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Discrete event simulation model to evaluate the performance of autonomous vehicle storage and retrieval systems

Supervisor:
Franco Lombardi
Co-Supervisors:
Giulia Bruno
Gianluca D'Antonio

Author:
Ahmed Mubarak Mekki Awouda

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Abstract

The complexity of material handling systems is a growing and critical issue for global supply chains. With the rapid advancement of technology and the incorporation of automation in many industries in the last few decades, great ventures have been made to develop innovative solutions supporting the automation of logistics activities, and specifically warehouses.

Autonomous vehicle storage and Retrieval systems are an important part of today's warehouses. Due to their ability to generate a high throughput and to adjust to different customer demands, they represent a viable alternative to traditional storage & retrieval machines (SRM).

However, to exploit the potential benefits of such a technology, an AVS/RS must be designed using a detailed understanding of the underlying dynamics and performance trade-offs. Design decisions such as rack configurations, the storage and retrieval policy employed, and initial rack status can have a significant impact on the performance of AVS/RSs. Despite the increasing deployment of such systems; there is an absence of performance evaluation methodologies and standards.

In this work a customizable simulation meta-model capable of generating different AVS/RS architectures is developed to assist system designers in evaluating the performance of their AVS/RS considering several realistic scenario's.

In the second part of this thesis, a set of experiments is planned and simulated using the developed model, these experiments vary three factors that could potentially affect the performance of the AVS/RS used. The factors considered are the storage allocation criteria, the rack topology & the average fill-ratio of the rack.

Several performance measures that provide an indication of the system performance have been considered in this work, these measures are the average & standard deviation of cycle times, rack throughput, and vehicles utilization. Finally, an ANOVA analysis has been performed for each performance measure with the data extracted from the simulations to examine which of the three factors has an impact on the performance of AVS/RS. It was found that all three factors have a significant effect on the value of each performance measure.

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Chapter 1

Introduction

In todays growing world of e-commerce and rapid technological advancement, companies are continuously seeking to develop innovative solutions to improve the performance of their production systems in order to increase their profits, satisfy their costumers demands and keep up with today's competitive scenario. However, the performance of a production system is not solely defined by the performance of its manufacturing operations, but it also depends on the behavior of the surrounding activities. One activity that plays an integral part in the production process is logistics.

Logistics is defined as the process of planning, implementing and controlling procedures for the efficient and effective transportation and storage of goods including services and related information from the point of origin to the point of consumption for the purpose of conforming to customer requirements and includes inbound, outbound, internal and external movements [5]. Many supply chain activities are incorporated and integrated under the banner of logistics such as: the integration of information flow, materials handling, production, packaging, inventory, transportation and warehousing.

With advances in globalization and technology, and an industry that thrives to obtain just-in-time production, distribution and warehouse operations are becoming more critical to supply chain operations. Therefore, huge efforts have been made in the last decades to improve the performance of warehousing facilities alongside the manufacturing part of the business.

In its simplest form, a warehouse is a building for storage of goods. Warehouses are used extensively in the production process, as shown in figure (1.1) they are used in many phases during the product life-cycle; from the storage of raw materials to the storage of finished goods and spare parts.

Uncertainty in demand and supply, production in lots, smoothing of peak demand, and many other reasons require to hold inventory in a warehouse. During the design phase of a warehouse, decisions have to be made about the type of storage system and the equipment which is used for the storage and retrieval process of the goods.

Simple storage types are ground block storage and different kinds of rack storage systems that are manually operated. In these systems, the operator moves to the storage location to store or retrieve the goods. An advantage of simple storage types is that the number of operators, and therefore the achievable throughput, is easy to adapt to the current needs. Also, the investments that have to be made are rather low. On the other hand, the operator can only reach a certain height of a storage shelf or a pallet rack that is served by forklift trucks. This causes inefficiencies in the usage of floor space and height. Moreover, due to the movement of

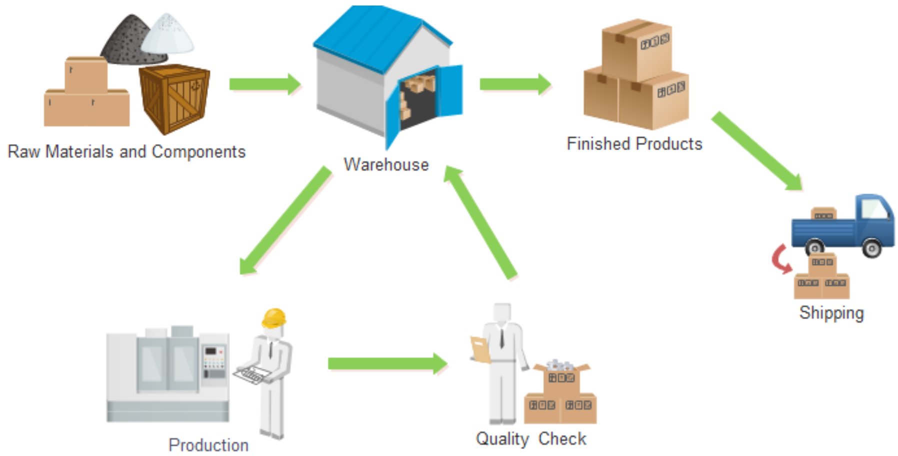


Figure 1.1: Warehouse usage in the production process, taken from Edrawsoft

the operators to the goods, the traveling times of the operators represent a considerable share of the total picking time [6]. This causes inefficiencies in throughput as well.

To reduce these inefficiencies and by following a global trend of automation, automated systems capable of storing and retrieving items from warehouses have been deployed, these systems are known as automated storage and retrieval systems (AS/RS). In AS/RSs, the goods are moved from their storage locations to the operators and vice-versa by automated material handling equipment.

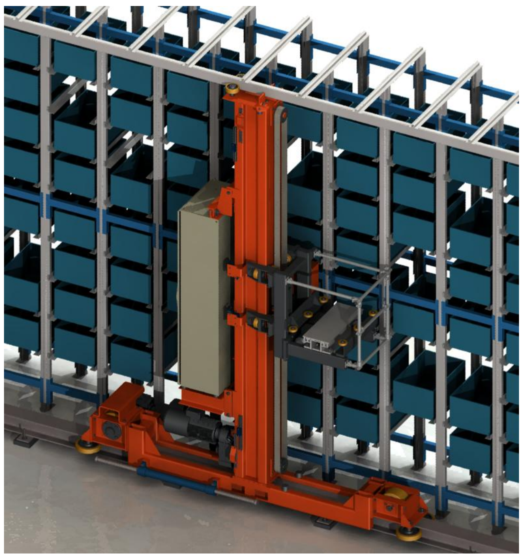


Figure 1.2: SRM (in red) mounted on a single depth rack, taken from Me-Jan d.o.o.

The fundamental element of an AS/RS is the stacker crane, also known as automated storage and retrieval machine (SRM), it can retrieve and store without workers onboard and with the possibility to move in horizontal and vertical direction simultaneously. It is formed by a movable frame sliding over a vertical column which, thanks to a beam laid on a track, can shift along an aisle. The fork can be raised or lowered to each level of the storage rack and can be extended into it to store and retrieve products, these cranes follow a Chebyshev movement pattern. An SRM is shown in figure (1.2).

These SRMs where characterized with high speed, reliability and the ability to serve huge warehouses (up to 55 meters high) but they did have their drawbacks, to name a few:

- High energy consumption: Due to both the big equipment masses to move, and the large building space engaged by cranes.

- High investments in equipment.
- Lack of flexibility in altering warehouse configuration and setup because SRMs are fixed to the warehouse structure.

With these liabilities in mind, the industry set out to find a more efficient solution to store and retrieve goods in warehouses, a solution that was fit for today's increasingly faster deliveries and smaller order sizes. By the late 1990's, Autonomous vehicle storage and retrieval systems where introduced (AVS/RS).

1.1 AVS/RS Overview

An AVS/RS is a System typically comprising several shuttle vehicles, the rack structure, at least one vertical conveyor (lift), a control and, if necessary, an additional conveying system, fire protection and safety equipment [7].

In a regular AS/RS, the unit loads are handled by cranes that simultaneously move in horizontal and vertical directions, whereas in an AVS/RS, the unit loads are handled by autonomous vehicles (shuttle carriers) moving horizontally and by an elevator (with lifting table) moving vertically. Therefore, several storage and retrieval commands can be performed simultaneously in an AVS/RS and better performance may be achieved [8].

As shown in figure (1.3), An AVS/RS system consists of the following components:

- A storage rack with an arbitrary number of levels, each of with a single cross aisle that goes from one side of the level to the other, to provide access to the channels
- A lift which provides the vertical movement
- An autonomous vehicle named shuttle that performs the movement along the aisle
- Another autonomous vehicle named satellite which is the storage/retrieval machine, the satellite moves into the channels to pick up or drop an item from/to a specific position in the channel

These three vehicles work together in an integrated manner to store and retrieve ULs (Unit Loads) to and from the rack, they can also be installed and configured in different ways. The configuration considered in this work is a tier-to-tier configuration where the shuttle has the freedom to change levels (using the lift) and is not constrained to a specific level such as a pier-captive configuration.

For the AVS/RS system to store or retrieve a UL; a series of operations and movements must be performed, this sequence is summarized as follows:

1. The UL is carried to the Input Bay (Storage Bay).

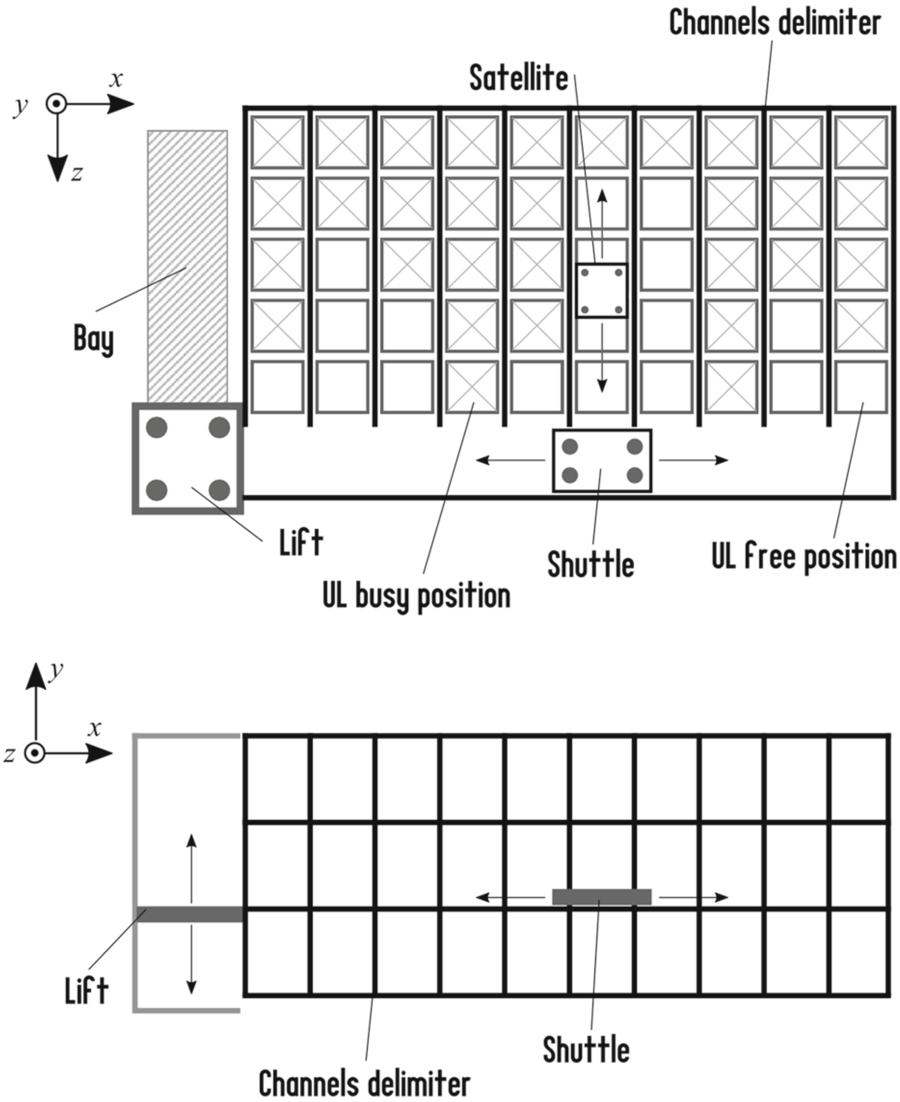


Figure 1.3: Top and Front view for a schematic representation of a rack and an AVS/RS system, figure taken from [9]

2. The UL is loaded by the satellite; the satellite then joins the shuttle, and they move on the lift.

3. The lift travels to the target level, and the shuttle (loaded with the satellite and UL) departs the lift.

4. The shuttle moves through the aisle and stops in front of the target channel

5. The satellite (loaded with the UL) leaves the shuttle and enters the channel.

6. The satellite moves along the channel towards the last pallet stored.

7. The satellite unloads the pallet at the last empty location, according to a LIFO (Last In First Out) policy.

8. The satellite moves back through the channel and joins the shuttle.

9. The Shuttle travels through the aisle back to the lift and is loaded onto it.

10. The lift returns to the base level.

11. The shuttle (loaded with the satellite) leaves the lift and returns to its starting position.

The retrieval cycle is performed in a symmetrically opposite manner. The type of cycle described here is known as a single command cycle, i.e: the system performs either a single storage or retrieval operation per deployment. The time required by the AVS/RS to perform the above-mentioned sequence of movements is known as the cycle time.

1.2 Problem Statement

The automated warehouse industry is growing at a rapid rate nowadays, a recent study conducted by [10] shows that the automated storage and retrieval system market is expected to reach USD 9.18 Billion by 2023, growing at a CAGR of 7.37% between 2017 and 2023. The major factors driving the growth of the market include limited space and minimal labor utilization enabled by the adoption of new ASRS-based technologies, improved supply chain efficiency and productivity, real time inventory control at lower costs, and multichannel supply chain strategy in retail.

The design of an AVS/RS has a direct impact on the investment costs, operational costs, and penalty costs (if the service level is not met), As a result, there is a need for performance evaluation tools that enable the warehouse designer to evaluate many different system designs in a short period of time. Since the system behavior, and therefore the system performance, is influenced by stochastic processes such as the arrival process of the retrieval transactions, the performance evaluation tools must consider these influences.

There is a rich literature on analytical methods for the performance evaluation of manually operated storage systems and AS/RS, however there is still a lack of performance evaluation techniques and there are no standards that provide performance evaluation criteria for AVS/RS. Most of the available AVS/RS performance evaluation tools either take into consideration a limited set of performance measures or only consider specific parts of the system. Hence there is a dire need for performance evaluation tools that can evaluate all aspects of the AVS/RS and also take into consideration the stochastic nature of such a process.

1.3 Objective

The performance evaluation of processes that are subject to stochastic influences can be done either by simulation or by analytical methods, however in many cases simulation models yield a more realistic approach compared to the analytical model. This is caused by the fact that a deterministic (analytical) approach normally requires simplifications of the model that are not required in a (stochastic) simulation model, therefore a simulation-based approach has been used in this work.

The objective of this work is to develop an accurate meta-model that takes into consideration different aspects of autonomous vehicle storage and retrieval systems and provides a degree of customization that enables the simulation & evaluation of various AVS/RS architectures. The ultimate goal of such a model is to assist warehouse equipment designers in evaluating the performance of their systems, considering a multiplicity of realistic scenarios.

