ± 1.57E-06	€ 7,154,730
	20	10	40	30	6	1,234,534	1.66E-03 ± 1.45E-06	€ 7,754,730

Table 2.3 results are also summarized in Figure 2.3 - 2.5. Successive points on the same line represent experiments with the different number of shuttles per aisle (left to right; 3, 4, 5, and 6) for tier-to-tier SBS/RS design. Increased n_s causes the increased *TC* in Figure 2.3, obviously. However, increasing n_s induce decreasing E (see Figure 2.4). Each chart is explained in the following paragraphs.

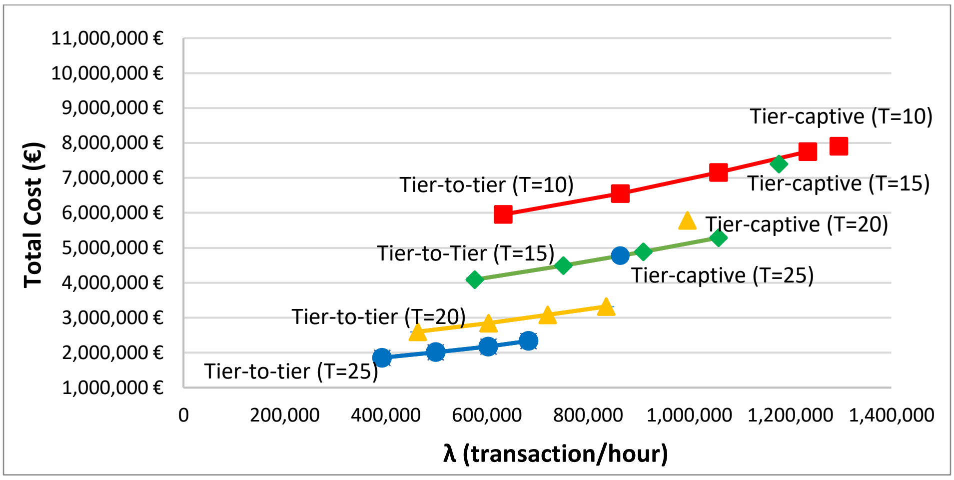


Figure 2.3. Throughput per month (λ) versus total investment cost (*TC*) chart

Figure 2.3 shows *TC* versus λ chart. In this figure, tier-to-tier and tier captive designs with equal *T* are shown in the same shape. For instance, tier-captive and tier-to-tier designs with 20 tiers are shown by a triangle. Also, the points on a single line show the *TC* and λ results of a single tier-to-tier design with 3, 4, 5, and 6 shuttles, respectively. Since we aim to minimize *TC* and maximize λ, points near the bottom right corner of the chart are more successful considering total cost and throughput rate performance. When *T* decreases in all scenarios, *TC* and λ are increase. We know that *T* decreases while *A* increases to meet the total capacity constraint in our designs (i.e., 12,000 storage compartments). This is the main reason for increasing *TC* because it causes the number of servers (i.e., lift 1, lift 2, and shuttle) in the system to increase in direct proportion to *A*. Similarly, increased A provides a capacity to process more transactions. Increased n_s ensures the increased *TC* and λ, clearly.

Note that, there is a trade-off between *TC* and λ values in Figure 2.3. It is observed that the scenario that has the highest λ results also in the highest *TC*. However, for instance, we can choose a better scenario at a certain *TC*. For instance, a better design that has lower *TC* and higher λ in a tier-to-tier design than a tier-captive design can found out. According to Figure 2.3, for example *TC* of a tier-captive SBS/RS design with $T = 20$ is (i.e., the triangle shape) €5,781,042 with λ = 997,154 transactions/month. Note that a design that is closer to the lower-right corner than the triangular shape is preferable to the tier-captive design with $T = 20$. It means that tier-to-tier- SBS/RS design with $T = 15$ and $n_s = 6$ outperforms with *TC* (i.e., €5,289,820) and λ (i.e., λ = 1,058,067 transactions/month). Thus, existing of a better design in tier-to-tier SBS/RS can queried by using Figure 2.3.

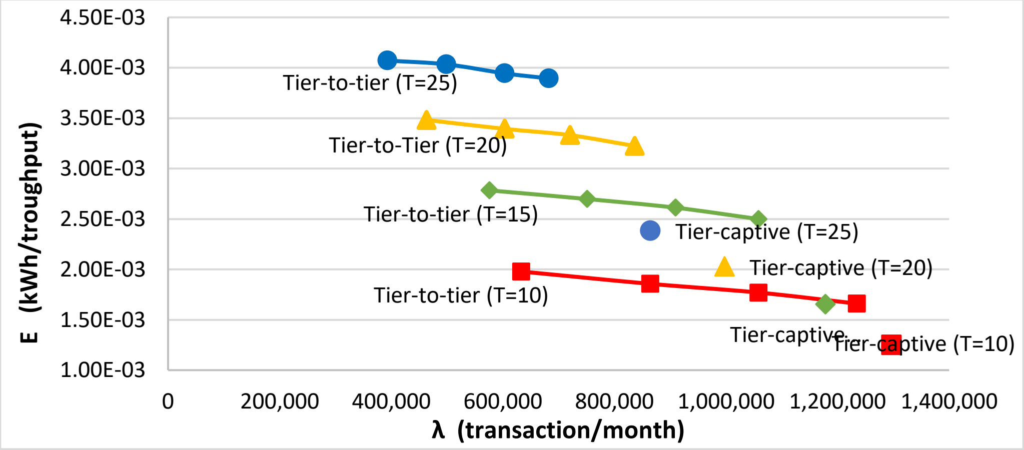


Figure 2.4. Throughput per month (λ) versus energy consumption per transaction (*E*) chart

Figure 2.4 represents the energy consumption per transaction (E) and throughput rate (λ) together. In this figure, we result that increasing n_s provides decreasing E. The reason is that the total travel distance of shuttles decreases by the decreasing number of changes between tiers per shuttle. Accordingly, the design that has decreasing T with increasing A provides better performance in E and λ. When we look at Figure 2.4, we also realize that an alternative tier-to-tier SBS/RS working with less E can found out instead of a tier-captive design. For example, the tier-to-tier design with $T = 10$ and $n_s = 4$ has low energy consumption compared to the tier-captive one with $T = 25$ although they are at the same throughput rate (i.e., 864,066 transactions/month). This is most probably because the decreased T provides decreased E in the system.

2.4. Energy Consumption and Time Analysis for Tier-to-Tier SBS/RS

In this subsection, we focus on the performance analysis of tier-to-tier SBS/RSs from energy consumption view. We already present that there exists an alternative tier-to-tier design having better total cost and throughput rate than a tier-captive design. We also research the factors that can affect the tier-to-tier design performance metrics significantly to propose a real efficient tier-to-tier SBS/RS design. Therefore, we determine different design scenarios from Section 2.3 which we explain in detail in the following subsection, Section 2.4.1.

2.4.1. Design Scenarios and Performance Metrics

In this subsection, we aim to present the factors that can affect the system performance such as average flow time per transaction (t), utilization of servers (U_s, U_{L1} and U_{L2}) (i.e., Lift 1, Lift 2, and shuttles) and, average energy consumption per transaction (E) where there is an energy regeneration mechanism.

Table 2.4 shows the rack configurations that have about 12,000 storage compartments for tier-to-tier SBS/RS.

Table 2. 4. Design Scenarios for Experiments

Design No	***T***	***B***	***A***	***W***
1	10	100	12	12,000
2	10	80	15	12,000
3	10	50	24	12,000
4	15	100	8	12,000
5	15	80	10	12,000
6	15	50	16	12,000
7	20	100	6	12,000
8	20	80	8	12,000
9	20	50	12	12,000

As it is seen, three different T levels and two different B levels are determined. To meet the desired warehouse capacity (W) (i.e., 12,000 storage compartment), A is calculated as W is divided by predefined T x B in Table 2.4. We run the defined designs for four different n_s such as 2, 3, and 4. Therefore, we have 27 experiments in total. Simulation models are run for 40 days with 10 days warm-up period for 5 replications. The mean arrival rate for all scenarios is considered to be 1,728,000 transactions/month at the warehouse where mean arrival rates are assumed to equal for storage and retrieval transactions. Namely, the mean arrival rate monthly in an aisle, λ, is calculated as 1,728,000 /A.

2.4.2. Simulation Results

Table 2.5 gives the simulation results of design scenarios at 95% confidence interval. Note that, the models run for the same arrival rate, 1,728,000 transactions/month for the warehouse. There are a few invalid values in Table 2.5 because the system blows up due to the insufficient service rate for some design scenarios.

Table 2. 5. Simulation Results of Conducted Experiments

Design No	T	B	A	n_S	t (sec)	U_s (%)	U_{L1} (%)	U_{L2} (%)	E $(kWh/transaction)$
1	10	100	12	2	41.55±0.1	72±0.07	33±0.04	44±0.13	2.3E-03±2.6E-06
1	10	100	12	3	29.26±0.02	46±0.09	33±0.05	39±0.09	2.2E-03±3.7E-06
1	10	100	12	4	26.13±0.02	32±0.09	32±0.07	33±0.08	2.1E-03±2.3E-06
2	10	80	15	2	27.06±0.04	48±0.03	24±0.06	32±0.06	2.3E-03±2.6E-06
2	10	80	15	3	22.79±0.02	30±0.04	23±0.05	27±0.04	2.2E-03±3.2E-06
2	10	80	15	4	20.97±0.02	21±0.04	22±0.06	24±0.04	2.1E-03±2.0E-06
3	10	50	24	2	16.49±0.02	21±0.04	11±0.04	15±0.06	2.2E-03±3.5E-06
3	10	50	24	3	15.2±0.02	13±0.04	11±0.03	13±0.04	2.2E-03±3.5E-06
3	10	50	24	4	14.2±0.01	9±0.03	10±0.04	11±0.03	2.0E-03±3.2E-06
4	15	100	8	2	n.a.	n.a.	n.a.	n.a.	n.a.
4	15	100	8	3	39.85±0.08	74±0.09	51±0.05	61±0.08	3.1E-03±2.7E-06
4	15	100	8	4	31.35±0.03	55±0.08	51±0.07	56±0.08	3.0E-03±2.9E-06
5	15	80	10	2	39.09±0.11	76±0.05	38±0.05	49±0.11	3.1E-03±1.1E-06
5	15	80	10	3	26.61±0.03	50±0.05	38±0.08	45±0.08	3.1E-03±2.7E-06
5	15	80	10	4	24.18±0.02	36±0.05	37±0.07	41±0.06	3.0E-03±2.4E-06
6	15	50	16	2	18.48±0.01	34±0.03	19±0.03	25±0.03	3.1E-03±4.3E-06
6	15	50	16	3	16.95±0.01	22±0.03	18±0.02	23±0.02	3.0E-03±4.3E-06
6	15	50	16	4	16.19±0.01	16±0.03	18±0.02	21±0.01	2.9E-03±2.0E-06
7	20	100	6	2	n.a.	n.a.	n.a.	n.a.	n.a.
7	20	100	6	3	n.a.	n.a.	n.a.	n.a.	n.a.
7	20	100	6	4	40.53±0.07	77±0.02	67±0.06	74±0.05	3.7E-03±1.3E-06
8	20	80	8	2	n.a.	n.a.	n.a.	n.a.	n.a.
8	20	80	8	3	31.31±0.06	66±0.06	49±0.04	59±0.07	3.8E-03±3.2E-06
8	20	80	8	4	26.81±0.02	48±0.06	49±0.05	54±0.06	3.7E-03±2.3E-06
9	20	50	12	2	20.81±0.01	47±0.08	27±0.06	35±0.1	3.8E-03±3.8E-06
9	20	50	12	3	18.42±0.01	31±0.08	27±0.06	32±0.07	3.7E-03±3.5E-06
9	20	50	12	4	17.69±0.01	22±0.09	27±0.06	30±0.06	3.6E-03±3.1E-06

The observations in Table 2.5 are summarized in Figure 2.5. To determine the factors affecting the average flow time and average energy consumption per transaction performance metrics statistically, ANOVA is performed shown in Table 2.6 and Table 2.7.