1.4 Thesis Organization

The thesis is decomposed as follows:

- **Chapter one (Introduction)** gives a brief description of the problem and outlines the motivation behind seeking suitable performance evaluation tools for AVS/RS.
- **Chapter two (Literature Review)** highlights the most recent studies and research in scientific literature conducted in the field of AVS/RS performance evaluation methods and techniques, a brief description of the state of the art system (EsmartShuttle) that has been modeled in this work will also be provided.
- **Chapter three (Methodology)** provides an exposition of the meta-model developed in this work, first by explaining the importance and usage of discrete event simulations, secondly by providing an overview of the software platform (FlexSim) used to develop the model, then by explaining in a detailed manner the architecture and operational aspects of the model. In the last part of this chapter a plan of experiments will be proposed.

- **Chapter four (Results)** highlights the findings and outputs of the simulations conducted, these will be presented in the form of ANOVA tables and various statistical plots. Furthermore the main outputs of the experiments will be emphasized & explained here.
- **Chapter five (Conclusion and Future Work)** contains a summary of the main outcomes of this thesis work and possible recommendations for further work are also reflected and shared in this chapter.

Chapter 2

Literature Review

2.1 Overview

Many Studies in Scientific Research have been conducted to provide a method of Evaluating the Performance of AVS/RS systems, Different approaches have been used to tackle this problem. In most of these studies, the performance evaluation was generally carried out using analytical models, which were then validated through simulation.

In this Chapter, the most recent developments published in scientific literature related to the performance evaluation of AVS/RS systems will be highlighted in the first section. The second section will provide a brief description the AVS/RS system that was modeled in this Work.

2.2 Scientific Literature

The first Study Conducted was by Malmborg [11] in 2002, the author proposed a state equation model to estimate vehicle utilization and cycle time as a function of the number of storage columns, tiers, vehicles and lifts.

A network Queuing Approach using Opportunistic interleaving was proposed by Fukunari & Malmborg [12] in 2007, their study focused on Single and Dual command cycles, this approach overcame the computational disadvantage of the state equation model used by [11], it also provided an effective screening of candidate design profiles in the initial design phase of such systems, however they only took into consideration random storage allocation policies.

A simulation based experimental design was conducted by Ekren et al [13], They Applied a DOE that took into consideration many design factors that could have an effect of on the performance measures (average cycle time for storage and retrieval transactions, average vehicle utilization, and average lift utilization) of the system, namely:

- Dwell Point Policy.
- Scheduling Rule.
- Input/Output Locations of Drop off and Pickups.
- Interleaving rule.

After Conducting an ANOVA Analysis and a Turkey Test analysis the Authors found a certain combination of design factors, number of vehicles and arrival rates that would optimize the performance of the AVS/RS system under study.

Ekren [14] built upon the previous research by conducting a case study into the performance evaluation of AVS/RS taking the Economic Aspects of Such a system into consideration, the author also added the rack configuration as a contributing factor to the performance of the AVS/RS, and concluded that the biggest portion of cost is due to the bay size and proposed the usage of smaller racks.

Roy et al. [15] investigated the performance impact of several design decisions using an analytical model. A semi open queuing network that was decomposed into two subsystems (a closed queuing network corresponding to the case when vehicles wait for transactions and an open queue corresponding to the case when transactions wait for vehicles) was proposed by the authors. System Size and Operational characteristics where taken as influencing factors on the AVS/RS throughput and transaction time. The Semi-open queuing network model was found to be able to accommodate a variety of design configurations such as rack size, vehicle assignments and zone distribution.

By building upon previous contributions in literature; An Analytical model based on Open queuing networks was proposed by Marchet et al [16]. Their model was tailored for smaller orders were the storage units where in the form of totes. The analytical Model also took into consideration the Waiting times which have not been considered in the previous literature, therefore the transaction time was computed as a function of Vehicle movements, lift movements and waiting times. After the results where validated via simulations; the authors concluded that the Model succeeded in estimating the cycle times and the waiting time (which was the critical component to be evaluated in the study), However their model took into consideration only single command cycles.

Marchet et al. [17] expanded on their previous research by providing a comprehensive design framework that was able to assist designers in the conceptualization phase of system development for the design of AVS/RS's. By taking into consideration the Cost structure of the Rack and after investigating the main design trade-offs via simulations; a framework that permits a rapid identification of the most appropriate rack configuration was developed. The authors also highlighted the key design differences between tier-captive and tier-to-tier configurations. The framework was applied to an existing warehouse and showed that it was able to identify the optimal solution from among the potential solutions (given the physical and service constraints of the warehouse).

In 2014 Kaczmarek et al. [18] developed a simulation-based model that focused on analyzing the Influence of storage management policies on the performance of AVS/RS's. The storage management policies that where taken into consideration are: Shelf space assignments, withdrawal strategies, Storage/Retrieval strategies and Vehicle selection strategies. After simulating various combinations of the mentioned storage management policies, it was found that immense performance effects can be achieved by intelligent control of AVS/RS without changing the physical configuration of the Rack.

Another Simulation-based approach (tailored towards SBS/RS) was provided by Lehrer et al. [19]. SBS/RS is a subset of an autonomous vehicle storage and retrieval system (AVS/RS), However the literature on AVS/RSs is mainly analyzing storage systems for unit-loads, whereas the literature on SBS/RS is often assuming mini-loads but both notations can be used to describe the same system [6]. The Rack configuration, velocity profiles of the AV's and Lifts were taken into consideration as performance affecting factors. By applying a randomized storage assignment policy; the authors observed that the SBS/RS performance significantly depends on the throughput performance of the elevator multiplied by the number of aisles, however they also found that with an extremely large number of columns in the rack; the shuttles becomes the bottleneck of the system if their velocity profile is low.

Ning et al. [8] developed a simulation-model that consisted of multiple elevators, a simulation case study that consisted of various rack alternatives under different arrival rates was also presented. The main capabilities of their model were that it could be remodeled for different rack configurations in addition to being able to show graphically the actual behavior of the system. Their Simulation model proved that it could be used as a useful tool to assist SBS/RS designers during the conceptualization phase of system development.

In 2017 D'Antonio et al [9] developed an Analytical model based on a probabilistic approach to assess the performance of AVS/RS applicable to deep lane tracks. Their focus was on a specific variation of AVS/RS design that consisted of Shuttle vehicles with an additional smaller AV on board (satellite); While the satellite transports ULs inside the channels, the shuttles connect the channels with the lift. Their research added to the available literature by taking into consideration the Storage/Retrieval allocation criteria and the ability of the shuttle and satellite to simultaneously perform different tasks as possible influences on the performance of the AVS/RS. In their work the authors validated the Analytical Model via simulations by varying the following factors:

- The rack Layout.
- Cycle type (homogenous or Heterogeneous).
- Storage and retrieval Allocation criteria's.

The proposed Analytical model proved to be an effective tool that can aid AVS/RS designers in the assessment of AVS/RS performance.

The Most Recently Published Study pertaining to the Performance evaluation of SBS/RS was conducted by Lerher [20] in 2017, by the usage of DOE analysis the author investigated the design that optimizes the throughput performance of an SBS/RS. His results indicated that several predefined factors have an interaction effect on each of the performance measures (average cycle times, throughput performances of vehicles and warehouse volume) of the system.

Year	Author	Modelling Methodology	Type of Cycle	Rack Depth	Performance Measure (Model Output)
2002	Malmborg [11]	State Equation	SC/DC	Single	CT, TH, u
2007	Fukunari & Malmborg [12]	Network Queuing	SC/DC	Multi aisle, Single	CT, u
2010	Ekren et al. [13]	Simulation Model	SC/DC	Single	CT, u
2011	Ekren [14]	Simulation Model	SCX	Single	CT, WT, u
2012	Roy et al. [15]	Network Queuing	SC	Multi aisle, Single	CT, u
2011	Marchet et al. [16]	Analytical Model	SC	Single	CT, u
2013	Marchet et al. [17]	Simulation Model	SC	Single	FT, TH
2014	Kaczmarek et al. [18]	Simulation Model	SC/DC	Multi aisle, Single	CT
2015	Lehrer et al. [19]	Simulation Model	SC/DC	Single	CT, TH
2016	Ning et al. [8]	Simulation Model	SC	Single	CT, TH
2017	D'Antonio et al. [9]	Analytical Model	Multi Command	Deep Lane	CT
2017	Lehrer [20]	Simulation Model	SC/DC	Double	CT, TH

Table 2.1: Summary of Recent Scientific Literature in the topic of AVS/RS

These predefined factors are the Number of columns, velocities of the shuttle and lift and the accelerations of the shuttle and lift.

It should be noted that the work presented in this thesis is an extension (or partially built upon) of the work conducted by [9].

Table (2.1) Summarizes the main characteristics of each scientific paper presented above.

2.3 Description of the EsmartShuttle

As mentioned previously, Eurofork's EsmartShuttle has been used as the AVS/RS case study in this thesis. A brief description of the EsmartShuttle will be presented in this section.

EsmartShuttle is an automated vehicle storage and retrieval system developed by Eurofork. It is designed for multi-deep storage racks. The EsmartShuttle consists of two modules that work with a lift, these modules are named Shuttle & Satellite.

2.3.1 Shuttle

The shuttle is the main trolley powered by battery which carry the satellite and/or the loading unit in the X-direction. The shuttle's parameters can be suited to the dimensions and weight of each loading unit in the warehouse. Figure (2.1) shows the shuttle module. The main specifications for this module are in Table (2.2) below.

2.3.2 Satellite

The Satellite is the smaller trolley powered by battery which lifts, carries and stores the loading unit in the warehouse channels (Z-direction). Figure (2.1) shows the satellite module. The main specifications for the satellite module are in table (2.3)

These two modules reach the warehouse's level (Y-direction) by means of an elevator (Lift). Multiple EsmartShuttle systems can be installed in a single warehouse and they can work simultaneously to provide higher throughput. With the usage of optical direct position reading (barcode) in all three axis the system can know the position of all vehicles always.

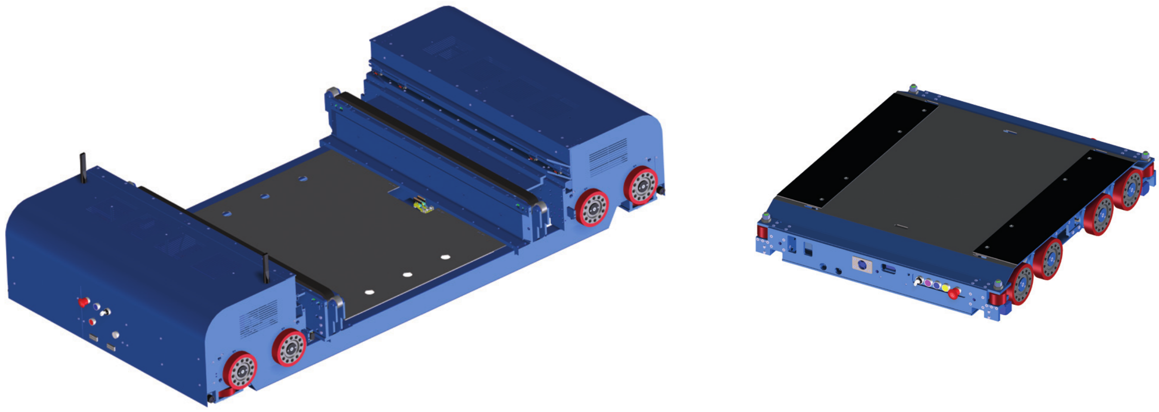


Figure 2.1: Shuttle (Left) & Satellite (Right) Modules of EsmartShuttle

Motor Type & Power	48V Brushless, 2 kW
Power Supply	Lithium Battery - 100 Ah
Wheels Number (Drive)	8 (4)
Max Pallet Dimensions	1000 × 1200
Max Payload	1500 kg
Max Speed with Load	150 m/min
Max Acceleration with Load	1.0 m/s^2
Chain Conveyor Motor Type & Power	48V Brushless, 0.8 kW
Weight	750 kg
Working Temperature	-24°C to +60°C

Table 2.2: Shuttle Specifications [3]

Compared to conventional AS/RS systems such as stacker cranes, the Esmartshuttle has the following advantages:

- **Scalability:** Can be installed in any warehouse size by increasing the number of modules.
- **Flexibility:** IN/OUT performances can be increased by adding modules after start-up
- **Energy Saving:** Modules operate with 2kw brushless motor
- **Reduced Startup time:** Software application automatically creates a 3D map of warehouse.
- **Positioning:** Absolute and precise localization of each module and each loading unit at any time via optical direct position reading.

Motor Type & Power	48V Brushless, 2 kW
Power Supply	Lithium Battery - 40 Ah
Wheels Number (Drive)	8 (8)
Max Pallet Dimensions	1000×1200
Max Payload	1500 kg
Max Speed with Load	75 m/min
Max Acceleration with Load	1.0 m/s^2
Lifting Motor Type & Power	48V Brushless, 1 kW
Lifting Principle	Crank & Connecting Rod
Weight	250 kg
Working Temperature	-24°C to +60°C

Table 2.3: Satellite Specifications [3]

Chapter 3

Methodology

3.1 Overview

In this chapter, the model development process will be explained, along with the model characteristics and the methodology of obtaining the results. An overview of the concept of Discrete event simulations will be provided first and an introduction into the different software's used for DES will also be briefly discussed.

3.2 Discrete Event Simulations

A discrete-event simulation (DES) models the operation of a system as a discrete sequence of events in time. Each event occurs at an instant in time and marks a change of state in the system [21]. It is assumed that between two successive events, no change in the system will occur.

Discrete event simulation quantitatively represents the real world, simulates its dynamics on an event-by-event basis. A discrete event simulation model is characterized by 3 attributes:

- **Stochastic:** Contains Random Variables
- **Dynamic:** The time evolution of the system state variables is of importance
- **Discrete Event:** System state variables change in relation to events that occur at discrete time instances

These 3 attributes can be seen in Figure (3.1) which shows the system model Taxonomy, i.e.: the classification of system models according to their variables and behavior.

On the other hand, there are many ways to study a system and simulation is a branch of these methodologies, this can be seen in Figure (3.2). There are many justifications on why one would use simulations to study a system as an alternative to experimenting with the actual system, to name a few:

- Cost: Experimentation with the real system can be costly, it is expensive to stop an actual system under operation to try new ideas.
- Time: In most systems it is required to study the behavior of a system for the significant lifespan of its operations, this can be months, years or even decades. With the aid of

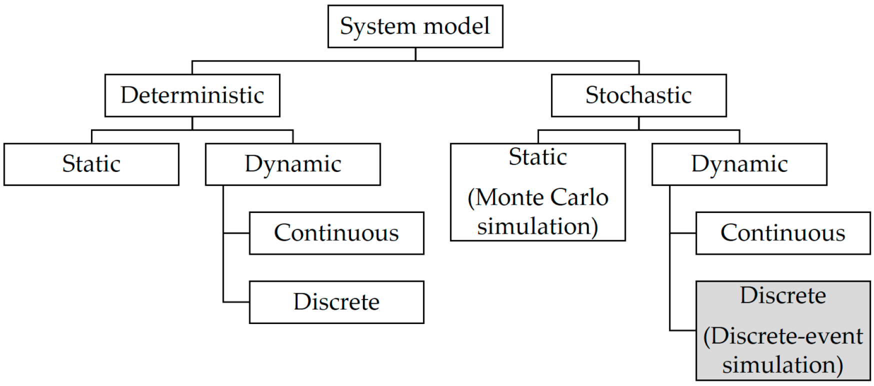


Figure 3.1: System Model Taxonomy [1]

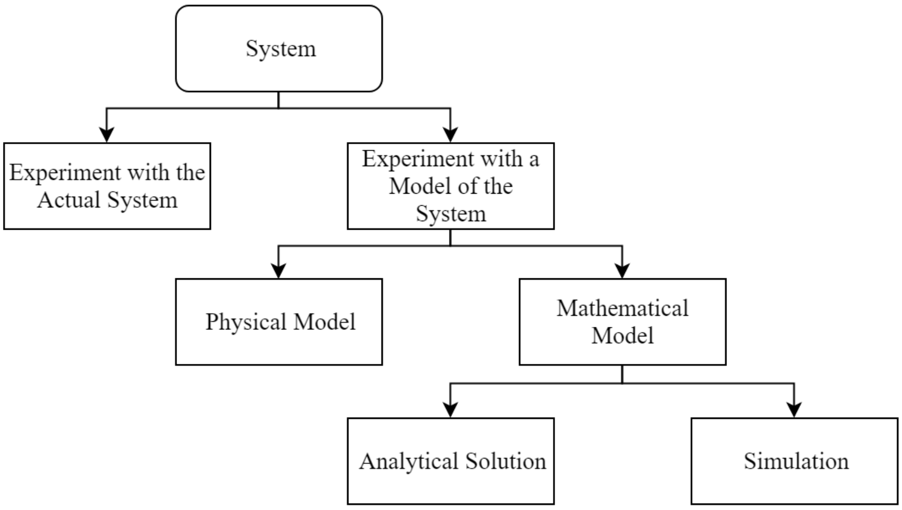


Figure 3.2: Ways to Study a System [1]

powerful computing power; this can be accelerated to a point where it only takes minutes to simulate years

- Control of Experimental Conditions: With a simulation model the conditions under which an experiment is performed can be repeated many times under different conditions. This is not possible in the actual systems. For example: it is not possible to control the number of patients entering a hospital, or as another example; it is not possible to control the number of orders received by a supply company.

- The real system may not exist yet: In some cases, certain events or states in the system may not have an actual presence in the real world yet; in such cases simulation would be a viable approach.

DES are used in many different sectors and specifically in service related sectors. The reason for this according to [22] is "Managers have tried to balance excellent customer service with operational efficiency (meaning shorter processing time, less waiting time for customers and higher resource utilization). Many of them have found that discrete event simulation can help them make right decision." DES are currently used in:

- Banking & Finance
- Healthcare & Hospitals
- Public Sector
- Logistics & Transportation

In this thesis; a DES software (FlexSim) has been used to Model the behavior of an AVS/RS system to evaluate the performance of such a system in order to optimize the system for real world applications.

3.3 Notes about FlexSim

3.3.1 Overview

FlexSim is an object-oriented software environment used to develop, model, simulate, visualize, and monitor dynamic flow process activities and systems [23]. FlexSim is classified as a discrete-event simulation software program which means that it is used to model systems which change state at discrete points in time due to specific events.

FlexSim's advantages can be summarized as follows:

- It can simulate Months and years in just a few minutes.
- Highly customizable in the sense that the user can create his own classes, libraries, GUIs, or applications
- FlexSim provides in-model charts and graphs to dynamically display output statistics and generate reports
- Provides realistic graphical animation that mimics the real-life behavior of the system under study

For the reasons mentioned above, FlexSim has been chosen over Arena & Tecnomatix Plant Simulation as a suitable DES tool for this Thesis. Table (3.1) taken from [4] compares FlexSim to the mentioned two softwares and highlights FlexSims ability to provide extensive reporting and its compatibility with database and C++ applications.

Software	Vendor	Typical Applications	Primary Markets	Compatible Software for specialized functions	Drag-and-Drop Model Building	Programming Capability	Output Analysis Support	Real Time Viewing	3D Animation
Arena	Rockwell Automation	Simulating and Analyzing Systems, Operational Analysis	Manufacturing, Supply Chain, Government, Healthcare, Logistics, Food and Beverage, Call Centers	OptQuest	YES	YES	Arena Output Analyzer and Process Analyzer to review results	YES	YES
FlexSim	FlexSim Software Products, Inc	Simulation and modeling of any process, with the purpose of analyzing, understanding, and optimizing that process	Manufacturing, Packaging, Warehousing, Material Handling, Supply Chains and Logistics, Healthcare, Factory, Aerospace, Mining	Excel, database software, C++ applications	YES	YES	A full suite of charts and graphs in the Dashboard, Extensive Excel output options	YES	YES
Tecnomatix Plant Simulation	Siemens	Discrete-event simulation,visualization, analysis and optimization of material flow, resource utilization and logistic	Automotive OEM, Automotive Tier-1, Consulting, Aerospace, CPG, Logistics, High-tech and Electronics, Machinery, Healthcare	Matlab, SAP, Simatic IT, Teamcenter, Autocad	YES	YES	Datafit, Bottleneck Analyzer, Energy Analyzer, Neural Networks	YES	YES

Table 3.1: FlexSim vs Arena, Tecnomatix [4]

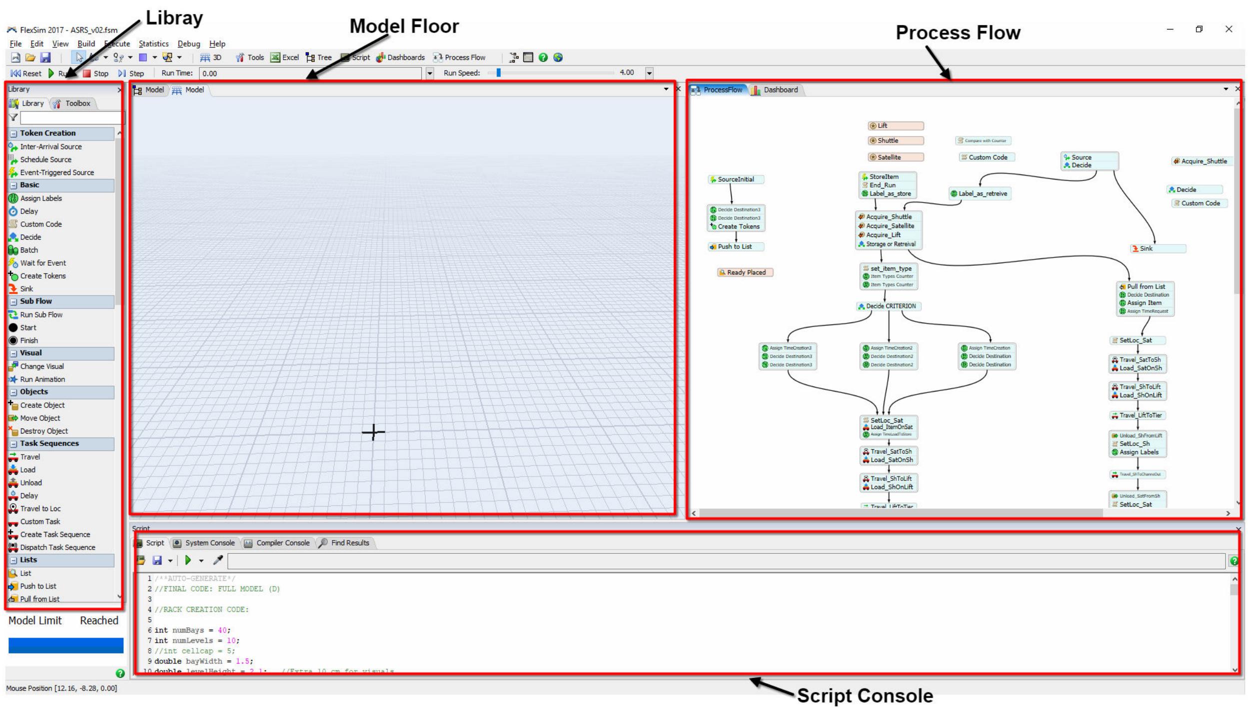


Figure 3.3: FlexSim Environment

3.3.2 Description of the FlexSim Environment

As mentioned previously; FlexSim is an object-oriented software environment, therefore it consists of objects, these objects are the basic building blocks used to create models. FlexSim objects range from Sources to generate UL's, totes, boxes etc. to robotic arms, automated guided vehicles and forklifts.

The FlexSim environment is divided into several sections or windows as seen in figure (3.3), the sections used in this work will be explained briefly. The main section where the objects are placed and where the visualization of the simulation animation occurs is called the model floor.

On the left of the model floor view is the library icon grid or simply the library, this consists of all the basic objects that may be used in the simulation, these objects can be dragged and dropped into the model floor, furthermore one can customize these objects to suit the needs of the simulation.

The section below the model floor view is named the script console, the script console allows the execution of flexscript commands without running the model. This section also allows debugging of the written code. It is relevant to note that flexscript is the FlexSim programming language. The script console is used in our model to auto-generate the model floor objects prior to runtime. This allows flexibility and saves time when re-running the model by replacing the process of dragging and dropping the objects and reconnecting them every time a simulation is initiated.

The most important section used in our model is the process flow module, this is where the model logic resides. The Process Flow module can break up large simulation models into small, manageable pieces. On the outside Process flow looks like a simple flow chart where the different blocks represent activities and resources that are used in the simulation model. The most basic components of a process flow are tokens, activities and shared assets.

1. **Tokens:**

   Tokens are objects that flow through the process flow activities during a simulation run, tokens move from one activity to the next. In our model; tokens are associated with UL's in the visual model. Each token has a name, an ID and a label which are linked to each UL that enters the model, by tracking the information available in the token we can keep track of every UL load in the system. Figure (3.4) shows a process flow activity with a token inside it.

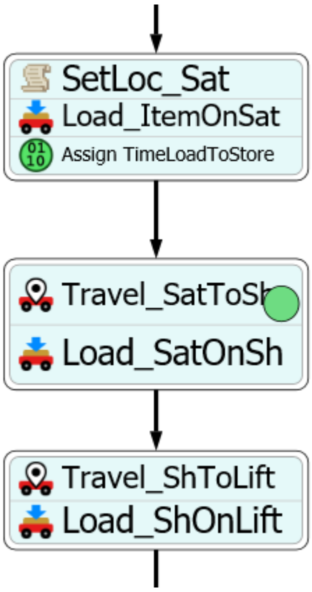


Figure 3.4: Token (green circle) moving from a group of activities to another [2]

2. **Activities:**

   An activity is a logical operation or step in a process flow. As such, activities are the basic building blocks of any process flow, Activities are dragged from the Library into a process flow and linked together with connectors. As a token enters an activity, it performs the logic associated with that type of activity. The types of activities used in this model are described in table (3.2).

3. **Shared Assets:**

   A shared asset is a finite resource that tokens may claim or release at certain points in the process flow, Shared assets can impose constraints on the tokens by making the token wait if the requested asset is unavailable, an example of a shared asset in the model is the shuttle. Table (3.3) shows the types of shared assets used in our simulation model.

Name	Icon	Description
Inter-Arrival Source	Source	Creates new tokens according to a specific interval of time. Used to Generate Retrieval Requests at a fixed rate
Event-Triggered Source	Source	Creates tokens in response to an event during a simulation run. This source will listen for that event to occur in the simulation model. When that event occurs, it will create a token. Used to Initiate the Process Flow when a UL enters the system
Assign Labels	Assign Labels	Creates or modifies labels on various objects. Labels can be used to store important data about various objects. Used to assign a location in the rack for each UL
Custom Code	Custom Code	Creates custom behavior in the process flow module. When a token enters the Custom Code activity, it will evaluate the user-defined code, execute it and then immediately be released to the next activity
Decide	Decide	Sends a token to one of two or more possible activities based on a pre-defined condition. Used to redirect tokens depending on allocation used
Create Tokens	Create	Creates one or more new tokens and automatically sends them to a different activity. Used to send copies of token data to database
Sink	Sink	Destroys tokens, removing all data stored on those tokens
Move Object	Move Object	Moves an object or multiple objects to another place in a simulation model
Travel	Travel	Makes a task executer travel to a specific object in the 3D simulation model. Used for vehicles movement
Load	Load	Makes a task executer load an object in the 3D simulation model. Used to load UL's on the satellite, satellite on shuttle & shuttle onto lift
Unload	Unload	Makes a task executer unload an object in the 3D simulation model. Used to Unload UL's from satellite, shuttle from lift etc.
Travel to Loc	Travel	Makes a task executer travel to specific X, Y, and Z coordinates in the 3D simulation model, different from regular travel activity as it deals with cordinates. Used for lift movement
Push to List	Push to List	Push's token Data to Lists (Database)
Pull from List	Pull from List	Retrieves Token Data from Lists (Database)
Acquire Resource	Acquire	Used to acquire a resource at some point during a process flow. Used to acquire the vehicles and lift by the tokens
Release Resource	Release	Used to release or return a resource at some point during a process flow

Table 3.2: Process Flow Activities [2]

Name	Icon	Description
Resource	Resource	Represents a limited supply of some resource that can be acquired and released. It can be used to simulate a supply of goods, materials, employees It is used to simulate the vehicles & the lift in our model
List	List	Represents a list of tokens, task executers, numbers etc Used as a Database to Store the UL Data such as: time of entry, time required for insertion, location in the Rack etc.

Table 3.3: Shared Assets Description [2]

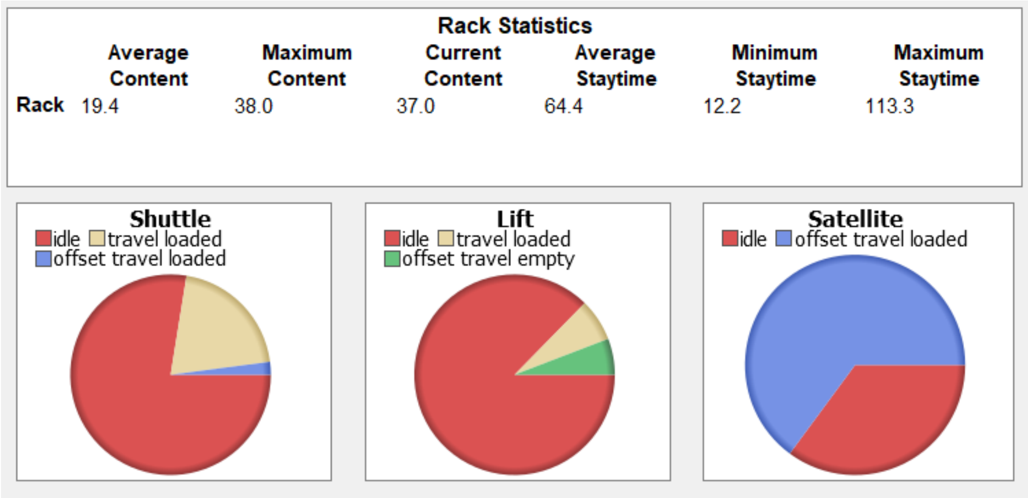


Figure 3.5: Dashboard with Rack Statistics & vehicles Utilization Charts

With the usage of the Script Module, the model objects are auto-generated and then linked to their associated Process flow blocks.

The Final section or view used in our model is the dashboard window, The Dashboard window allows you to view graphs and statistics for the model as it runs. It is especially useful for comparing objects side by side and then generating reports in the form of csv or html files after the simulation run is finished. The dashboard collects data such as vehicles utilization, rack content and average I/O rates as shown in figure (3.5).