We test three main factors: T, B, and n_S to observe how two responses: E and t are affected by those factors. Table 2.6 shows the ANOVA results of E. As it is seen, all one-way, two-way and three-way interactions are tested and it is observed that all factors affect the E, significantly (i.e., p >0.05). For instance, the highest F-value show that T has the most significant effect on E.

Table 2.6. ANOVA results for average energy consumption per transaction (E)

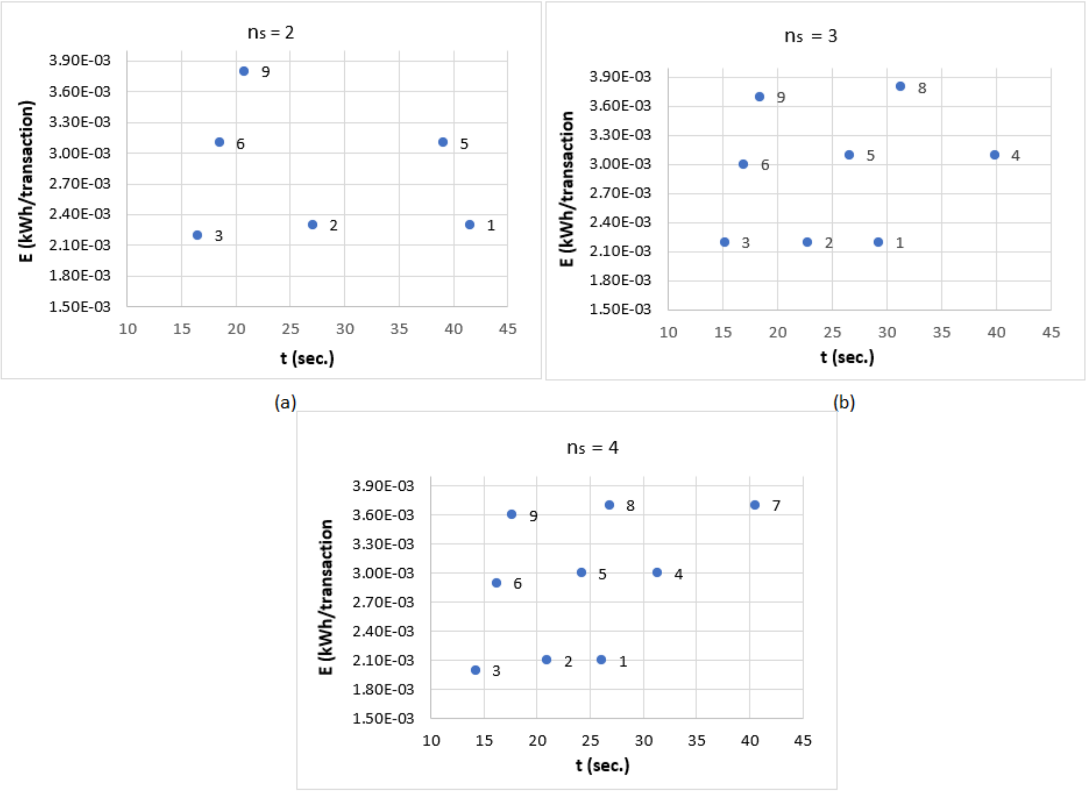
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Tier	2	0.000041	0.00002	3638119.1	0.00
Bay	2	0.000001	0.000001	115900.15	0.00
Shuttle	2	0	0	43850.84	0.00
Tier*Bay	4	0.000002	0	82037.33	0.00
Tier*Shuttle	4	0.000002	0	80563.62	0.00
Bay*Shuttle	4	0.000002	0.000001	98141.11	0.00
Tier*Bay*Shuttle	8	0.000002	0	38945.69	0.00
Error	108	0	0		
Total	134	0.00005			

ANOVA is also performed for response, t. However, since a non-constant variance is observed, t is transformed as $1/t$ to satisfy the ANOVA model adequacy. Thus, Table 2.7 shows the ANOVA results for $1/t$. Similar results are also obtained in this analysis. All factors and interactions of their combinations have significant affect on $1/t$. Additionally, the highest effect belongs to B factor because of its F-value.

Table 2.7. ANOVA results for reverse of average flow time per transaction ($1/t$)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Tier	2	0.005794	0.002897	2089569	0.00
Bay	2	0.031832	0.015916	11480155	0.00
Shuttle	2	0.005617	0.002808	2025592	0.00
Tier*Bay	4	0.00022	0.000055	39633.88	0.00
Tier*Shuttle	4	0.000227	0.000057	40861.07	0.00
Bay*Shuttle	4	0.000651	0.000163	117392.7	0.00
Tier*Bay*Shuttle	8	0.000296	0.000037	26706.64	0.00
Error	108	0	0		
Total	134	0.044637			

The observations in Table 2.5 are summarized in Figure 2.5. From Figure 2.5, energy consumption alters by the number of tiers, strongly. Figure 2.5 shows that there is very low change between these three following designs. However, there are quite differences between E performance of designs that have different number of tiers. The meaning is that increasing T results in increasing E.



(a) (b)

(c)

Figure 2.5. Results when (a) $n_s = 2$; (b) $n_s = 3$; (c) $n_s = 4$

The other perspective, the sequencing three designs have also decreasing t. Namely, Design 1 has the highest t value between Design 1, Design 2, and Design 3. The similar pattern is observed at the other groups in all n_s level scenarios. The reason is probably that these three following designs have decreasing number of bays with stable number of tiers. Thus, this is expected that the travel time of the shuttle decreases and it causes decreasing t.

When Figure 2.5 is examined with multi-objective perspective, the design that is closest to origin is the best one to minimize both E and t performance metrics together. Hence, when we consider this objective, Design 3 has the best performance metrics among all designs. Remember that, Design 3 has 10 tiers in an aisle, 50 bays in a tier, and 24 aisles. Therefore, it can be concluded that low number of tier and wide number of aisle result in improving of t and E performance metrics. Such a design can preferred by a user.

According to the other physical configurations, Design 3 gives the best E and t performance metrics. However, the utilization of servers, U_s, U_{L1}, and, U_{L2}, is very low by given arrival rate. The highest server utilization is obtained as 21% with two shuttles for Design 3. To examine the t and E performance according to each other more accurately, we run Design 3 with two shuttles for increased arrival rates. Remember that, λ is defined as the mean arrival rate in an aisle monthly. The total mean arrival rate at the warehouse monthly is calculated by the product of λ and A, $\lambda x A$. The simulation results are given in Table 2.8.

Table 2. 8. Simulation Results for Design 3 by Changing Arrival Rate

T	B	A	n_S	λ	t (sec)	U_s (%)	U_{L1} (%)	U_{L2} (%)	E $(kWh/transaction)$
10	50	24	2	162,000	18.81±0.01	47±0.08	25±0.08	32±0.04	2.28E-03±2.42E-06
				185,400	19.81±0.01	54±0.04	28±0.04	36±0.08	2.28E-03±1.55E-06
				216,000	21.55±0.04	63±0.07	32±0.07	41±0.04	2.27E-03±3.17E-06
				259,200	25.23±0.05	74±0.04	38±0.04	48±0.04	2.25E-03±1.00E-06
				324,000	36.35±0.09	89±0.04	44±0.04	53±0.06	2.15E-03±1.23E-06
				372,000	54.11±0.06	96±0.02	48±0.02	53±0.07	2.01E-03±8.72E-07

As it is seen in Table 2.8, increased arrival rates result in higher server utilization. Shuttle server is the bottleneck in this system through lack of it. Concurrently, when t is increased, E is decreased withs rising arrival rates. Figure 2.6 shows the graphical display of Table 2.8. Figure 2.6 is drawn for t and E with U_s by arrival rate. Remember that, Design 3 is run again with two number of shuttles to show the changes by rising arrival rates. From Figure 2.6, it is seen that E decreases extremely after a certain point of U_s of corresponding arrival rate. Thus, working with high utilization provides an advantage in terms of energy consumption. This is because probably that vertical movements of lifts decrease with high throughput rate. A shuttle has more probability of the operating a transaction in the same tier with itself. Thus, total travel time of vertical movement decreases and energy consumption is affected positively.

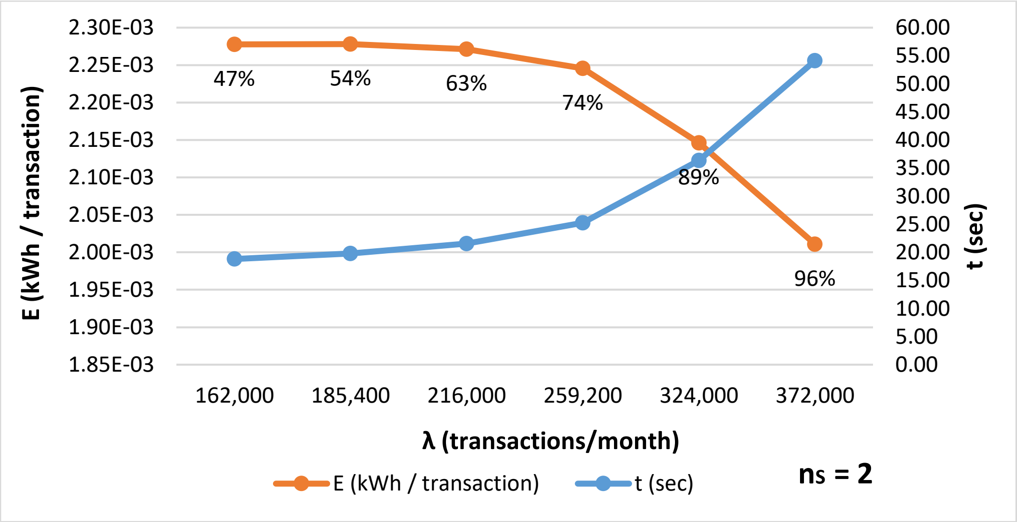


Figure 2.6. E and t Values by Changing Arrival Rate for Design 3

We research if there is better tier-to-tier SBS/RS design compared to tier-captive SBS/RS in terms of average flow time per transaction, average energy consumption per transaction, and total investment cost in this chapter. All these results from Section 2.3 and Section 2.3 show us there is an alternative tier-to-tier SBS/RS design to tier-captive SBS/RS in terms of average flow time per transaction, average energy consumption per transaction, and total investment cost. Moreover, tier-to-tier SBS/RS designs provide us the flexibility to reach our aims. Because we can change the shuttle numbers by the company's target performance metrics.

In the next chapter, we focus on more dynamic decision makings in the design of tier-to-tier SBS/RS by considering multi-objectives of in terms of the flow of the transactions for shuttles, Lift 1, Lift 2, and transactions. We aim to build a tier-to-tier SBS/RS structure by using real time tracking of data and information.

CHAPTER 3

DYNAMIC PRIORITY ASSIGNMENT RULES FOR TIER-TO-TIER SBS/RS BY REAL-TIME DATA TRACKING

The preceding chapter provides the advantages of tier-to-tier SBS/RS designs against the tier-captive SBS/RS designs especially in terms of investment cost. Tier-captive designs provide higher throughput rate within the same number of tiers and bays designs than tier-to-tier designs.

In this chapter, we propose a novel tier-to-tier SBS/RS design with smart operation policies developed on real-time tracking of data and information to improve multiple objectives: average flow time per transaction, average maximum flow time of transactions, average flow time of outliers, standard deviation of flow times as well as outliers' flow time, etc. For that, we aim to adopt dynamic priority assignment rules (PARs) for waiting transactions in queues. System definition, considered assumptions are given in the next subsection.

3.1. System Definition and Assumption of the Novel Tier-to-Tier SBS/RS

In this part, we detail the system definition and the assumption of the proposed novel tier-to-tier SBS/RS. Note that the assumptions of the proposed novel system design is described in the previous chapter. All those assumptions are also valid for that system.

In this novel system, the main task is to store the transactions to the pre-defined storage compartments or to deliver them to I/O points. In this work, if the arriving transaction is a retrieval process then a shuttle is selected. Otherwise, Lift 1 is selected if required. Once entities (i.e., totes) enter Lift 1 queue, Lift 1 selects a proper entity according to the pre-defined PAR and it travels to the tier address accordingly. Namely, simultaneous movement of devices may take place.

Shuttles initiate the process of the retrieval transactions and drop off them at the buffer location at the related tier. Shuttles pick up the storage transactions that are dropped off by Lift 1 at buffer locations. If it requires to change its current tier then, it enters the Lift 2 queue. The detailed working principle of the shuttles, Lift 1 and Lift 2 is presented in the following subsections.

3.2. Description of the Agent-Based Model

An SBS/RS is already a complex system including several parameters to manage efficiently. There are mainly two resource queues (i.e., queues for lifts and shuttles) whose efficient management would also affect the whole system performance. Here, since we propose a new SBS/RS design where shuttles are able to travel between tiers by a separate lifting mechanism, management of this separate lifting mechanism adds extra complexity to the system. To consider efficient management of those queues, real-time decision making on tracked information of transactions waiting in queues might help. Since analytical models might be incapable of a model such a dynamic decision-making environment, we model the system by simulation where we treat lifts, shuttles, and demands as intelligent agents that are able to sense and track real-time information from their environment and interact with each other for intelligent decision making. We simulate the system to identify those agents' best decision behaviors by using the ARENA 16.0 commercial simulation software. Here, besides a more dynamic and effective system design, we aim to adapt the priority assignment policies for waiting transactions in queues so that the performance of the system increases.

By an agent-based managed system, more flexibility in decision making by considering real-time information from the environment is possible (Wooldridge, 2002). To detail, in the model, we treat the shuttles, Lift 1, Lift 2, and transactions (i.e., orders) as agents so that they can sense and evaluate real-time information from their environment. Here, real-time information about the environment are: current tier of shuttles/lifts, current bay of shuttles, as well as transaction type and desired address information, etc. The attributes and the behavior of the agents are shown in Figures 3.1-3.4 for demand, shuttle, Lift 1, and Lift 2 agents, respectively.

In the simulation models, the agents are defined to be entities in the system so that they become dynamic objects. For instance, the shuttles and lifts are entities which are never disposed from the system. The assigned tasks are performed by the following state charts (see Figure 3.1-3.4). To collect all transporters' (e.g., lifts and shuttles) real-time data, we create the non-disposed entities. The process times of transporters for a transaction process can be estimated during the simulation run. We use this information to apply the priority assignment rules explained in the following sections. The transporter agents are able to track real time information from the system and those agents select the transactions based on the pre-defined priority assignment rules.

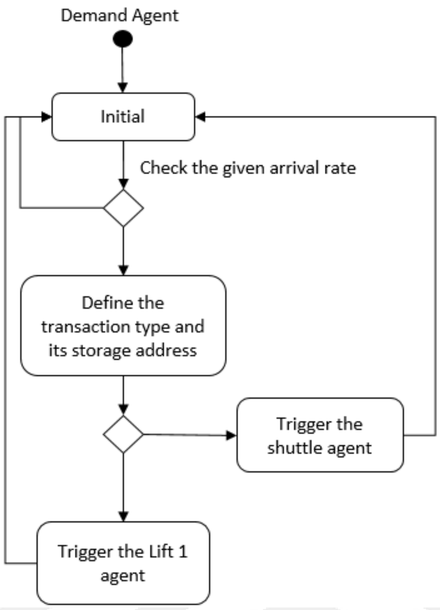
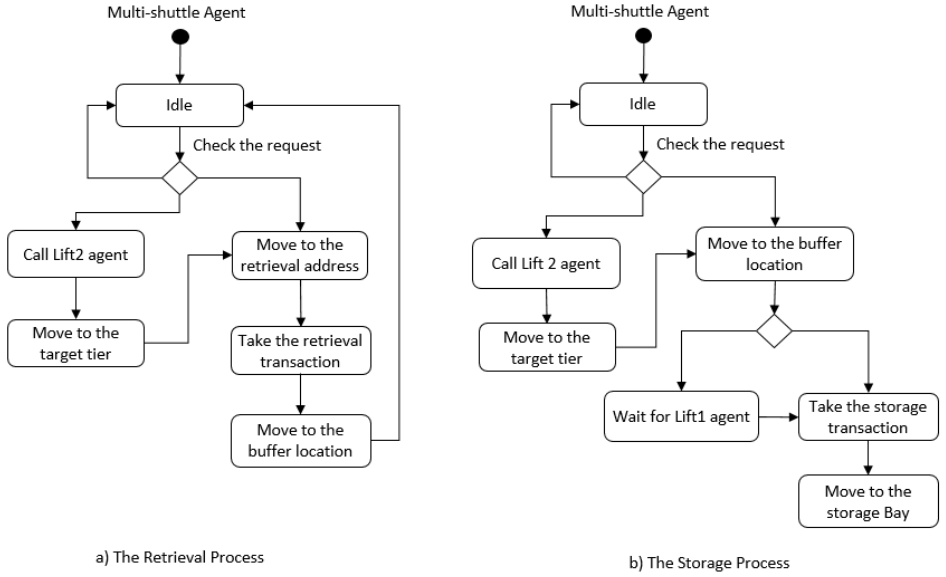


Figure 3.1. State transition model of demand agent

The demand agent creates transactions according to the pre-defined arrival rate and assigns random storage or retrieval address on it. If the transaction is a retrieval transaction, it triggers the shuttle agent, otherwise, it triggers the Lift 1 agent at the regarding aisle. Thus, the shuttle picks up the retrieval transaction from the storage compartment and drops off it at the buffer area of the regarding tier. As soon as the shuttle decides to process the retrieval transaction, an entity also enters the Lift 1 queue, if necessary. Meanwhile, Lift1 picks up the storage transaction from the I/O point and drops off it at buffer area at the target tier. Similarly, as soon as Lift 1 decides to process the storage transaction, this transaction also enters shuttle queue. Remember that, Lift 1 is not utilized if the transaction is in the first tier.

Figure 3.2 shows the behavior of shuttle agents based on retrieval and storage processes separately. An available shuttle agent first checks the most advantageous waiting transaction according to the pre-defined priority assignment rule (PAR). If there is currently a shuttle running or available at the selected transaction’s tier address then, that active shuttle agent ignores the selected transaction and checks another advantageous transaction waiting in its queue. Once a transaction is selected by a shuttle, the process starts based on the selected transaction's type (see Figure 3.2a or 3.2b). First, the shuttle agent checks whether or not Lift 2 would be required for its process. If it is required, the shuttle duplicates an entity and this entity enters the Lift 2 queue, immediately. At the same time, the shuttle travels to the Lift 2 location (the end point of its aisle) to take Lift 2. If the process is a retrieval process, then the shuttle first travels to the retrieval address to pick up the tote. Later, the shuttle travels to the buffer location with the tote and drops off it at an available buffer location. If the process is a storage process, then the shuttle first travels to the buffer location to pick up the tote. If the tote does not arrive at the buffer location before the shuttle arrives there, then the shuttle waits for Lift 1 at the buffer location. If the tote is already at the buffer location before the shuttle arrives, then the shuttle picks up the tote, and both travel to the transaction's storage address, immediately.



a) The Retrieval Process

b) The Storage Process

Figure 3.2. State transition model of multi-shuttle agent

Figure 3.3 shows the behavior of Lift 1 agent. Lift1 agent is triggered by a storage transaction entity or by a shuttle agent completing a retrieval process. If Lift 1 is to process a retrieval transaction, then first it travels to the buffer tier address to pick up the tote. If the retrieval tote does not arrive at the buffer location before Lift 1 arrives then, Lift 1 waits until the tote arrives. After the tote arrives at the tier address, Lift 1 picks up the tote, and both travel to the I/O point. If the processed transaction is a storage process then, Lift 1 travels to the I/O point (i.e., the first tier) to pick up the tote. Later, Lift 1 and tote travel to the storage tier together.

Lift 1 agent follows a priority assignment rule (PAR) that is dual command (DC) and shortest process time (SPT) together referred as DC&SPT rule in this paper. This rule is detailed in the following section. According to our initial observation from the simulation, this rule works better up to 5% than the shortest process, SPT, or solely DC rules. Therefore, we apply the DC&SPT PAR rule for Lift 1 agent.