3.4 Simulation Model

3.4.1 Model Overview

In this section the functionality of the implemented simulation Model will Explained. This model was created to model an AVS/RS system consisting of 3 Vehicles (Shuttle, Satellite and Lift).The model floor consists of the following objects:

- The 3 Vehicles
- A Storage Rack to Store the UL's

- Source to Generate the UL's during Runtime (Named *SourceInput*)
- A Source to generate the amount of UL's that will be available in the rack at startup (Named *Source1*)
- A Queue to Model the Storage Bay, this is where the Vehicles pick up the Items for Storage
- Another Queue to Model the Retrieval Bay, this where the Retrieved Items are Placed by the Vehicles
- A Travel Network to Provide Paths for the Vehicles to follow

The Models Operation Logic is in the Process Flow Section, this Includes the Store and Retrieve Cycles, Item Labels and Lists for stored and retrieved Items.

The Flexscript Script Module; contains the code to create all the Model Objects, the Travel Network and certain Parameters in these Objects are also edited here. It Also Links the objects to the Process Flow.

After the Model is successfully started; the Input Source starts creating UL's and sends them to the Storage Bay, on the entry of a UL into the queue; a token is generated in the Process flow and this token is associated with that specific UL. After that the UL is picked up by the satellite, the satellite then travels to the Shuttle and is loaded on to it. Then both vehicles are loaded onto the lift and they will travel to the required Level that contains the bay that the UL will be stored in.

When the Shuttle (loaded with the satellite & a UL) arrives in the level, the shuttle will leave the lift and travel to the required Bay, then the satellite departs the shuttle to store the UL in its predefined channel location. The satellite then returns to the shuttle and they both make it back to the lift and back to the ground level to pick up another UL from the storage bay and start this cycle again.

The retrieval cycle is done in similar manner; except that the retrieved item is sent to the Retrieval bay.

The UL Placement in the Rack is assigned in the Process Flow, each UL is assigned 2 specific labels named *rackbay* and *racklevel*, these labels contain the Bay and Level in the rack that has been assigned to this UL. The Next Section Describes the Model Startup Sequence.

3.4.2 Model Operation Sequence

1. **The User starts by opening the Model**

   The *OnModelOpen* Trigger is Executed: this trigger is executed every time the model is opened;

   - Trigger Operation:

  - All the Objects in the Model are selected
  - All Selected Objects are Deleted
- Trigger Result:
  - Model is Cleared and Ready for New Objects Generation

2. **The User Defines Certain Object Parameters in the Script:**

   These parameters are:

   - Number of Bays in the Rack
   - Number of Levels in the Rack
   - Width of each bay
   - Height of each Level
   - Depth of the items that will be inserted into the Rack
   - Desired Cell Capacity
   - Desired UL Insertion Criteria into the Rack
   - Velocity & acceleration of the vehicles and lift
   - Rate of arrival of the UL's into the system

   These parameters are used to customize & define the Rack Dimensions in the Model as well as the allocation criteria to be used

3. **The User RUNs the Script**

   The Script Executes the Following Operations:

   - Creation of the Rack (with the previously defined dimensions)
   - Creation of the Storage Bay
   - Creation of the Retrieval Bay
   - Creation of the Input Source
   - Creation of Source1
   - Creation of the Lift
   - Creation of the Shuttle
   - Creation of the Satellite
   - Connection of the Input Source to the Storage bay
   - Connection of Source1 to the Rack
   - Links the Satellite to the Resource Block *Satellite* in the Process Flow

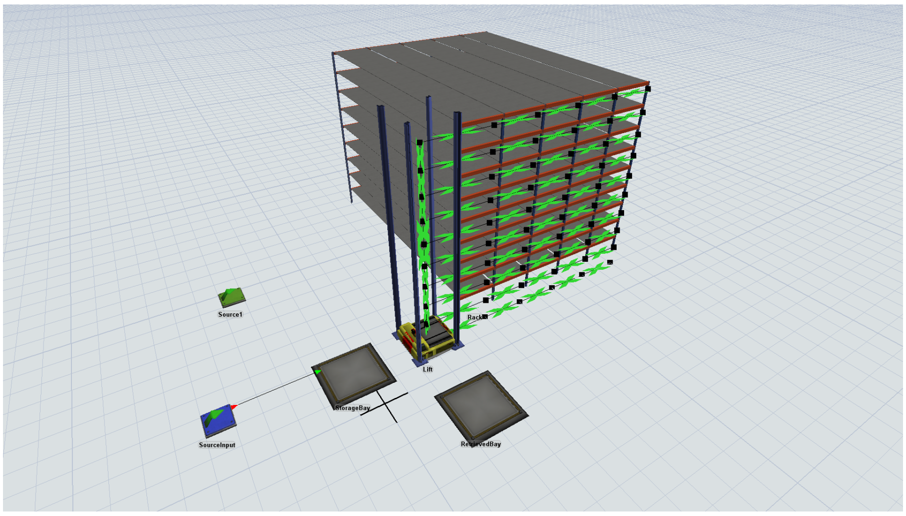


Figure 3.6: The Flexsim Model after the Objects have been Created (an example of a rack with 5 bays, 10 levels and a cell capacity of 10 items)

- Links the Shuttle to the Resource Block *Shuttle* in the Process Flow
- Links the Lift to the Resource Block *Lift* in the Process Flow
- Links the remainder of the objects to their associated process flow variables
- Sets the UL size that will be generated by the Input source
- Sets the vehicles parameters (acceleration, speed & deceleration)
- Sets the UL's rate of arrival in the Input source
- Creation of the Travel Network
- Connection of the vehicles to the travel network

After the script has executed correctly the Model floor will be similar to the Image shown in Figure (3.6)

4. **The User sets and performs all non automated parameters & operations**

   Non-automated parameters & operations are the parameters & operations that are not configured or executed by the script module, these parameters are:

   - Number of items Generated by Source1, i.e the of UL's that will all ready be in the rack at the beginning of the simulation run (Named *Initial Fill*)
   - Connection of the vehicles to their associated dashboards
   - Total Number of storages & retrievals that will be simulated (Named *SimTotal*)
   - Rate of which the retrieval requests are generated

5. **The User RESETs the Model**

The *OnModelReset* Trigger is Executed, This trigger Sets the *Destroy on Reset* flag of Each Object to 1; This is done to ensure that all the Model View will be Cleared Completely (Full Model Reset) when reset is pressed for a second time at the end of each simulation Run.

- Necessity of RESET:

  A Reset is *necessary* any time new connections are made between objects in FlexSim. Reset must be pressed because Resetting the model initializes & sets all system variables to their starting values and therefore you should always press the Reset button before starting a new simulation run.

6. **The User RUNs the Model and the Simulation Starts**

7. **When the total number of required storages & retrievals (*SimTotal*) is achieved; the simulation ends**

8. **The User saves the Data acquired by the dashboard module.**, this data includes:

   - vehicles utilization
   - rack statistics such as: Average UL stay time, maximum content during run, input/output per hour etc.

9. **The user saves the data available in the Lists (database)**, this data was acquired in the process flow via the information stored in each UL token, this data includes but is not limited to:

   - Store & retrieve cycle time the UL
   - The Time it entered the system
   - Location of the UL in the Rack (Bay, Level, channel position)
   - How long it stayed in the Rack
   - Time of when the storage and/or retrieval request was made
   - Time of when the storage and/or retrieval request was fulfilled

10. **After all the Simulation data is acquired; the user presses Reset & the simulation model is completely cleared**, the process is repeated again to perform another run.

The next section provides a detailed explanation of the Process Flow Operation and gives an insight on the vehicles movement and operation.

3.4.3 Process Flow

The process flow module is where the most of the model logic has been implemented, the process flow operates like a sequential flow chart where each token passes from one activity to the next. Each activity represents an operation or a sequence that occurs in the actual graphical animation of the AVS/RS. In this model the process flow is divided into sections, each section contains a number of activities and performs a specific function, these sections are:

1. Rack Initialization

   This section is responsible for the Initial Filling of the rack. After the number of UL's to be available in the rack before startup is defined; each UL is assigned a specific location in the rack. This data is then sent and stored in the Database section.

2. Resources

   All the blocks that represent the model resources are found here. As mentioned previously, these resources are the vehicles and the lift. The resources are then managed by the resource management section (see no.5 below).

3. Storage Requests

   Storage requests are managed here, this section works along with Input Source by monitoring its output and creates a token every time a UL enters the system, this token will be associated with that specific UL until the simulation finishes. This section also keeps a count of the total number of UL's entering the system and ends the simulation when *Simtotal* is reached.

4. Retrieval Requests

   Retrieval requests are generated from this section; tokens are created according to a predefined specific interval of time. These tokens are then passed to the resource management section in order to acquire the needed resources (vehicles & lift) for retrieval.

5. Resource Management

   This section is responsible for managing the resource allocation. It receives as input the storage & retrieval requests in the form of tokens, then via a first-come-first-serve method; it assigns the resources to either a storage or retrieval token. If the resources are given to a storage token, it sends the token to the storage cycle section, if they are assigned to a retrieval token then a retrieval cycle is initiated by passing the token to the retrieval section. If a token enters the resource management section and the resources are not available; the token is put into a queue, the token will leave the queue when the resources are free and its turn to use them has arrived.

6. Storage Management

   The storage cycle is executed in this section. When a token arrives it is first assigned an empty slot in the rack, this assignment is given depending on the allocation strategy used, these strategies can be:

   - Closest Channel (CC): The UL will be sent to the closest channel (bay) to the lift, the closest level to the floor in that bay
   - Closest Floor (CF): The UL will be sent to the nearest floor to the ground, the closest channel to the lift on that floor
   - Random Allocation (RND): The UL is sent to a random location in the rack according to a uniform distribution

   After the location is assigned via one of the above mentioned criteria, the storage management section then deploys the vehicles and performs the whole storage cycle, at the end of the cycle; the token is pushed to the database to preserve the UL data.

7. Retrieval Management

   The retrieval management section performs the retrieval cycle, this initiated by pulling a token from the *StoredItems* list in the database section. The vehicles are then set to retrieve the UL that is associated with the pulled token. The retrieval request is performed randomly according to a uniform distribution. After the Retrieval Cycle is complete; the information about the retrieved UL (available in its token) is sent to the *Retrieved Items* list in the database section.

8. Database

   All the information about the UL's available in the tokens is stored in this section. The Database section consists of the following Lists:

   - ***All Items* List:** Stores the token information of every UL that has entered the system, this includes UL's in the rack, storage bay & retrieval bay.
   - ***Stored Items* List:** Stores the Information of every UL currently stored inside the rack, this acts like a rack log, whenever a UL is removed from the rack; its token is removed from this list. This list interacts with: the initialization section to store the *Initial Fill* UL's and with the storage management section to retrieve the data of UL's that have completed a storage cycle. Furthermore; the retrieval management section also selects the UL's to be retrieved from this list.
   - ***Retrieved Items* List:** Stores the information of every UL that has been retrieved, i.e UL's that are currently in the retrieval bay

Figure (3.7) shows a flow chart that illustrates how the process flow module operates in this model & how the above mentioned sections interact with each other.

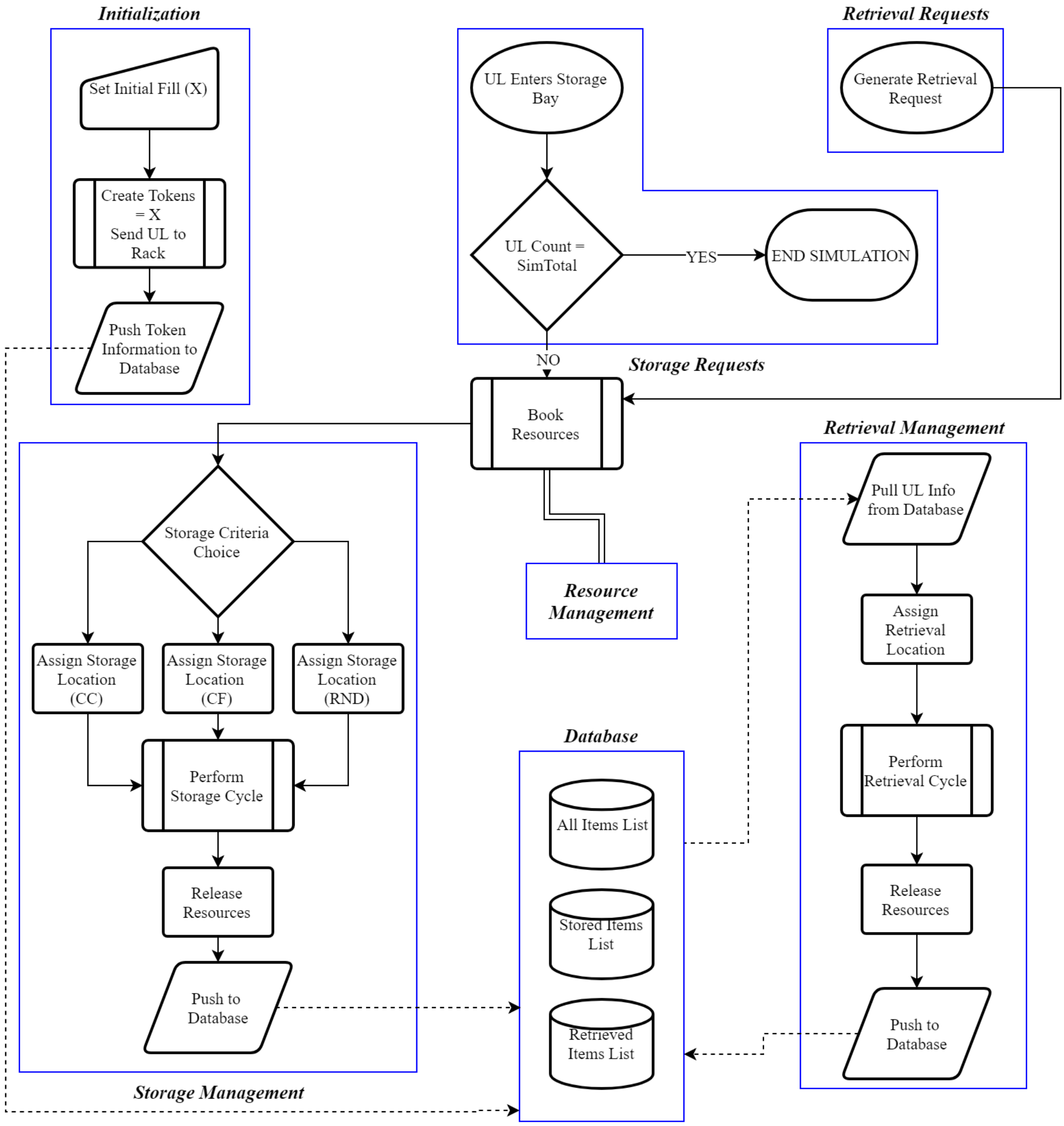


Figure 3.7: Process Flow Operation

Parameter			Layout 1	Layout 2	Layout 3
Rack Size (no. of ULs)	Bays	x	11	22	40
	Cell Capacity	y	19	9	4
	Levels	z	10	10	10
Total			2090	1980	2000
Rack Size (m)	Bay	x	16.5	33	60
	Cell Capacity	y	22.8	10.8	4.8
	Levels	z	21	21	21
Scale factor			0.73	0.33	0.08
UL Size (m)		x		1.5	
		y		1.2	
		z		2	
Vehicles speed (m/s)	Shuttle	x		2	
	Satellite	y		1.2	
	Lift	z		0.2	
Vehicles Acceleration (m/s^2)	Shuttle	x		0.5	
	Satellite	y		0.5	
	Lift	z		0.3	

Table 3.4: Summary of Rack Topologies & Vehicle Parameters

3.5 Plan of Experiments

A set of experiments has been performed to mimic different operating conditions of the AVS/RS system under study, these experiments have been conducted by varying three factors:

- The rack layout
- The storage criteria
- The fill percentage of the rack (amount of UL's already stored in the rack at the start of the process)

3.5.1 Rack Layout

Three different rack layouts have been used in the experiments, each layout has a different scale-factor value (i.e. the ratio between the length and the width of the rack) but the rack height is the same for all three layouts. These layouts have been taken from [9]. Table (3.4) shows the different layouts adopted along with the vehicles kinematic parameters & the UL dimensions.