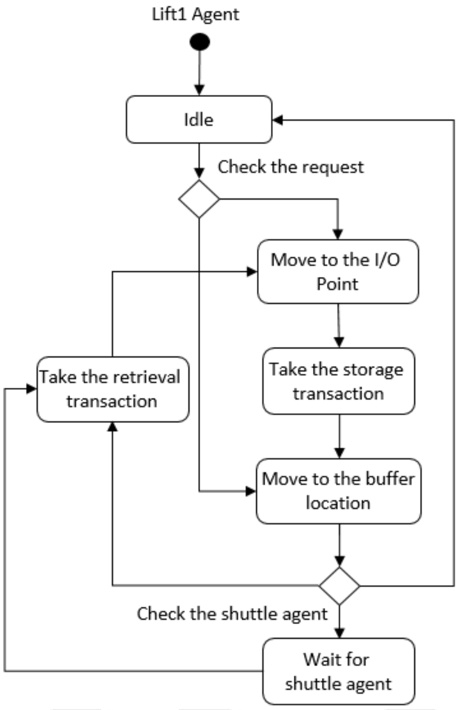


Figure 3.3. State transition of Lift 1 agent

Figure 3.4 shows the behavior of the Lift 2 agent. Lift 2 is triggered by a shuttle agent. When a shuttle agent requests Lift 2, it also travels to the Lift 2 location, immediately. Later, Lift 2 and shuttle travel to the destination tier together.

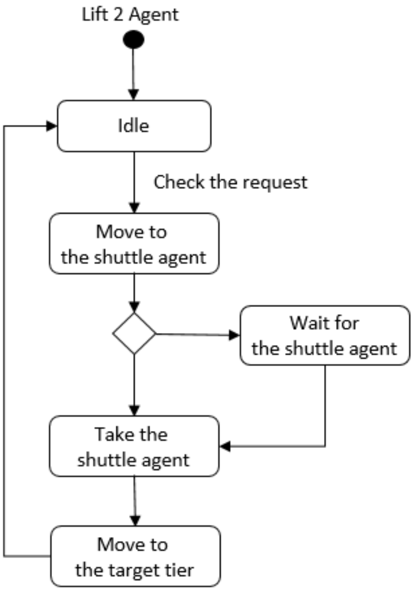


Figure 3.4. State transition of Lift 2 agent

3.3. Design Scenarios and Performance Metrics

Remember that we aim to design the agents such that they sense and collect real-time information from their environments (i.e., queues as well as current locations). Hence, shuttles and Lift 1 can assign priority to a waiting transaction in their queues resulting in increased performance metrics. Here, flow time is defined to be the time between when a transaction is created until it is disposed from the system. Namely, it also includes waiting times in queues. In this study, we firstly aim to show the proposed novel tier-to-tier SBS/RS design is working better than the pre-defined tier-to-tier SBS/RS design in Chapter 2 in terms of throughput rate. Secondly, we aim to propose improvement with the defined PARs by real-time data tracking.

With those PARs and improvement on them, we do not only target to minimize the average flow time per transaction but also to minimize the maximum flow time of transactions, average flow time of outliers, standard deviation of flow times, etc. It is important in today’s competitive supply chain environment to consider all those performance metrics simultaneously. With the recent increase in e-commerce purchasing, customer response time requests are getting tighter. Hence, companies are seeking ways to provide short response times for their customers. If a company cannot reduce that maximum flow time of a transaction, then customer orders might not be shipped on their planned delivery time.

It is well known that the shortest process time (SPT) rule provides in long run reduced average flow time per item performance. However, maximum flow time may increase under that rule. To prevent this, we develop a PAR considering current process time and waiting time of transactions in the shuttle queue. The detailed information about the considered PARs is given in the following subsections.

In this chapter, we focus on a physical warehouse configuration having 15 tiers in each aisle and 25 bays at each side of a tier (i.e., 50 bays in a tier of an aisle). We simulate the model for a single aisle. Besides, we assume that there are five shuttles in each aisle. To do a steady-state analysis, we run the model for 45 days with 15 days warm-up period with 5 independent replications. We implement a common variance reduction technique in the simulation runs.

Table 1 shows all performance metrics observed from the system with their units. While t represents the average flow time per transaction, s shows the standard deviation of these realized flow times. Similarly, t_{out} represents the average of outlier transactions, and s_{out} is the standard deviation of those outlier flow times. Outlier transactions represent the transactions with estimated flow times larger than $t + 3 * s$. The average number of outlier transactions is illustrated by N. The average maximum flow time observed from independent five replications is shown as t_{max}. Besides, the maximum flow time among these five replications is represented by t_{ind}. The utilization of shuttles, Lift 1 and Lift 2 is shown as U_s, U_{L1}, and U_{L2}, respectively. Finally, λ defines the average throughput rate per month at a single aisle.

Table 3. 1. Definition of Performance Metrics

Performance Metric	**Definition**	**Unit**
t	Average flow time per transaction	*sec.*
t_{out}	Average flow time per outlier transaction	*sec.*
t_{max}	Average maximum flow time	*sec.*
t_{ind}	Maximum flow time realized among all replications	*sec.*
s	The standard deviation of transactions	*sec.*
s_{out}	The standard deviation of outlier transaction	*sec.*
N	The average number of outlier transactions	
U_s	Average utilization of shuttles	%
U_{L1}	Average utilization of Lift 1	%
U_{L2}	Average utilization of Lift 2	%
λ	Average throughput rate	*Number of transactions/month*

In this study, we track the real-time information from the environment to calculate the estimated process time and waiting time of the waiting transaction by using location and queue information of shuttles, Lift 1, and Lift 2. Besides, we tend to assign priority to some transactions not to increase the maximum flow times in the system. Specifically, for instance, if there is a transaction whose current flow time is estimated to be larger than the defined critical point then, this transaction may be given a priority in processing. If there is more than one transaction under that condition, then based on the pre-defined PAR one, among those outliers would be given priority. Those priority assignment rules are explained in following.

Note that in the systems, there are three types of queues belonging to shuttles, Lift 1, and Lift 2. To search for a good priority assignment policy for transactions waiting in those queues, we mainly pre-define two PARs for transactions in shuttle queue, and several variants on those. According to our initial trials, since it is observed that it works well, we consider SPT&DC PAR for Lift 1 queue and first-in-first-out (FIFO) PAR for Lift 2 queue. We explain the details of PARs applied for the shuttle, Lift 1 and Lift 2 queues along with their working principles in the following subsections.

3.3.1. First-In-First-Out Sequencing Rule

First-in-first-out (FIFO) scheduling rule considers the sequencing of tasks in a queue based on their arrival times. Namely, the priority is given to the first arriving task at the queue. FIFO is implemented for the waiting tasks in the Lift 2 queue. Remember that Lift 2 is the server providing vertical travel for shuttles between tiers. A shuttle sends a request signal to Lift 2 when it requires to travel to a tier different than its current tier. Because the shuttle’s travel time to the target destination tier would not change once Lift 2 is seized by the shuttle, minimal waiting time for processing first by Lift 2 might be the best one for tasks for a decreased flow time output. We tried several options here and observed that FIFO works well for the Lift 2 server. Hence, we fix this rule as the main PAR for the Lift 2 queue.

3.3.2. Shortest Process Time Sequencing Rule

Based on the shortest process time (SPT) rule, priority is assigned to the transaction having the least travel time to its destination point. For that, we calculate the estimated process times for all waiting transactions in the regarding queues. To calculate the estimated process times, agents receive real-time distance information from their environment. Besides, the waiting times of the servers that will affect the process time are also calculated according to the transactions in their queues. Then, they calculate the time metrics by using those distance information.

In estimating the travel time of transactions waiting for the shuttle, both lifts’ travel times are also included. Namely, the demand agent evaluates both shuttle’s horizontal and vertical travel times by also taking into consideration the estimated waiting time in Lift 2 queue as well as simultaneous movement with Lift 2. After each demand’s estimated travel time is calculated based on these assumptions, the shuttle agent selects the transaction with the least travel time.

3.3.3. Dual Command & Shortest Process Time

Dual Command (DC) rule considers the application of process order: a storage transaction follows a retrieval process or vice versa. Since Lift 1's dwell point before it is released is the first tier for a retrieval process and it is any tier for a storage process, then to decrease Lift 1's process time it might be a good idea to consider these two types of processes in order. This is because a storage process starts at the I/O point while a retrieval process starts at any bay of a tier, and a combination of both would result in decreased travel time. Since there is no such a following pattern for shuttle where shuttle may require to change its current tier, we consider this rule for only Lift 1 queue's sequencing. In this rule, instead of assigning priority to the first waiting transaction related to the required pattern in the queue, we assign the priority to the transaction having the least estimated travel time under the DC rule. Namely, in the combination of DC and SPT, Lift 1 selects the transaction in the order of storage, retrieval, storage, ... so on, by also assigning the priority to the transaction having the least estimated travel time.

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

While running the models under the above-mentioned rules, it is observed that although in long run the average flow time per transaction decreases by the SPT PAR, the maximum flow time of a transaction tends to increase. This is probably because, since SPT assigns priority to transactions with the least estimated travel time, transactions with larger travel time always tend to wait to cause increased maximum flow time in the system. In another word, SPT rule may assign a priority to a newly arriving task in the queue while postponing the process of the transaction with the largest estimated travel time. This may increase both the waiting time and maximum flow time of a transaction in the system.

In this work, we aim to search for such a rule considering both minimization of average flow time and maximum flow time-related performance metrics in the system.

We propose a ratio (R) calculated by (6) to assign priority to the transaction with the minimum R one in the waiting queue. This ratio considers the priority assignment for a transaction with low process time and long waiting time simultaneously.

$$R = (process\ time)/(waiting\ time) \tag{6}$$

Compared to the SPT rule, by this rule we may anticipate obtaining increased average flow time however, we anticipate decreased maximum flow time.

3.3.5. Real-Time Outlier Tracking Rule (RTOTR)

One of the significant novelty implementations in chapter is to propose a dynamic PAR rule based on real-time tracking of flow time information of waiting transactions. Namely, this rule is developed on whether or not to assign priority to one of waiting transactions rather than the already implemented pre-defined PAR. The RTOTR is implemented basically on either SPT or PT/WT rule. For instance, while we apply SPT as PAR for transactions in the shuttle queue, if there is a transaction assuring the pre-defined RTOTR, then we give priority to that transaction. The detailed steps of this approach are as follows:

1- Calculate average flow time per transaction (t) and its standard deviation (s) during the simulation run (in steady-state).

2- Calculate the critical point, CP_1 by (7), where transactions waiting in the queue with estimated flow times higher than CP_1 is assumed to be outliers.

$$CP_1 = \mathrm{t} + 3 * \mathrm{s} \qquad (7)$$

3- Calculate the average flow time of outliers (t_{out}) and its standard deviation (s_{out}) during the simulation run.