Parameter	Estimated Fill Percentage	Layout 1	Layout 2	Layout 3
Total		2090	1980	2000
Fill Ratio (No. of ULs)	25%	500	500	400
	50%	1000	1000	800
	75%	1500	1500	1200
	95%	2000	1900	1500

Table 3.5: Summary of Initial Fill Percentages

3.5.2 Storage Criteria

Three different storage criteria have been chosen to test the impact of the allocation strategy on the system performance, these criteria are:

- Closest Channel (CC): The UL will be sent to the closest channel (bay) to the lift, the closest level to the floor in that bay. This criteria utilizes the shuttle more.
- Closest Floor (CF): The UL will be sent to the nearest floor to the ground, the closest channel to the lift on that floor. This criteria utilizes the lift more.
- Random Allocation (RND): The UL is sent to a random location in the rack according to a uniform distribution

3.5.3 Fill Percentage

This factor has been included to evaluate the performance of the AVS/RS under different rack densities, i.e: Will the AVS/RS performance be affected by how full the rack is?. To answer this question four fill percentages have been used in the experiments, these fill percentages along with the number of UL's representative of them are shown in table (3.5). Note that the exact number of ULs is an estimation of the actual percentage.

By varying the above mentioned factors, 36 types of experiments are conducted to evaluate the performance of the system. To ensure the robustness of the results, ten repetitions have been performed for each case. The other elements that characterize the simulations are the following:

1. A sequence of 10,000 ULs is to be stored and the same amount to be retrieved.
2. The ratio between storage and retrieval orders is kept equal to 1 in order to simulate a steady-state scenario.
3. Storage units arrive at time zero.
4. The inter-arrival time of the storage units is $250 \pm x \rightarrow x \sim dU(0, 5)$ seconds.

Experiment Number	**Simulation Identifier**	**Experiment Number**	**Simulation Identifier**
1	L1/CC/25%/500	19	L2/CC/75%/1500
2	L1/CC/50%/1000	20	L2/CF/75%/1500
3	L1/CC/75%/1500	21	L2/RND/75%/1500
4	L1/CC/95%/2000	22	L2/CC/95%/1900
5	L1/CF/25%/500	23	L2/CF/95%/1900
6	L1/CF/50%/1000	24	L2/RND/95%/1900
7	L1/CF/75%/1500	25	L3/CC/25%/400
8	L1/CF/95%/2000	26	L3/CF/25%/400
9	L1/RND/25%/500	27	L3/RND/25%/400
10	L1/RND/50%/1000	28	L3/CC/50%/800
11	L1/RND/75%/1500	29	L3/CF/50%/800
12	L1/RND/95%/2000	30	L3/RND/50%/800
13	L2/CC/25%/500	31	L3/CC/75%/1200
14	L2/CF/25%/500	32	L3/CF/75%/1200
15	L2/RND/25%/500	33	L3/RND/75%/1200
16	L2/CC/50%/1000	34	L3/CC/95%/1500
17	L2/CF/50%/1000	35	L3/CF/95%/1500
18	L2/RND/50%/1000	36	L3/RND/95%/1500

Table 3.6: List of Experiments conducted

5. The inter-arrival time of the retrieval orders is 250 seconds.

6. Only Single command cycles are considered.

To efficiently and easily identify each experiment, the index below has been created, all 36 experiments with their identifiers are shown in table (3.6).

$$A/B/C/X$$

Where:

- A= Rack Layout (A=L1, L2, L3)
- B= Storage Criteria (B= CC, CF, RND)
- C= Estimated Initial Fill Percentage (C= 25%, 50%, 75%, 95%)
- X= Exact Number of Initial ULs Placed

3.6 Collection Methodology of Results

A total of 8 parameters have been tracked and collected from each experiment. As mentioned previously, each experiment is repeated 10 times for the sake of robustness, therefore an average of every 10 simulations runs for the same experiment has been taken. The parameters that have been analyzed and interpreted are:

- Lift Utilization
- Satellite utilization
- Shuttle Utilization
- Number of UL's entering the rack every hour (Input per hour)
- Number of UL's exiting the rack every hour (Output per hour)
- Average value and Standard deviation for Storage Cycle Time
- Average value and Standard deviation for Retrieval Cycle Time
- Average value and Standard deviation for Staytime of UL's in the Rack

The analysis has been conducted using the statistical software package "Minitab". ANOVA (Analysis of variance) has been used as a suitable statistical method to identify the factors that have a significant impact on each of the 8 parameters mentioned above. ANOVA is a collection of statistical models and their associated procedures used to analyze the differences among group means, Analysis of Variance enables to identify the factors that have a significant impact on the output.

The Outputs Obtained from the Analysis of variance for each of the previously mentioned parameters along with other supporting graphs and tools to better validate and interpret the statistical data will presented in the next chapter.

Chapter 4

Results

4.1 Overview

In this chapter the results obtained by the simulation experiments conducted will be presented, as mentioned previously 3 factors have been varied in the simulations to assess the performance of an AVS/RS system, these factors are: Layout of the rack, Criteria employed for the insertion of unit loads into the Rack & the number of items already available in the rack from startup.

For each of the performance measures ANOVA tables will be presented to determine whether the association between the response and each term in the model is statistically significant i.e. what are the factors that mostly influence each of the previously mentioned responses. Secondly boxplots which provide a graphical summary of the data distribution will be used to examine the center & spread of Data. Finally, by the usage of residual plots; the validity of the model and the assumptions of the analysis have been verified.

For all the Conducted ANOVA tests; the Value of R^2 & the adjusted R^2 are above 93% except for the Standard Deviation of the UL Staytime where the adjusted R^2 is 78%. As a result, it is safe to say that the statistical model fits the data to a very high extent, and that for most of the responses the model can explain 93% of the variation.

In the ANOVA analysis the main effects and the two-way interactions have been included, the rows of all the significant factors ($P < \alpha = 0.05$) are shown in **Bold**.

For each of the Boxplots presented in this section, the following index (table 4.1) is used in the x-axis to identify the different values of each of the three factors varied in the simulations:

Factor	Value	Boxplot Index
Rack Layout	Layout 1	1
	Layout 2	2
	Layout 3	3
Storage Criteria	CC	1
	CF	2
	RND	3
Fill Perentage	25%	1
	50%	2
	75%	3
	95%	4

Table 4.1: Boxplots x-axis Index

The following model assumptions can be verified from each of the residual plots (Figures 4.1d to 4.11d) found in the results:

1. Residuals vs fits plot: Verifies the Assumptions that the residuals are randomly distributed and have constant variance
2. Residuals vs order plot: verifies the assumption that the residuals are independent from one another
3. Normal probability plot: verifies the assumption that the residuals are normally distributed
4. Histogram of Residuals: shows that the data is not skewed and does not include significant outliers

By verifying each of the above assumptions, it is possible to determine that the statistical model is adequate and meets the assumptions of the analysis.

4.2 Vehicles Utilization

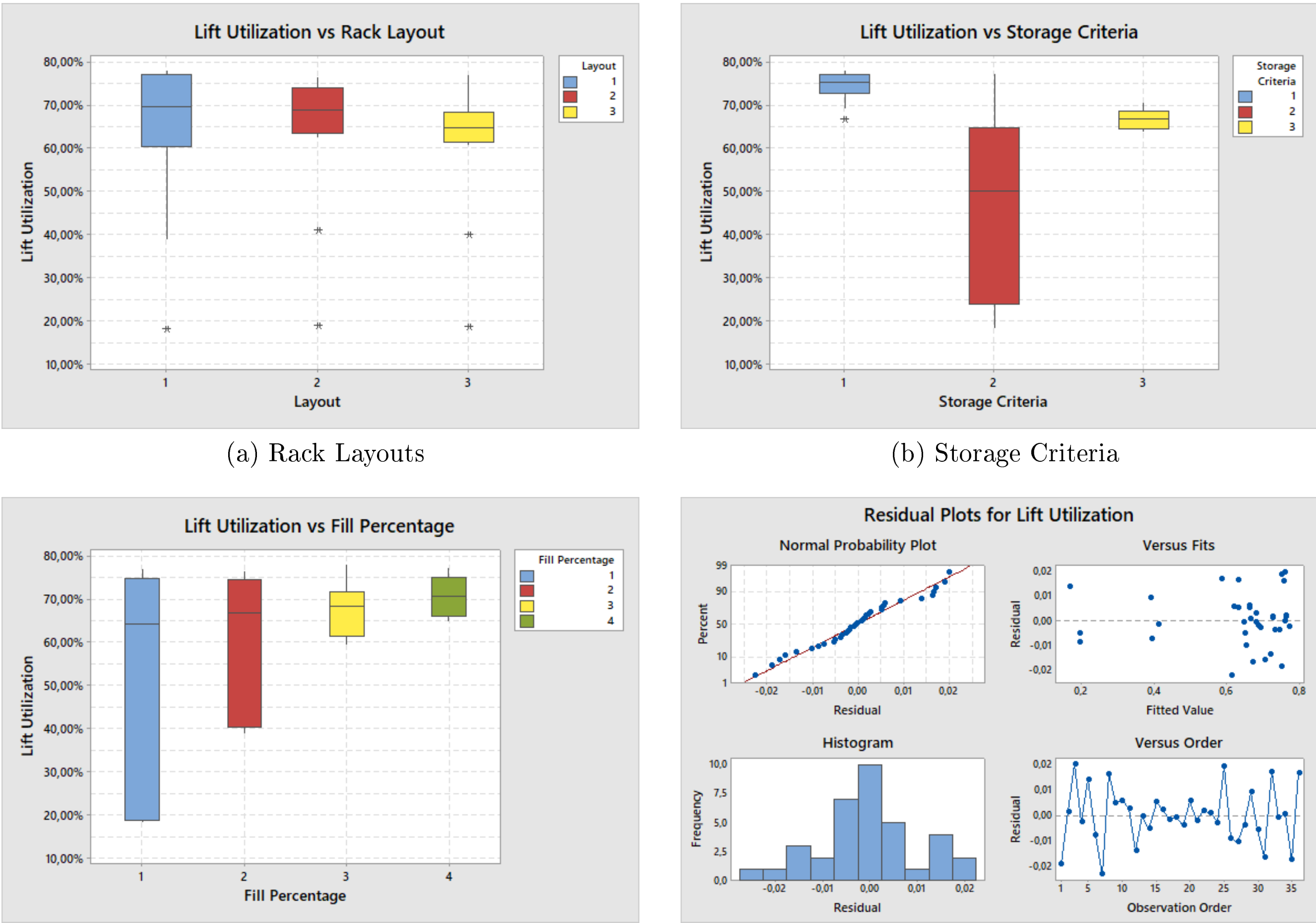
4.2.1 Lift Utilization

It is Evident from table (4.2) that all three main factors have a significant impact on the lift utilization in addition to the Interaction effects of Layout*Fill Percentage & storage criteria*fill percentage. Figure 4.1a shows similar medians of lift utilization of around 67% for all three layouts but several outliers exist. High variability is present in the data when using Storage criteria 2 (CF) (figure 4.1b) in addition to a high median with the other two criteria. A similar behavior is evident in figure 1c where a high spread occurs when the rack is 25% and 50% full but the medians are very similar.

Source	DF	SS	MS	F	P
Layout	**2**	**0,008543**	**0,004272**	**12,86**	**0,001**
Storage Criteria	**2**	**0,445313**	**0,222657**	**670,54**	**<0,001**
Fill Percentage	**3**	**0,165793**	**0,055264**	**166,43**	**<0,001**
Layout*Storage Criteria	4	0,000878	0,000219	0,66	0,631
Layout*Fill Percentage	**6**	**0,009786**	**0,001631**	**4,91**	**0,009**
Storage Criteria*Fill Percentage	**6**	**0,336895**	**0,056149**	**169,10**	**<0,001**
Error	12	0,003985	0,000332		
Total	35	0,971192			

Table 4.2: ANOVA for Lift Utilization

S = 0,0182224
R^2 = 99,59%
R^2(adj) = 98,80%



(a) Rack Layouts

(b) Storage Criteria

(c) Fill Percentages

(d) Residual Plots

Figure 4.1: Lift Utilization Boxplots & Residual Plots

4.2.2 Shuttle Utilization

All the main factors have a significant effect on the Shuttle utilization, all interactions except Layout*Fill Ratio are also significant. In figure 4.2a; the medians vary between the three layouts with layout 3 providing the highest utilization of the shuttle although an outlier exists. A high variation occurs for all insertion criteria with storage criteria 2 giving the highest shuttle utilization (Figure 4.2b). Figure 4.2c also shows a high variation but similar variation for all fill ratio's. It is evident from these boxplots that the maximum shuttle utilization achievable in all variations is just below 30%.

Source	DF	SS	MS	F	P
Layout	**2**	**0,0982554**	**0,0491277**	**298,46**	**<0,001**
Storage Criteria	**2**	**0,0170061**	**0,0085031**	**51,66**	**<0,001**
Fill Percentage	**3**	**0,0038205**	**0,0012735**	**7,74**	**0,004**
Layout*Storage Criteria	**4**	**0,0051087**	**0,0012772**	**7,76**	**0,003**
Layout*Fill Percentage	6	0,0004013	0,0000669	0,41	0,861
Storage Criteria*Fill Percentage	6	**0,0086106**	**0,0014351**	**8,72**	**0,001**
Error	12	0,0019753	0,0001646		
Total	35	0,1351779			