4- Calculate a critical point, CP_2 by (8) where it is assumed that transactions with flow times that are larger than CP_2 are outliers of outliers. Here, C is a coefficient where we aim to find the best value of it by experimental work.

$$CP_2 = t_{out} + C * s_{out} \qquad (8)$$

5- To decrease $t_{\max}$ and t_{ind}, if there are transactions waiting in shuttle queue having larger than CP_2 estimated flow times, then we give priority to the one with the shortest travel time (SPT).

```
$i = 1$
$while\ i \leq$ number of transactions in queue
    $if\ estimated\ flow\ time_i > CP_2$
        $Assign\ attribute\ as\ label = 1$
        $i = i + 1$
    $else$
        $i = i + 1$
    $end$
$end$
$search\ i\ for\ min(estimated\ flow\ time_i)\ where\ label = 1$
```

```
    $if\ i = 0$
        $search\ i\ for\ min(estimated\ flow\ time_i)$
    $end$
  $select\ i^{th}\ transaction\ in\ queue$
```

In above, we give the algorithmic flow of the RTOTR under SPT rule.

To observe how the performance metrics are affected under those defined PARs, we conduct experiments summarized in the following section.

3.4. Simulation Results

Remember that we focus on a single physical configuration of tier-to-tier SBS/RS. This is the design that has 15 tiers and 25 bays at each side of a tier in an aisle. Also, we assume that there are five shuttles that can travel between tiers in an aisle. The models are run for five independent replications. Once again, we implement the defined PARs in Lift 1 and Lift 2 queues as DC&SPT and FIFO, respectively.

Experiments are conducted for the same warehouse configuration to compare the performance of different tier-to-tier SBS/RS designs described in Chapter 2 and Chapter 3. The sequencing rule is assumed as FIFO for the shuttle queues in these experiments. The models are defined as Model 1 and Model 2 in Chapter 2 and Chapter 3, respectively. Table 3.2 shows the results of the simulation experiments.

Table 3. 2. The Results of Model 1 and Model 2

Model Type	T	B	n_S	t (sec)	U_s (%)	U_{L1} (%)	U_{L2} (%)	E ($kWh/transaction$)	λ ($throughput/month$)
Model 1	15	50	5	47.4±0.32	97±0.13	90±0.06	82±0.11	2.55E-03±3.04E-06	836,217±1,426
Model 2				48.1±0.16	97±0.08	80±0.02	93±0.06	2.53E-03±2.67E-06	864,133±510

Model 1 and Model 2 are run for high utilization levels of shuttles. As it is seen, while the average flow time per transaction increases in Model 2, the throughput rate also increases. This is because probably, Lift 1 and shuttles can process more independent from each other. Therefore, the number of transactions processed in the system rises. Meanwhile, utilization of Lift 1 decreases by Model 2 because Lift 1 is run with a better sequencing rule by its independence. Thus, we show that Model 2 described in Chapter 2 has the potential to improve the performance of the system. However, we still implement different sequencing rules with their improvement policies.

The following experiments are run by using Model 2 assumptions and different PARs. Experiments are done to determine the best PAR for waiting transactions in the shuttle queue in terms of different performance metrics mentioned in Table 3.1. Table 3.3 and Table 3.4 shows the PARs implemented the shuttle queue when with RTOTR and with no RTOTR, respectively.

Table 3. 3. Experimental Design for PAR when no RTOTR

Design no	Initial PAR
1	SPT
2	PT/WT

We apply firstly SPT and PT/WT PAR for the shuttle queue where RTOTR is not considered.

Table 3. 4. 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

According to Table 3.4, we apply the RTOTR rule based on the initial PAR (i.e., SPT or PT/WT). The C-value is for CP_2 calculation that is shown by (8). For CP_1, the coefficient is assumed as 3 in equation (7). The last column of Table 3.4 shows whether or not we update the CP_1 and CP_2 values during the simulation run. Namely, because CP_1 and CP_2 contain t, s, t_{out}, and s_{out} values, these values are updated during the simulation run. We aim to observe how these dynamic changes affect the system performance with both initial PARs (i.e., SPT and PT/WT). For instance, the first policy, static-static, follows this procedure. t, s, t_{out}, and s_{out} values obtained from Design no 1 or Design no 2 are given the model that uses SPT and PT/WT PARs with no RTOTR. Another example, for the last policy, dynamic-dynamic, uses the value of t, s, t_{out}, and s_{out}, changing dynamically during the simulation run.

Remember that by implementing RTOTR, mainly we aim to make improvements on t_{max}, t_{out}, s, and s_{out}, N performance metrics while trying not to affect the t value negatively. Five replication simulation results along with their confidence intervals are summarized in Table 3.5.

Practically, companies tend to work with high utilization values of resources. In this work, we adjust the arrival rates such that the average utilization of the bottleneck server, (i.e., shuttle) is around 99% in the scenario producing the worst t value. Then, we fix that arrival rate scenario and apply it for all experiments. For instance, in simulation, we consider the mean inter-arrival time for transaction arrivals as Expo (2.6) sec.

We draw the dot plots of the results provided in Table 3.5. For instance, Figure 3.5 shows the dot plot of Design 1. Remember that, Design 1 has SPT PAR where there is no RTOTR. Similarly, Figure 3.6 shows Design 2 by using PT/WT PAR where there is no RTOTR. The "a" part of these plots shows the all realized flow time of transactions among five replications. The "b" part of them shows the outlier transactions that have larger flow time than CP_1 (i.e., $t + 3 * s$) among five replications. However, note that the other statistics writing on the plots the average values of five replications except t_{ind}. It defines the realized maximum flow time within five replications.

All dot plots are drawn by using Table 3.5 are given in the Appendix-1.

Table 3. 5. 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	997,281±1,206
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	997,214±1,139
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	997,271±1,104
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	997,303±1,168
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	997,312±1,174
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	997,247±1,219
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	997,283±1,261
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	997,235±1,156
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	997,318±1,172
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	997,297±1,160
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	997,294±1,209
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	997,253±1,194
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	997,275±1,241
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	997,170±1,337
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	997,238±1,179
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	997,293±1,232
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	997,278±1,296
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	997,221±1,219
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	997,251±1,165
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	997,223±1,164

Note: n.a. refers not applicable

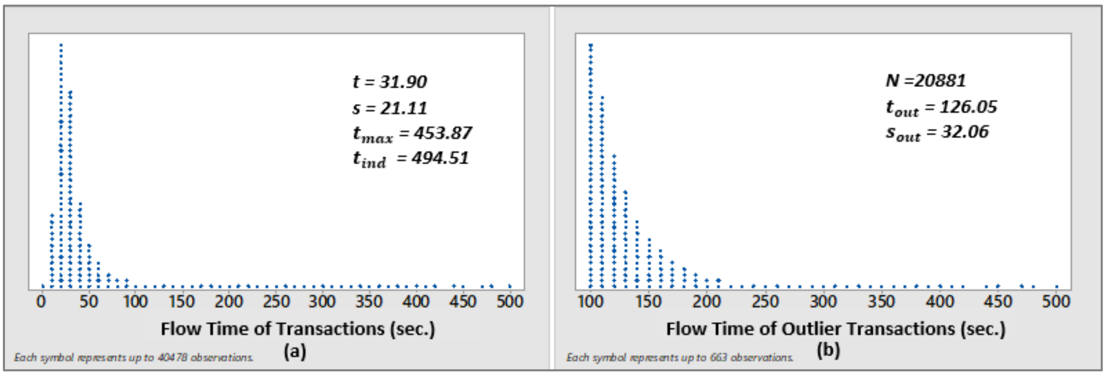


Figure 3.5. (a) Dot plots for flow times of transactions for Design 1; (b) Dot plots for flow times of outlier transactions for Design 1

As it is seen in Figure 3.5, it is observed with SPT PAR, t, t_{max}, t_{ind} values are obtained as 31.90, 453.87, and 494.51 sec., respectively. Hence, CP_1 value calculated from equation (7), as 95.24 sec. Therefore, Figure 3.5b shows the realized flow times that are larger than 95.24 sec. In addition to this, 20,881 transactions of 997,281 process on average 126.05 sec. We aim to decrease t_{max}, t_{ind}, t_{out} as well as s and s_{out} while not increasing the t value significantly.

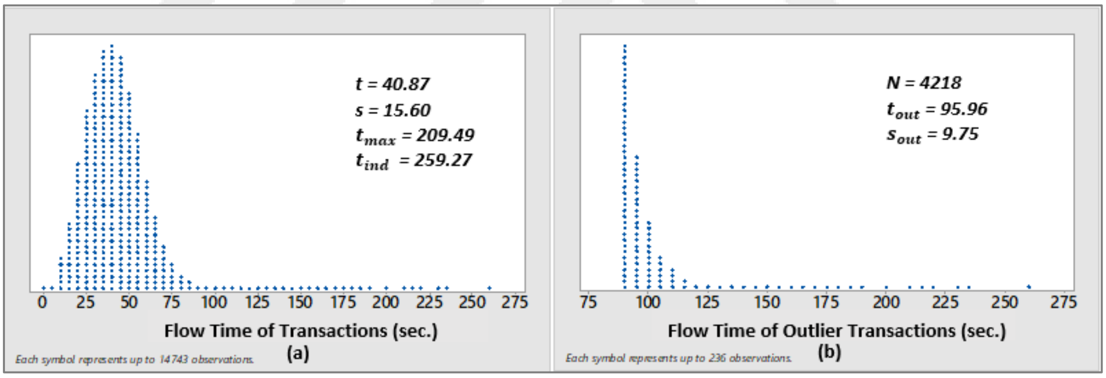


Figure 3.6. (a) Dot plots for flow times of transactions for Design 2; (b) Dot plots for flow times of outlier transactions for Design 2

Figure 3.6 shows the dot plot of Design 2 that uses PT/WT PAR where there is no RTOTR. t, t_{max}, t_{ind} values are obtained as 40.87, 209.49, and 259.27 sec., respectively. Hence, CP_1 value calculated from equation (7), as 87.67 sec. Therefore, Figure 3.6b shows the realized flow times that are larger than 87.67 sec. In addition to this, 4,218 transactions of 997,214 process on average 95.96 sec. We still aim to decrease t_{max}, t_{ind}, t_{out} as well as s and s_{out} while not increasing the t value significantly in this design.

When we compare Figure 3.5 and Figure 3.6, PT/WT PAR has a big potential to decrease t_{max}, t_{ind}, t_{out}, as well as s, and s_{out}. However, decreasing these statistics causes to increase t value. Nevertheless, we can not underestimate the power in decreasing outlier transactions' statistics. It might be a satisfying contribution to overall flow time in PT/WT PAR.

When we examine the designs that use RTOTR, Design 9 and Design 13 gives better results in terms of defined performance metrics. Note that while C value increases, CP_2 value gets larger. It means that the number of transactions that are given priority gets smaller by the policy rule described in Section 3.3.5. Design 9 and Design 13 plots are shown in Figure 3.7 and 3.8.

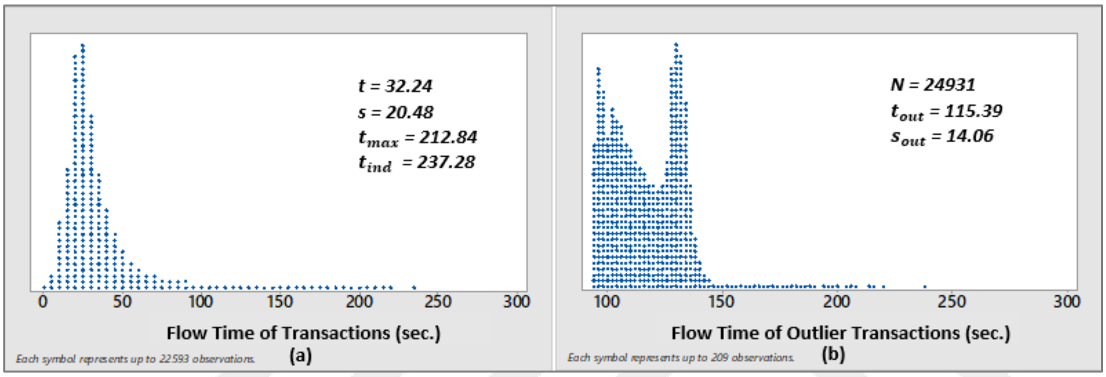


Figure 3.7. (a) Dot plots for flow times of transactions for Design 9; (b) Dot plots for flow times of outlier transactions for Design 9

Figure 3.7 shows the plot of Design 9 results. This design considers SPT PAR where there is dynamic RTOTR with $C = 1$. SPT rule is applied for outlier transactions that have larger flow time than CP_2 as well as the other transactions. CP_1 and CP_2 values are updated dynamically during the simulation time. According to Desing 9, t_{max}, t_{ind}, t_{out}, and s_{out} values decrease significantly comparing with Design 1 where solely SPT rule is applied. Along with other statistics, the increase in t is not considered significant.

When we compare Design 2 and Design 9, it is observed that t value in Design 9 outperforms the t value in Design 2. Although there is not quite differences t_{max} values between Design 2 and Design 9, t_{out} and s_{out} values in Design 2 overcome Design 9's performance.

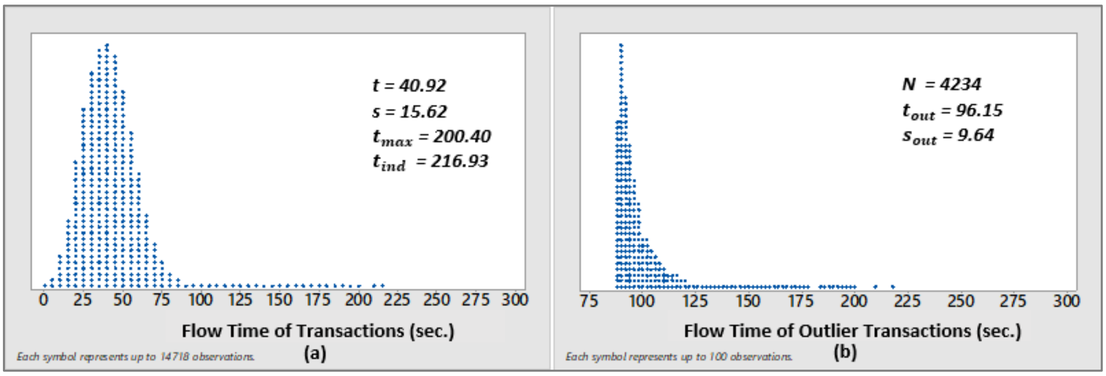


Figure 3.8. (a) Dot plots for flow times of transactions for Design 13; (b) Dot plots for flow times of outlier transactions for Design 13

Figure 3.8 shows the dot pot of Design 13 that is applied to PT/WT PAR where there is static RTOTR with $C = 2$. Namely, CP_1 and CP_2 values are not updated during the simulation time. CP_1 and CP_2 have constant values coming from Design 2 results as 87.67 sec and 115.46 sec, respectively. Among all experiments, Design 13 has the lowest t_{out}, t_{max}, and t_{ind} and, s_{out} performance metrics. One may prefer utilizing this policy under significant t_{max} minimization restriction.

Once again, We summarize all dot plots in Appendix-1. As a result of this simulation work, we provide results showing how they outperform the others in terms of different performance metrics. By real-time decision making, rather than a static approach, one may improve several performance metrics at a time.

CHAPTER 4

CONCLUSIONS AND FUTURE RESEARCH

In this thesis, we study a novel tier-to-tier shuttle-based storage and retrieval system design by considering several performance metrics such as throughput rate, total investment cost, average flow time per transaction, average energy consumption per transaction, and variability within realized flow time of transactions by using the simulation modeling approach. This thesis is based on three main research questions given in Chapter 1. To handle those questions, we first propose the tier-to-tier SBS/RS design as an alternative design to tier-captive SBS/RS design. Then, we investigate whether or not there exists sub-designs for tier-to-tier SBS/RS design meeting the desired performance metrics with low total investment cost. Results show that there might be a tier-to-tier design outperforming the tier-captive one from reduced investment cost while also providing reasonable operational performance metrics.

Second, we analyze a group of designs having several physical configurations considering the assumptions of the defined fundamental tier-to-tier SBS/RS model. We research the factors that affect the system performance of tier-to-tier SBS/RS design under different physical configurations and the number of shuttles. Results show that an increasing the number of tiers results with decreased average energy consumption per transaction and average flow time per transaction. In addition to this, a decreased number of bays results in decreased average flow time per transaction.

Finally, we propose dynamic priority assignment rules for tier-to-tier SBS/RS developed on real time tracking of data. We treat the shuttles, Lift 1, Lift 2, and transactions (i.e., demand) as agents that can make autonomous decisions by evaluating the real time information. We consider multi-objectives related with flow time performance metrics to improve.

As future works, more priority assignment rules can be developed and they can be experimented under different racking designs. Besides, different number of shuttles scenarios may also be considered as a sensitivity analysis in the system.

REFERENCES

Carlo, H. J., & Vis, I. F. (2012). Sequencing dynamic storage systems with multiple lifts and shuttles. *International Journal of Production Economics,* 140(2), 844-853.

Eder, M. 2019. An analytical approach for a performance calculation of shuttle-based storage and retrieval systems. *Production & Manufacturing Research,* 7(1), 255-270.

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.

Ekren, B. Y., Akpunar, A. (2020). An Open Queuing Network Based Tool for Performance Estimations in a Shuttle-Based Storage and Retrieval System. *Applied Mathematical Modelling,* in press. https://doi.org/10.1016/j.apm.2020.07.055

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.

Ekren, B. Y., S. S. Heragu, A. Krishnamurthy, and C.J. Malmborg. (2010). Simulation based experimental design to identify factors affecting performance of AVS/RS. *Computers & Industrial Engineering*, 58 175-185.

Ekren, B. Y., Z. Sari, T. Lerher, (2015). Warehouse design under class-based storage policy of shuttle-based storage and retrieval system. *IFAC-PapersOnLine,* 48(3), 1152-1154.

Ekren, B.Y. (2020a). A Simulation-based experimental design for SBS/RS warehouse design by considering energy related performance metrics. *Simulation Modelling Practice and Theory, i*n press. https://doi.org/10.1016/j.simpat.2019.101991.

Ekren, B.Y. (2020b). A multi-objective optimisation study for the design of an AVS/RS warehouse. *International Journal of Production Research,* in press, https://doi.org/10.1080/00207543.2020.1720927.

Ekren, B.Y., and S.S. Heragu. (2010a). Simulation based regression analysis for the rack configuration of autonomous vehicle storage and retrieval system. *International Journal of Production Research,* 48(21), 6257-6274.

Ekren, B.Y., and S.S. Heragu. (2010b). Approximate analysis of load dependent general queuing networks with low service time variability. *European Journal of Operational Research,* 205, 381-389.

Ekren, B.Y., S. S. Heragu (2011). Simulation-based performance analysis of autonomous vehicle storage and retrieval system. *Simulation Modeling Practice and Theory,* 19, 1640-1650.

Ekren, B.Y., S.S. Heragu, A. Krishnamurthy, and C.J. Malmborg. (2014). Matrix-geometric solution for semi-open queuing network model of autonomous vehicle storage and retrieval system. *Computers & Industrial Engineering,* 68, 78-86.

Ekren, B.Y., S.S. Heragu, A. Krishnamurthy, and C.J. Malmborg. (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, 205-215.

Ekren, B.Y., S.S. Heragu. (2012). Performance comparison of two material handling systems: AVS/RS and AS/RS. *International Journal of Production Research,* 50, 4061-4074.

FEM (2017). Statistics for S/R machines results. Retrieved 15 September 2020, from https://www.fem-eur.com/wp-content/uploads/2019/02/IS-Annual-Factsheet-2017.pdf.

Grand View Research. (2021, January 9). Material Handling Equipment Market Size, Share, & Trends Analysis Report By Products (Industrial Trucks, Automated Storage & Retrieval System), By End-use, By Region, And Segment Forecasts, 2019 – 2025. https://www.grandviewresearch.com/industry-analysis/materials-handling-equipment-market

Güller, M., & Hegmanns, T. (2014). Simulation-based performance analysis of a miniload multishuttle order picking system. *Variety Management in Manufacturing-Proceedings of 47th CIRP Conference on Manufacturing Systems*, 17, 475‑480.

Güller, M., Karakaya E., Uygun Y. and Hegmanns, T. (2018). Simulation-based performance evaluation of the cellular transport system. *Journal of Simulation*, 12(3), 225-237.

Ha, Y., & Chae, J. (2018a). Free balancing for a shuttle-based storage and retrieval system. *Simulation Modelling Practice and Theory*, 82, 12-31.

Ha, Y., & Chae, J. (2018b). 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.

Heragu, S.S., X. Cai, A. Krishnamurthy, and C. J. Malmborg. (2011). Analytical models for analysis of automated warehouse material handling systems. *International Journal of Production Research*, 49 (22), 6833‑6861.

Küçükyaşar, M., Ekren, B. Y., Lerher, B. (2020a). Cost and Performance Comparison for Tier-Captive and Tier-to-Tier SBS/RS Warehouse Configurations. *International Transactions in Operational Research*, in press, https://doi.org/10.1111/itor.12864.

Küçükyaşar, M., Ekren, B. Y., Lerher, B. (2020b). Energy efficient automated warehouse design. *Solving Urban Infrastructure Problems Using Smart City Technologies, Amsterdam, Elsevier,* 269-292

Lehrer, T., Ekren, Y. B., Sari, Z., & Rosi, B. (2015a). Simulation analysis of shuttle based storage and retrieval systems. *International Journal of Simulation Modelling,* 14(1), 48-59.

Lerher, T. (2016). Travel time model for double-deep shuttle-based storage and retrieval systems. *International Journal of Production Research*, 54(9), 2519-2540.

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.

Lerher, T., Ekren, B.Y., Sari, Z., Rosi, B. (2016). Method for Evaluating the Throughput Performance of Shuttle Based Storage and Retrieval Systems. *Tehnicki Vjesnik ‐ Technical Gazette*, 23, 715-723.