Table 4.3: ANOVA Results for Shuttle Utilization

S = 0,0128299
R^2 = 98,54%
R^2(adj) = 95,74%

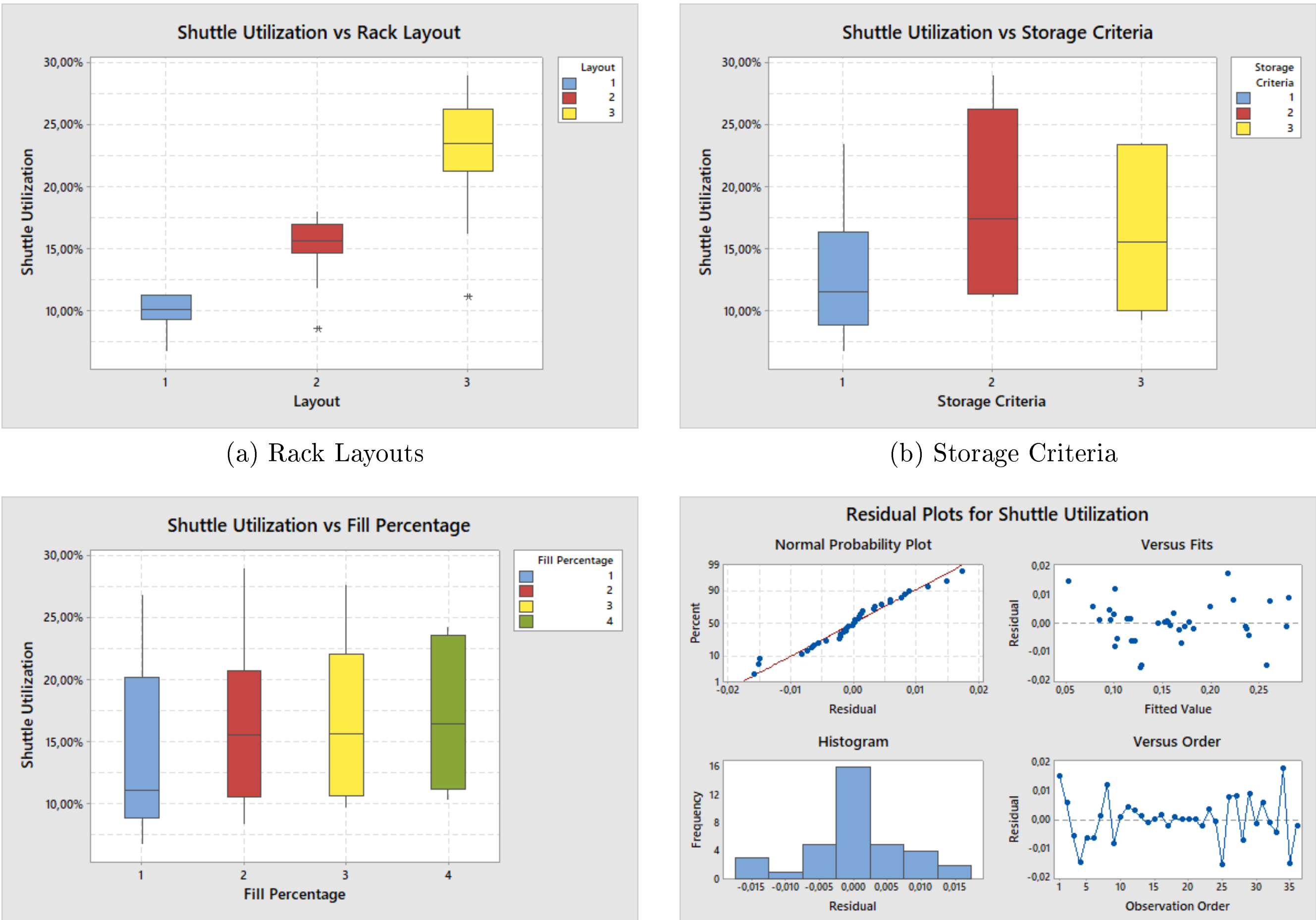
4.2.3 Satellite Utilization

All three factors have significant effect on the Satellite utilization in addition to the interaction of the Rack Layout with the insertion criteria. From Figure (4.3): It is evident that satellite utilization is low for all possible combinations of layout, insertion criteria and fill percentage, A relatively high variability is shown for layout 1 (Figure 4.3a) and Insertion Criteria 3 (Figure 4.3b) (RND). In Figure 4.3c a single outlier (which better utilizes the satellite) exists in each Rack fill percentage.

Source	DF	SS	MS	F	P
Layout	**2**	**0,0118386**	**0,0059193**	**62,74**	**<0,001**
Storage Criteria	**2**	**0,0236774**	**0,0118387**	**125,49**	**<0,001**
Fill Percentage	**3**	**0,0024141**	**0,0008047**	**8,53**	**0,003**
Layout*Storage Criteria	**4**	**0,0126446**	**0,0031611**	**33,51**	**<0,001**
Layout*Fill Percentage	6	0,0003740	0,0000623	0,66	0,683
Storage Criteria*Fill Percentage	6	0,0008637	0,0001439	1,53	0,251
Error	12	0,0011321	0,0000943		
Total	35	0,0529443			

Table 4.4: ANOVA Results for Satellite Utilization

S = 0,00971295
R^2 = 97,86%
R^2(adj) = 93,76%



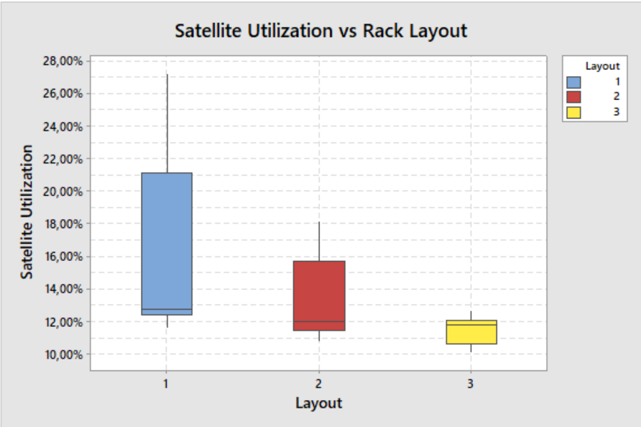
(a) Rack Layouts

(b) Storage Criteria

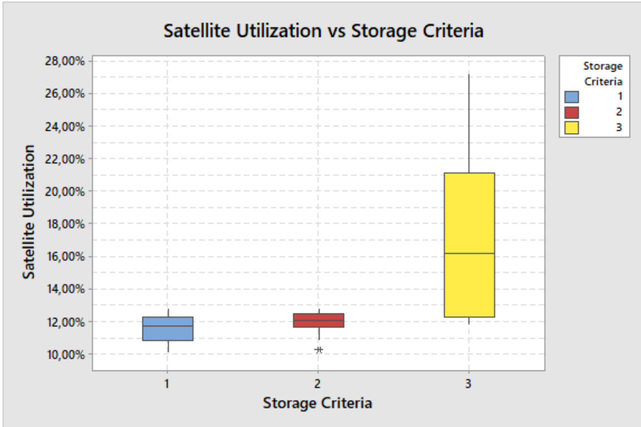
(c) Fill Percentage

(d) Residual Plots

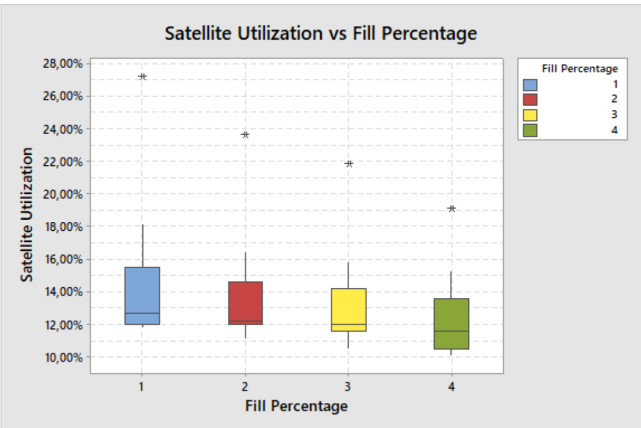
Figure 4.2: Shuttle Utilization Boxplots & Residual Plots



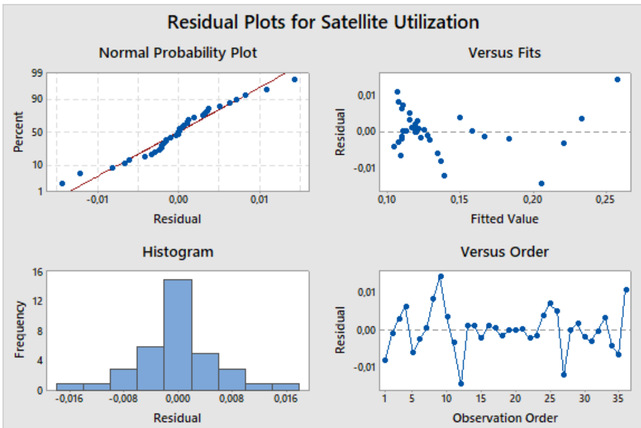
(a) Rack Layouts



(b) Storage Criteria



(c) Fill Percentages



(d) Residual Plots

Figure 4.3: Satellite Utilization Boxplots & Residual Plots

4.3 Rack Throughput

4.3.1 Input per hour (UL/h)

All Main effects and interactions have significant effect on the Rate of UL's entering the rack. The spread is Similar for the three rack layouts (figure 4.4a) with layout 3 having a slightly lower median than the other two. In figure 4b the median of Insertion criteria 3 (RND) with a value of 13.4 UL/h is much lower than the median of criteria one and two. The variation of the data For the Initial Rack fill percentage (figure 4.4c) is also high with the majority of the spread in the 2nd quartile, it is also evident that when the rack is 25% full (fill ratio=1) the data is severely skewed.

Source	DF	SS	MS	F	P
Layout	**2**	**10,5330**	**5,2665**	**137,43**	**<0,001**
Storage Criteria	**2**	**33,2024**	**16,6012**	**433,22**	**<0,001**
Fill Percentage	**3**	**7,3757**	**2,4586**	**64,16**	**<0,001**
Layout*Storage Criteria	**4**	**1,1970**	**0,2992**	**7,81**	**0,002**
Layout*Fill Percentage	**6**	**4,6201**	**0,7700**	**20,09**	**<0,001**
Storage Criteria*Fill Percentage	**6**	**3,9667**	**0,6611**	**17,25**	**<0,001**
Error	12	0,4598	0,0383		
Total	35	61,3548			

Table 4.5: ANOVA Results for Inputs per Hour

S = 0,195757
R^2 = 99,25%
R^2(adj) = 97,81%

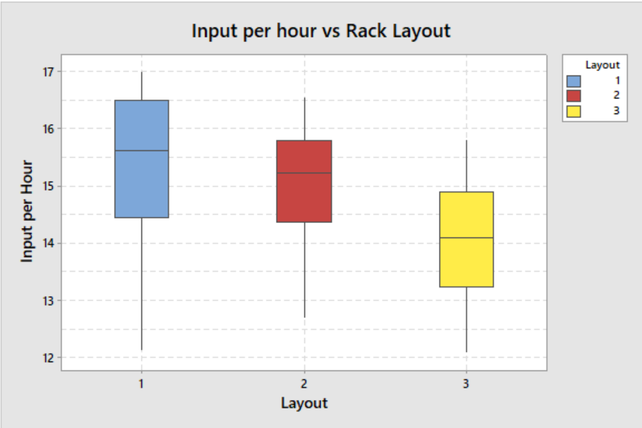
4.3.2 Output per hour (UL/h)

All Main effects and interactions have significant effect on the Rate of UL's exiting the rack. The rates of output per hour are highly spread for the three rack layouts (Figure 4.5a) with a severe skew occurring in layout 1, the medians are also quite different. In figure 4.5b Insertion criteria 2 (CF) gives the highest output rate and the least variability but two outliers exist. When comparing Output rate with the Rack fill percentage (figure 4.5c) a high spread is occurrent. In addition, when the rack is 25% full (Fill ratio=1) the data is severely skewed.

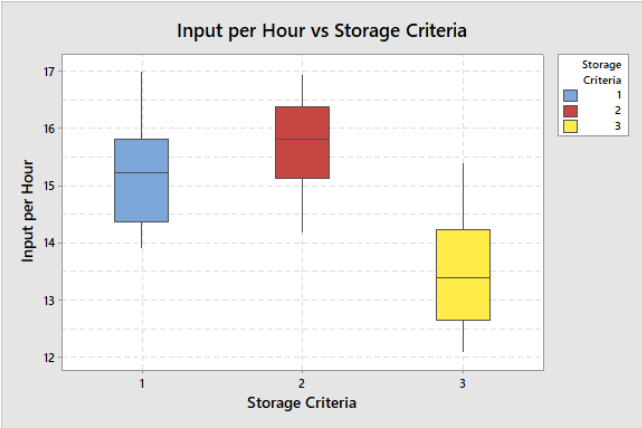
Source	DF	SS	MS	F	P
Layout	**2**	**4,0361**	**2,0181**	**67,05**	**<0,001**
Storage Criteria	**2**	**27,2800**	**13,6400**	**453,19**	**<0,001**
Fill Percentage	**3**	**1,7704**	**0,5901**	**19,61**	**<0,001**
Layout*Storage Criteria	**4**	**0,9581**	**0,2395**	**7,96**	**0,002**
Layout*Fill Percentage	**6**	**2,0371**	**0,3395**	**11,28**	**<0,001**
Storage Criteria*Fill Percentage	**6**	**4,0085**	**0,6681**	**22,20**	**<0,001**
Error	12	0,3612	0,0301		
Total	35	40,4514			

Table 4.6: ANOVA Results for Output per Hour

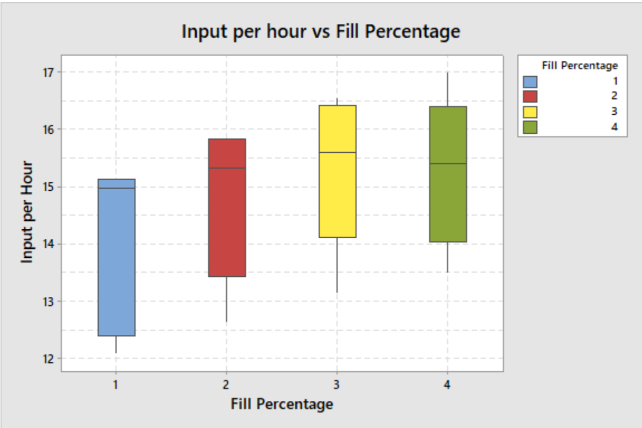
S = 0,173488
R^2 = 99,11%
R^2(adj) = 97,40%



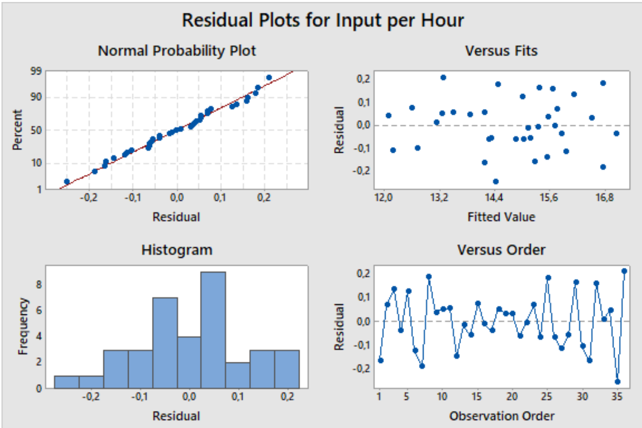
(a) Rack Layouts



(b) Storage Criteria

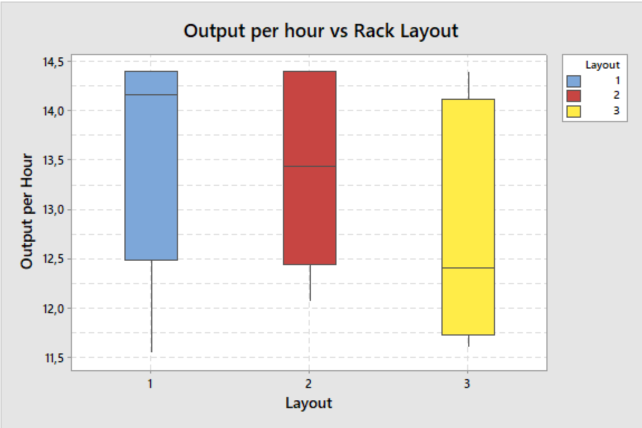


(c) Fill Percentages

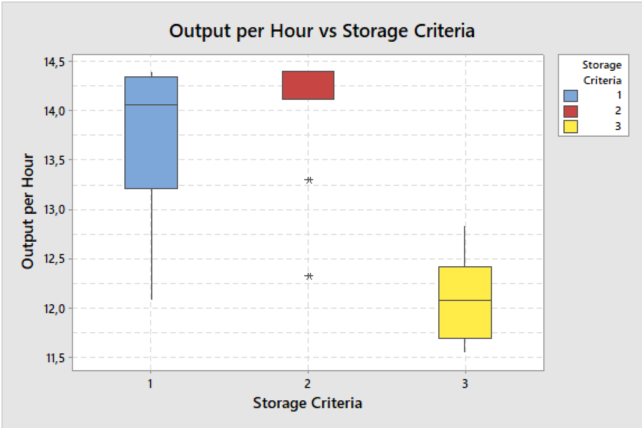


(d) Residual Plots

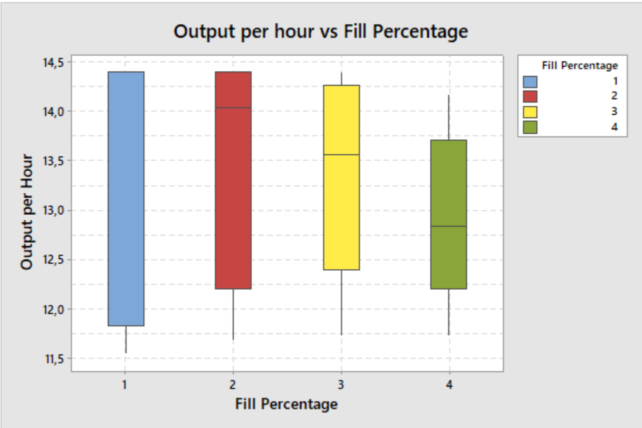
Figure 4.4: Rack Input per hour Boxplots & Residual Plots