Lerher, T., Potrè, I. (2006). The Design and Optimization of Automated Storage and Retrieval Systems. *Journal of Mechanical Engineering,* 52(5), 268-291.

Marchet, G., Melacini, M., Perotti, S., & Tappia, E. (2013). Development of a framework for the design of autonomous vehicle storage and retrieval systems. *International Journal of Production Research*, 51(14), 4365-4387.

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*, 51(14), 4365‐4387.

Roy, D., Krishnamurthy, A., Heragu, S. S., & Malmborg, C. J. (2013). Blocking effects in warehouse systems with autonomous vehicles. *IEEE Transactions on Automation Science and Engineering*, 11(2), 439-451.

Tappia, E., Marchet, G., Melacini, M., Perotti, S. (2015). Incorporating the environmental dimension in the assessment of automated warehouses. *Production Planning & Control*, 26(10), 824-838.

Tappia, E., Roy, D., De Koster, R., & Melacini, M. (2016). Modeling, analysis, and design insights for shuttle-based compact storage systems. *Transportation Science,* 51(1), 269-295.

Wang, Y., Mou, S., & Wu, Y. (2015). Task scheduling for multi-tier shuttle warehousing systems. *International Journal of Production Research*, 53(19), 5884-5895.

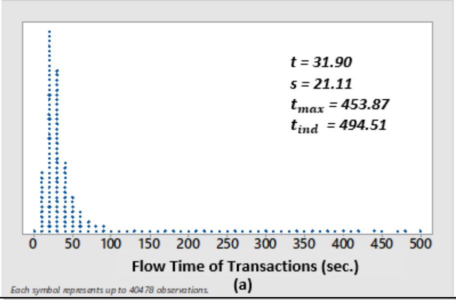
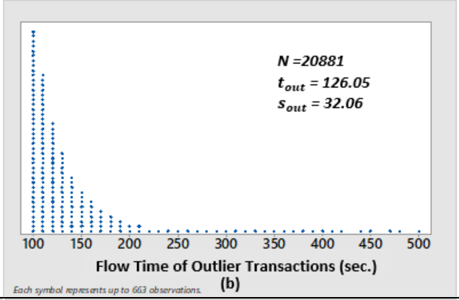
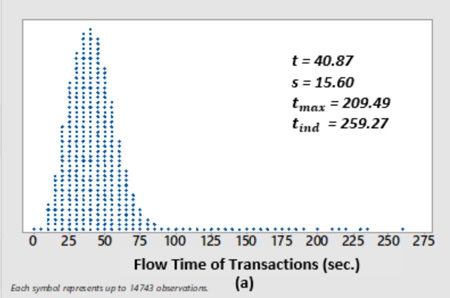
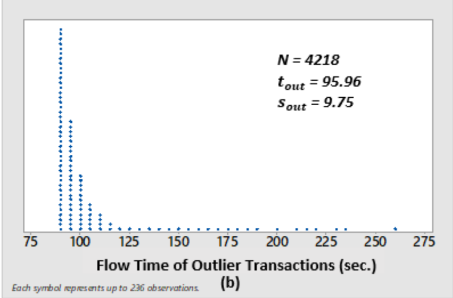
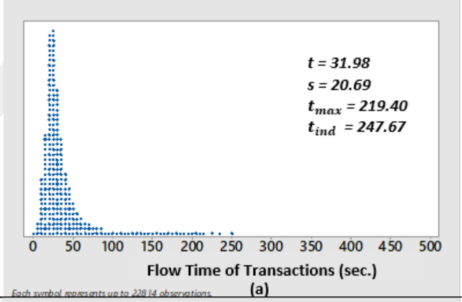
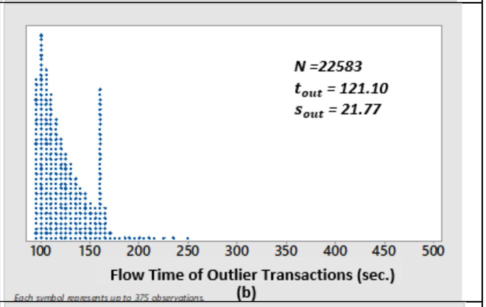
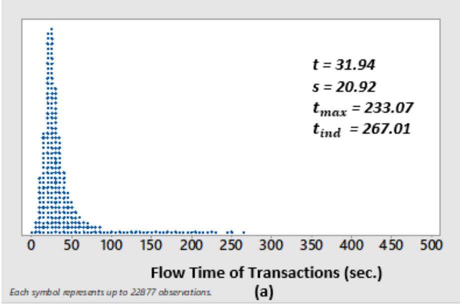
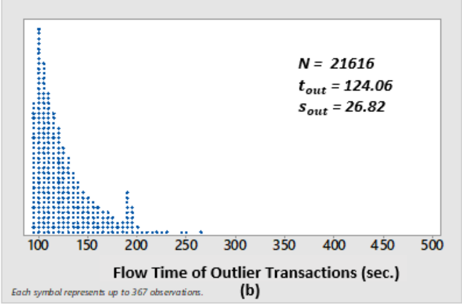
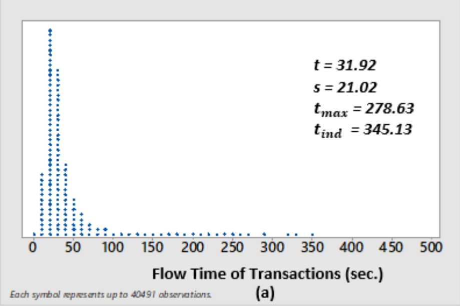
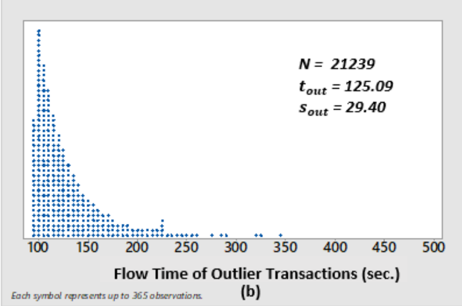
Wooldridge, M. (2002). An introduction to multiagent systems. England, Wiley.

Zhao, N., Luo, L., and Lodewijks, G. (2018). Scheduling two lifts on a common rail considering acceleration and deceleration in a shuttle based storage and retrieval system. *Computers & Industrial Engineering*, 124, 48-57.

Zhao, X., Wang, Y., Wang, Y., & Huang, K. (2019). Integer Programming Scheduling Model for Tier-to-Tier Shuttle-Based Storage and Retrieval Systems. *Processes*, 7(4), 223.

Zou, B., Xu, X., Gong, Y., Koster, R. (2016). Modeling parallel movement of lifts and vehicles in tier-captive vehicle-based warehousing systems. *European Journal of Operational Research,* 254(1), 51–67

APPENDIX 1 – Dot Plots of Results in Table 3.5

Design No	Dot plots for flow times of transactions	Dot plots for flow times of outlier transactions
1	 (a)	 (b)
2	 (a)	 (b)
3	 (a)	 (b)
4	 (a)	 (b)
5	 (a)	 (b)

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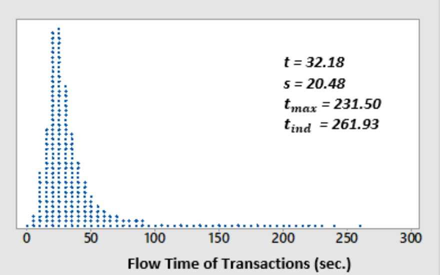

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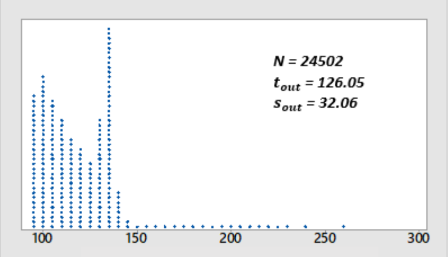

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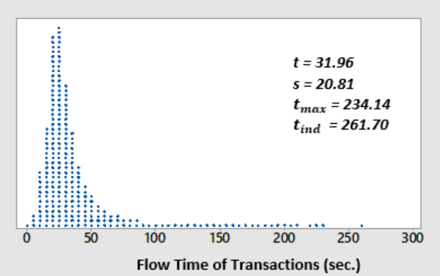

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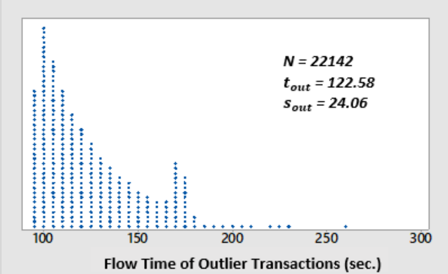

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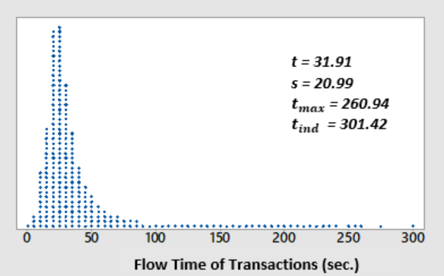

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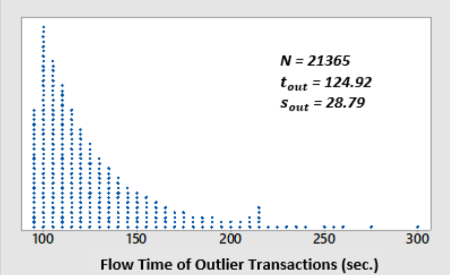

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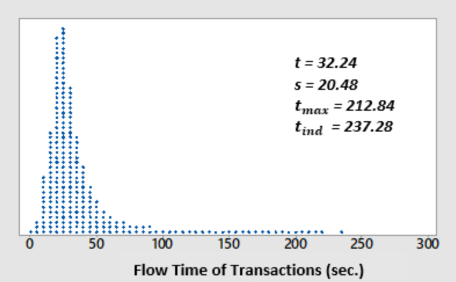

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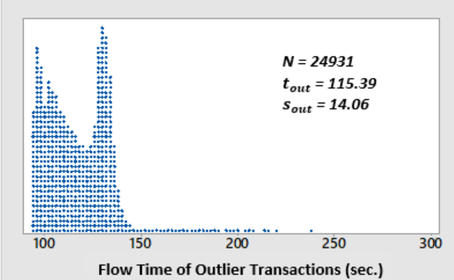

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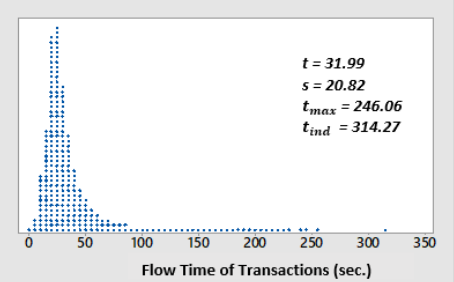

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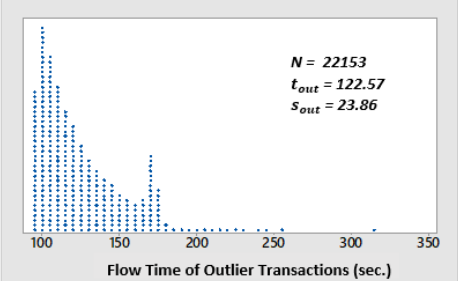

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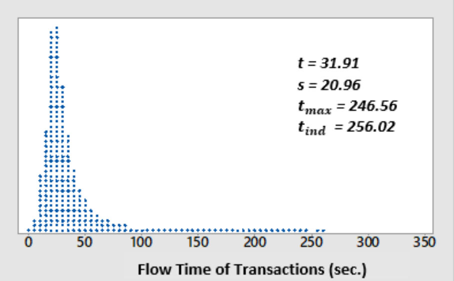

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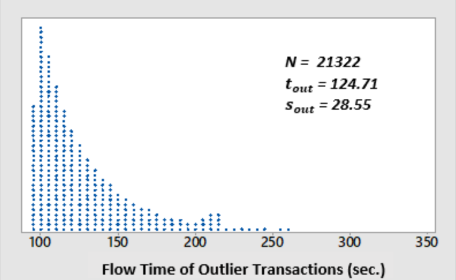

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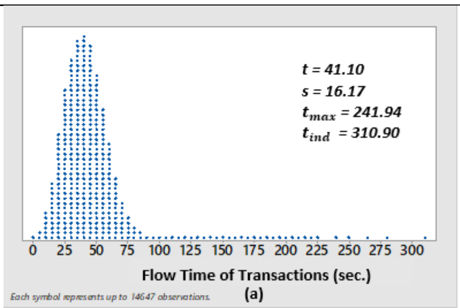
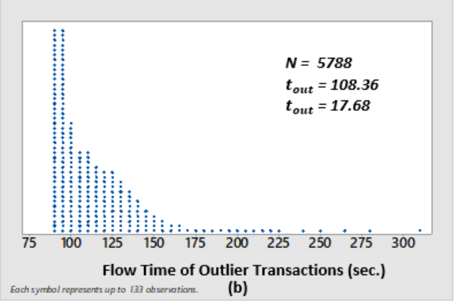
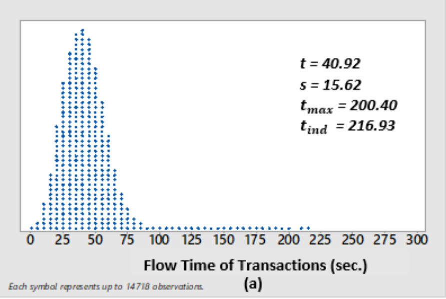
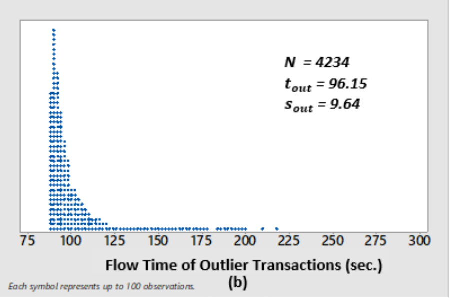
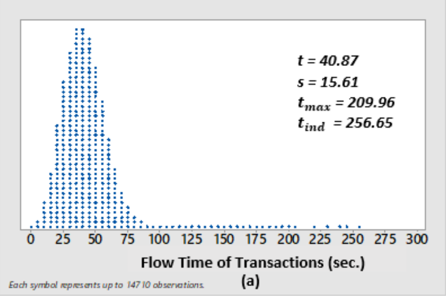
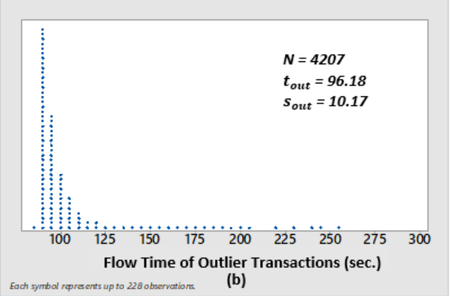
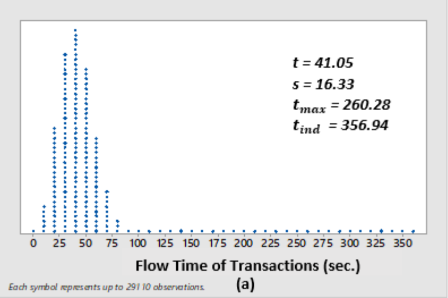
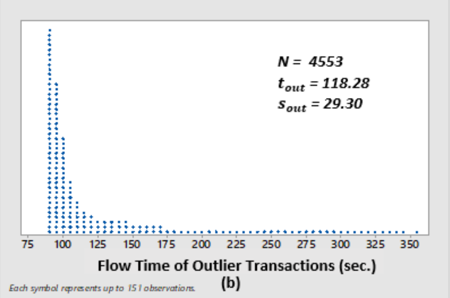
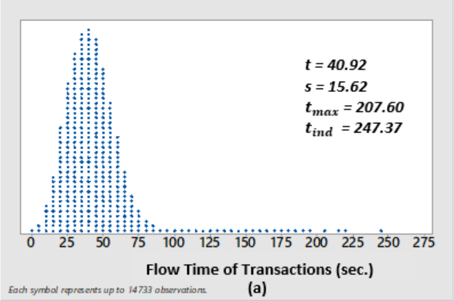
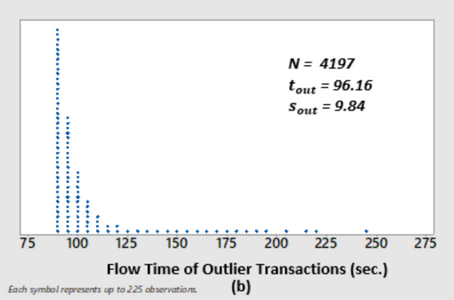
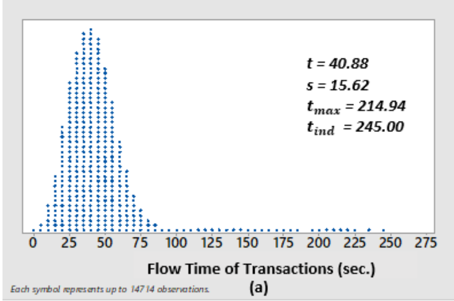
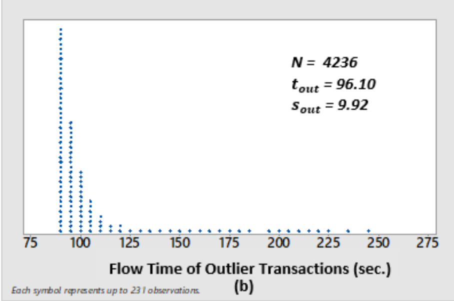
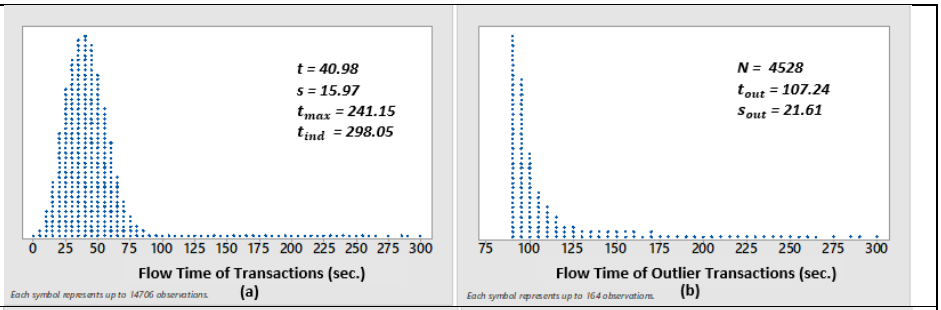
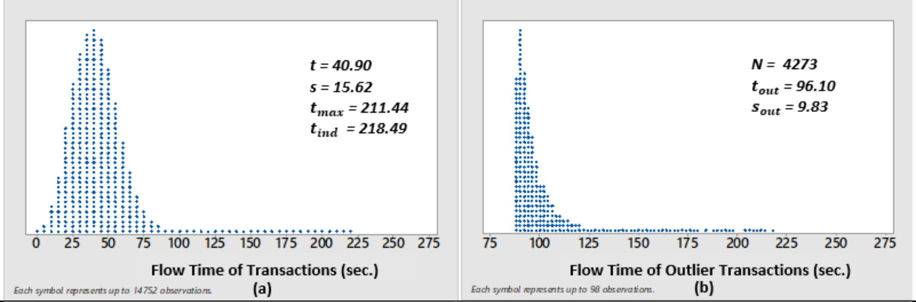
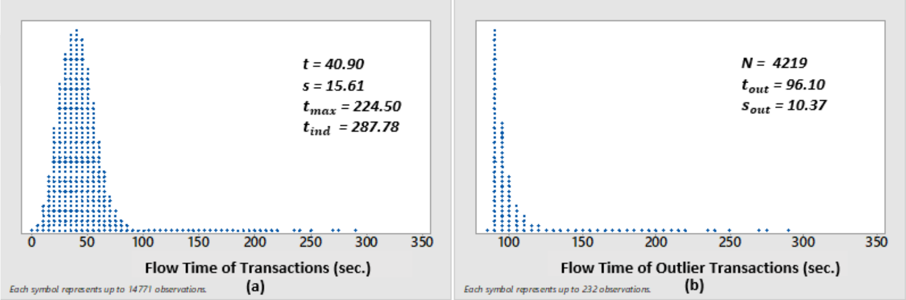
12		
13		
14		
15		
16		
17		

18	t = 40.98 s = 15.97 t_{max} = 241.15 t_{ind} = 298.05 0 25 50 75 100 125 150 175 200 225 250 275 300 Flow Time of Transactions (sec.) Each symbol represents up to 14706 observations. (a) N = 4528 t_{out} = 107.24 s_{out} = 21.61 75 100 125 150 175 200 225 250 275 300 Flow Time of Outlier Transactions (sec.) Each symbol represents up to 164 observations. (b)
19	t = 40.90 s = 15.62 t_{max} = 211.44 t_{ind} = 218.49 0 25 50 75 100 125 150 175 200 225 250 275 Flow Time of Transactions (sec.) Each symbol represents up to 14752 observations. (a) N = 4273 t_{out} = 96.10 s_{out} = 9.83 75 100 125 150 175 200 225 250 275 Flow Time of Outlier Transactions (sec.) Each symbol represents up to 98 observations. (b)
20	t = 40.90 s = 15.61 t_{max} = 224.50 t_{ind} = 287.78 0 50 100 150 200 250 300 350 Flow Time of Transactions (sec.) Each symbol represents up to 14771 observations. (a) N = 4219 t_{out} = 96.10 s_{out} = 10.37 100 150 200 250 300 350 Flow Time of Outlier Transactions (sec.) Each symbol represents up to 232 observations. (b)