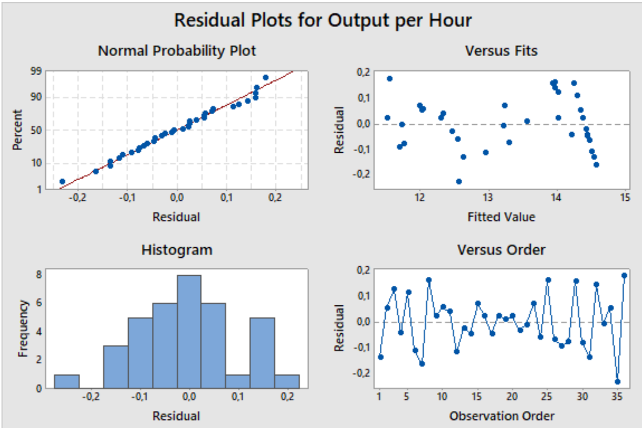
(a) Rack Layouts



(b) Storage Criteria



(c) Fill Percentages



(d) Residual Plots

Figure 4.5: Rack Output per hour Boxplots & Residual Plots

4.4 Storage Cycle Time

4.4.1 Average Storage Cycle Time

All the main factors have a significant effect on the Average storage cycle time, all interactions except Layout*Fill Ratio are also significant. In figure 4.6a it is evident that the medians are similar for all the rack configurations but layout 1 has a higher spread than the others, an outlier exists for layouts 2 & 3. When looking at the Storage cycle time vs the insertion criteria (figure 4.6b) a divergence between the medians is witnessed and high variability in Insertion criteria 2 (CF) but the lowest cycle time also occurs when using this criterion. A similar behavior can be seen in figure 4.6c with Fill Ratio 1.

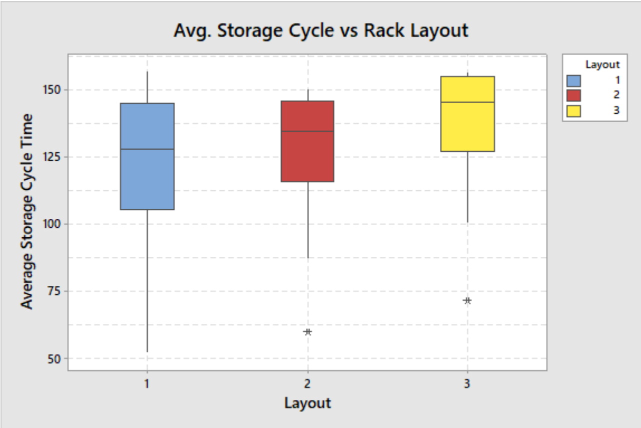
Source	DF	SS	MS	F	P
Layout	**2**	**349,20**	**174,60**	**152,06**	**<0,001**
Storage Criteria	**2**	**3911,16**	**1955,58**	**1703,08**	**<0,001**
Fill Percentage	**3**	**1003,24**	**334,41**	**291,23**	**<0,001**
Layout*Storage Criteria	**4**	**61,80**	**15,45**	**13,46**	**<0,001**
Layout*Fill Percentage	6	13,30	2,22	1,93	0,157
Storage Criteria*Fill Percentage	**6**	**1533,39**	**255,56**	**222,57**	**<0,001**
Error	12	13,78	1,15		
Total	35	6885,87			

Table 4.7: ANOVA Results for Average Storage Cycle Time

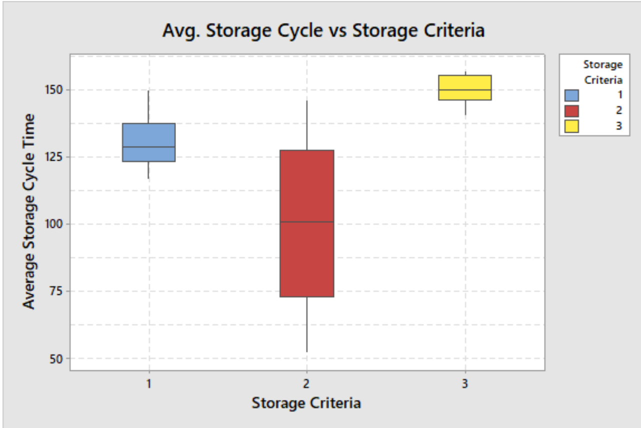
S = 1,07157
R^2 = 99,80%
R^2(adj) = 99,42%

4.4.2 Standard Deviation of Storage Cycle Time

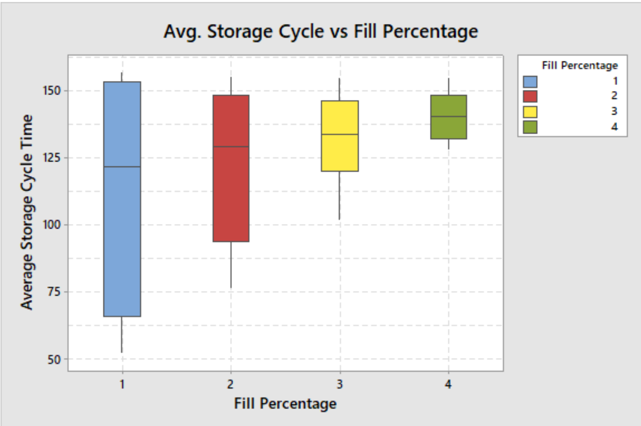
All the main factors have a significant effect on the Standard Deviation of the Storage Cycle, the interaction of Storage criteria & Fill ratio is also significant. The boxplot in figure 4.7a show similar characteristics for all three layouts; the spread, median, skewness and outliers are alike, it is also evident that the three outliers are from the same source (CF storage & a 25% Rack fill percentage on startup). In figure 4.7b it can be noticed that insertion criteria's 1 & 3 (CC & RND respectively) exhibit low spread and high medians, however the data corresponding to Insertion Criteria 2 (CF) is highly spread but with a much lower median. Figure 4.7c shows similar medians in all four Rack fill percentages but the spreads are very different with Fill ratio 1 having the highest variability of data and fill ratio 4 the lowest, it can also be seen that the data for Fill ratio's 1,2 & 3 is severely skewed.



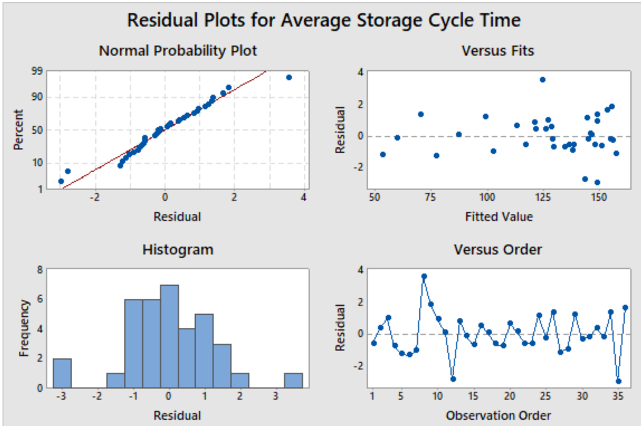
(a) Rack Layouts



(b) Storage Criteria



(c) Fill Percentages



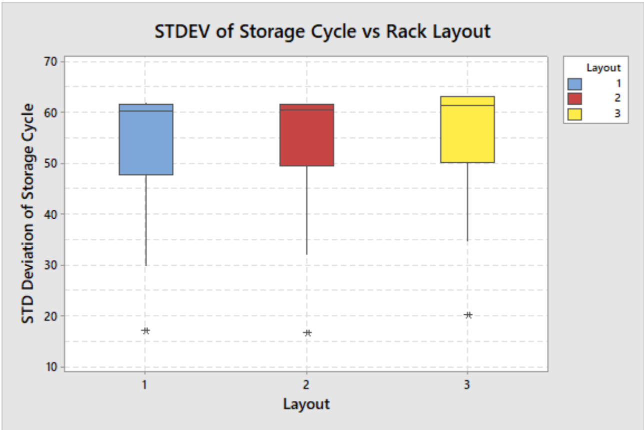
(d) Residual Plots

Figure 4.6: Average Storage Cycle Boxplots & Residual Plots

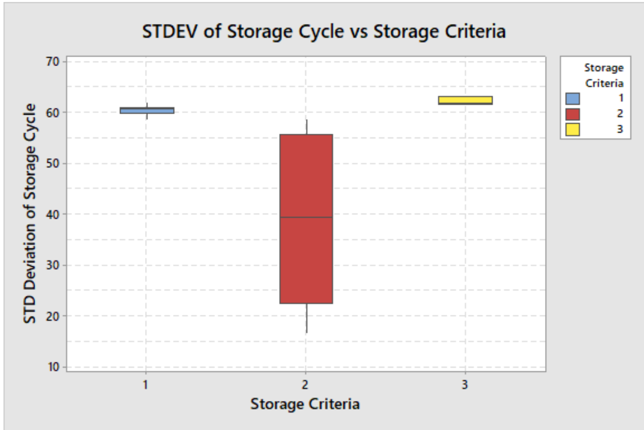
Source	DF	SS	MS	F	P
Layout	**2**	**5,916**	**2,958**	**15,21**	**0,001**
Storage Criteria	**2**	**1043,407**	**521,703**	**2682,24**	**<0,001**
Fill Percentage	**3**	**246,576**	**82,192**	**422,57**	**<0,001**
Layout*Storage Criteria	4	0,637	0,159	0,82	0,538
Layout*Fill Percentage	6	0,416	0,069	0,36	0,893
Storage Criteria*Fill Percentage	**6**	**452,538**	**75,423**	**387,77**	**<0,001**
Error	12	2,334	0,195		
Total	35	1751,823			

Table 4.8: ANOVA Results for Standard Deviation of Storage Cycle Time

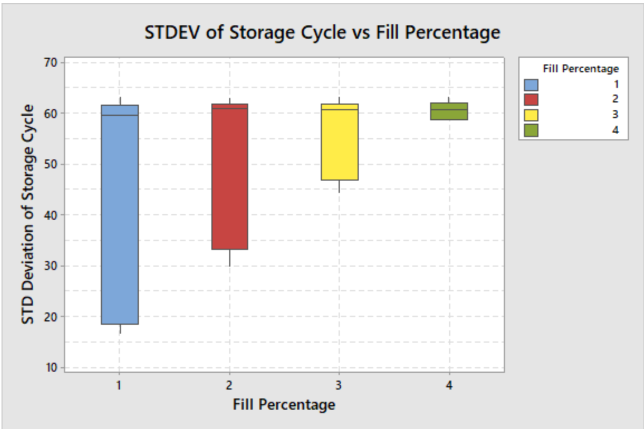
S = 0,441025
R^2 = 99,87%
R^2(adj) = 99,61%



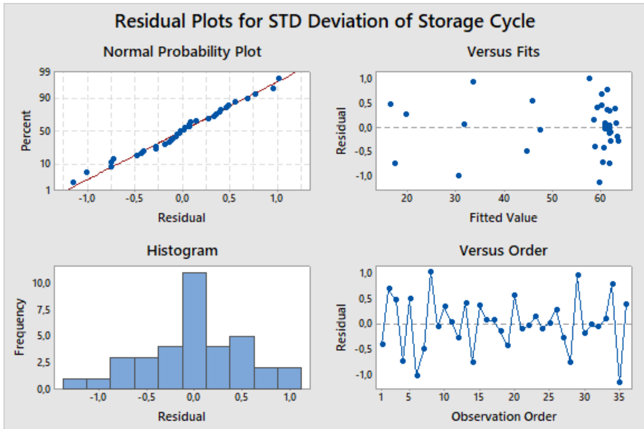
(a) Rack Layouts



(b) Storage Criteria



(c) Fill Percentages



(d) Residual Plots

Figure 4.7: Standard Deviation of storage Cycle time Boxplots & Residual Plots

4.5 Retrieval Cycle Time

4.5.1 Average Retrieval Cycle Time

All the main factors have a significant effect on the Average Retrieval cycle time, all interactions except Layout*Fill Percentage are also significant. The data given for average retrieval times for all 3 layouts (figure 4.8a) is similar with a spread of about 70 seconds and a significant outlier in each layout, also it should be noted that the 3 outliers are of similar origin (Insertion criteria 2 and the rack is 25% full on startup for all 3). When comparing the average retrieval time with the insertion criteria used and the initial Fill percentage (figures 4.8b & 4.8c), it can be clearly noticed that the shape, central tendency, and the variability of the data is almost identical to figures 4.6b & 4.6c (Average Storage cycle) respectively.

Source	DF	SS	MS	F	P
Layout	**2**	**358,46**	**179,23**	**72,57**	**<0,001**
Storage Criteria	**2**	**3420,22**	**1710,11**	**692,38**	**<0,001**
Fill Percentage	**3**	**915,52**	**305,17**	**123,56**	**<0,001**
Layout*Storage Criteria	**4**	**61,68**	**15,42**	**6,24**	**0,006**
Layout*Fill Percentage	6	22,03	3,67	1,49	0,263
Storage Criteria*Fill Percentage	**6**	**1495,97**	**249,33**	**100,95**	**<0,001**
Error	12	29,64	2,47		
Total	35	6303,52			

Table 4.9: ANOVA Results for Average Retrieval Cycle Time

S = 1,57159
R^2 = 99,53%
R^2(adj) = 98,63%

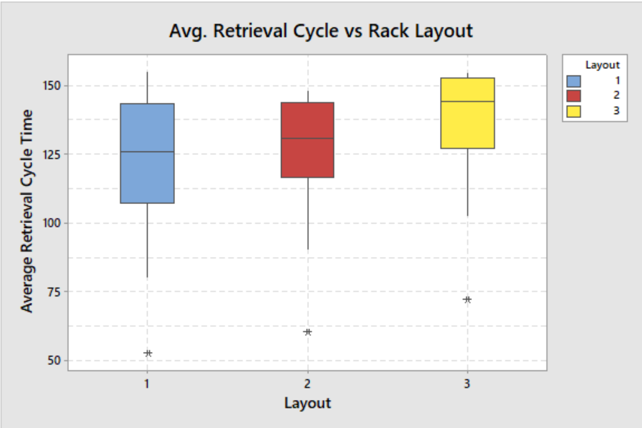
4.5.2 Standard Deviation of Retrieval Cycle Time

Insertion Criteria & Rack Initial Fill percentage have significant effect on the Standard Deviation of Retrieval Cycle, the Interaction of Insertion Criteria and Fill Ratio is also Significant. Figure 4.9a is similar to figure 4.8a (Standard deviation of storage cycle vs layout) but exhibits a fairly lower data spread. Figure 4.9b is also similar to figure 4.8b in terms of spread and skewness however an outlier exists in the data of insertion criteria 1 (CC). It can also be seen in figure 4.9c that the characteristics of the boxplots are almost like figure 4.8c but with more spread in the top 25% of values in the data of fill ratio 3.

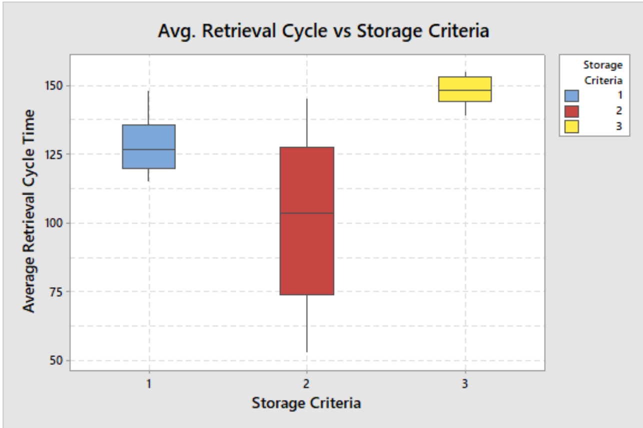
Source	DF	SS	MS	F	P
Layout	2	0,139	0,070	0,13	0,881
Storage Criteria	**2**	**539,370**	**269,685**	**496,18**	**<0,001**
Fill Percentage	**3**	**137,688**	**45,896**	**84,44**	**<0,001**
Layout*Storage Criteria	4	5,170	1,293	2,38	0,110
Layout*Fill Percentage	6	3,355	0,559	1,03	0,453
Storage Criteria*Fill Percentage	**6**	**231,320**	**38,553**	**70,93**	**<0,001**
Error	12	6,522	0,544		
Total	35	923,566			

Table 4.10: ANOVA Results for Standard Deviation of Retrieval Cycle Time

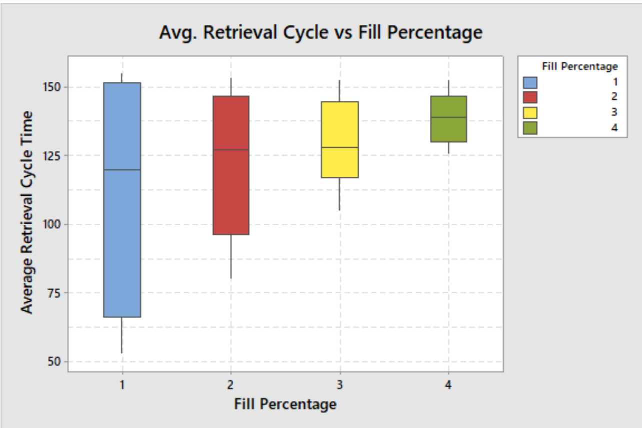
S = 0,737241
R^2 = 99,29%
R^2(adj) = 97,94%



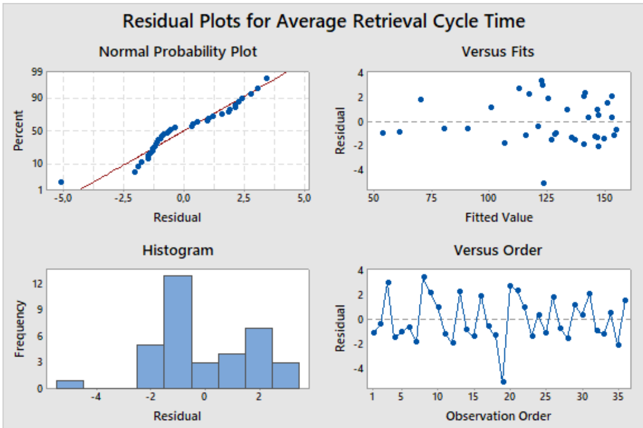
(a) Rack Layouts



(b) Storage Criteria

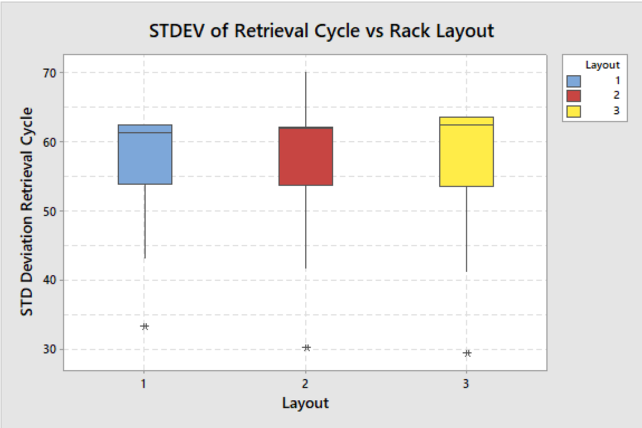


(c) Fill Percentages

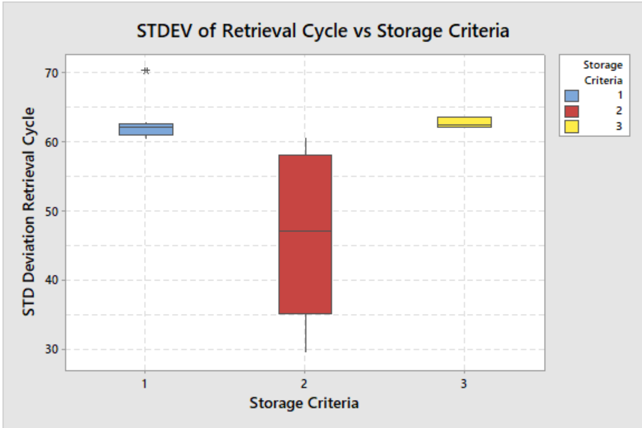


(d) Residual Plots

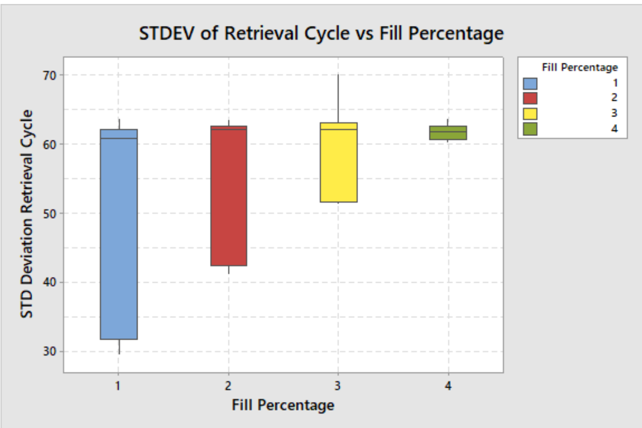
Figure 4.8: Average Retrieval Cycle Boxplots & Residual Plots



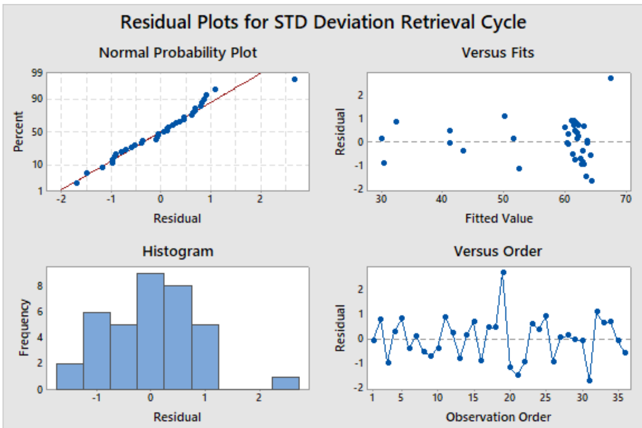
(a) Rack Layouts



(b) Storage Criteria



(c) Fill Percentages



(d) Residual Plots

Figure 4.9: Standard Deviation of Retrieval Cycle Boxplots & Residual Plots

4.6 Staytime of UL in the Rack

4.6.1 Average Staytime

All the main factors have a significant effect on the Staytime of the UL's in the Rack, all interactions except Layout*Fill Percentage are also significant. Figure 4.10a shows a variability of the data for all three Layouts and an outlier is present in layout 3, in addition the data is skewed with layout 1 having the highest degree of skewness. In figure 4.10b it can been noticed that Insertion criteria's 1 & 2 (CC & CF) have similar medians and spread, in the same figure; the data of criteria 3 shows much higher variability and median than the other two criterion's. An extremely high spread is witnessed in figure 4.10c when the fill Ratios are 3 & 4 (Rack is 75% & 95% full at startup respectively), for the other values of fill ratio the spread is much less but all four medians are relatively close.

Source	DF	SS	MS	F	P
Layout	**2**	**5608215550**	**2804107775**	**25,39**	**<0,001**
Storage Criteria	**2**	**4,90426E+11**	**2,45213E+11**	**2220,66**	**<0,001**
Fill Percentage	**3**	**1,00927E+11**	**33642441253**	**304,67**	**<0,001**
Layout*Storage Criteria	**4**	**13703027554**	**3425756888**	**31,02**	**<0,001**
Layout*Fill Percentage	6	1964622368	327437061	2,97	0,052
Storage Criteria*Fill Percentage	**6**	**74419870038**	**12403311673**	**112,33**	**<0,001**
Error	12	1325080699	110423392		
Total	35	6,88374E+11			

Table 4.11: ANOVA Results for Average Staytime

S = 10508,3
R^2 = 99,81%
R^2(adj) = 99,44%

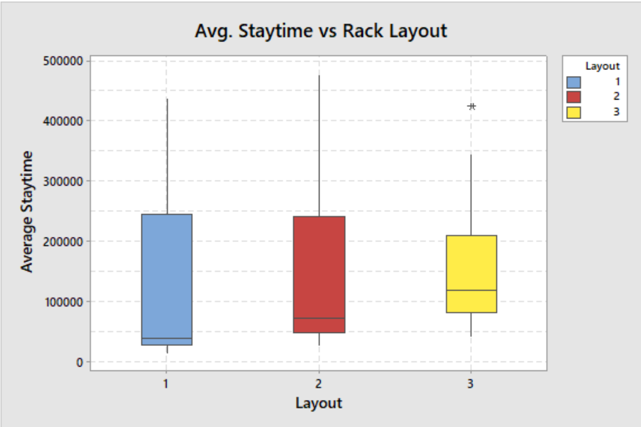
4.6.2 Standard Deviation of Staytime

All the main factors have a significant effect on the Standard Deviation of Staytime, all interactions except Layout*Fill Percentages are also significant. Figure 4.11 shows a Low degree of variability of the data corresponding to the standard deviations of the staytime for all possible combinations of Layout, Insertion criteria and Rack Initial Fill Percentage with extreme outliers in some cases. It is also noticable that the medians for Figures 4.11a & 4.11c are relatively similar.

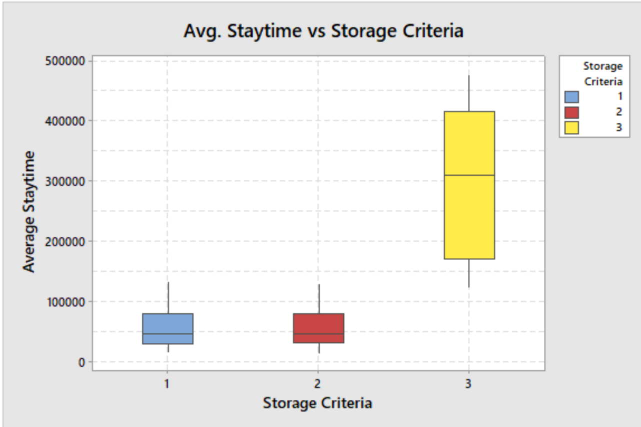
Source	DF	SS	MS	F	P
Layout	2	34763043	17381521	0,02	0,979
Storage Criteria	**2**	**8993635623**	**4496817811**	**5,41**	**0,021**
Fill Percentage	**3**	**45689983966**	**15229994655**	**18,32**	**<0,001**
Layout*Storage Criteria	**4**	**45311517400**	**11327879350**	**13,62**	**<0,001**
Layout*Fill Percentage	6	3381607703	563601284	0,68	0,671
Storage Criteria*Fill Percentage	**6**	**20924236747**	**3487372791**	**4,19**	**0,017**
Error	12	9977202429	831433536		
Total	35	1,34313E+11			

Table 4.12: ANOVA Results for Standard Deviation of Staytime

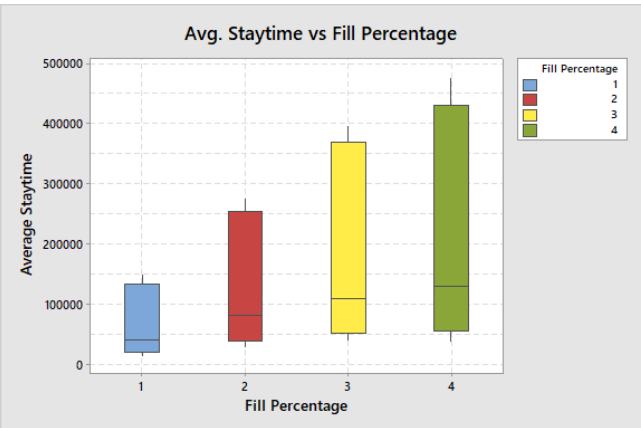
S = 28834,6
R^2 = 92,57%
R^2(adj) = 78,33%



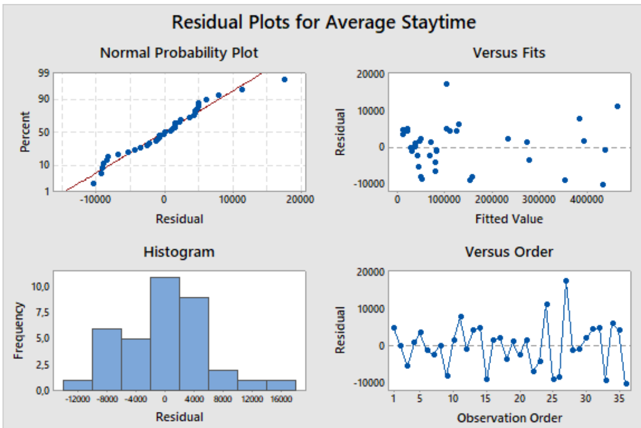
(a) Rack Layouts



(b) Storage Criteria

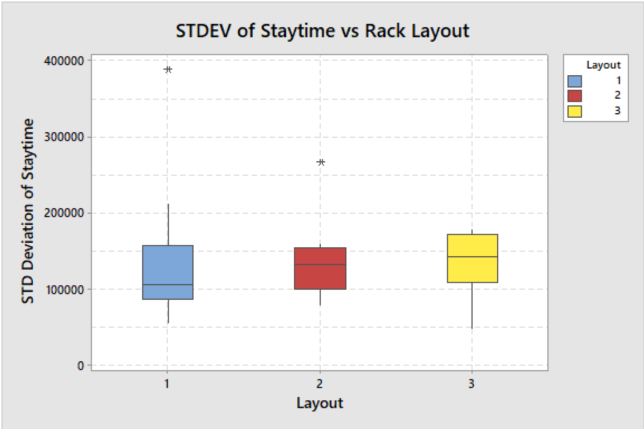


(c) Fill Percentages

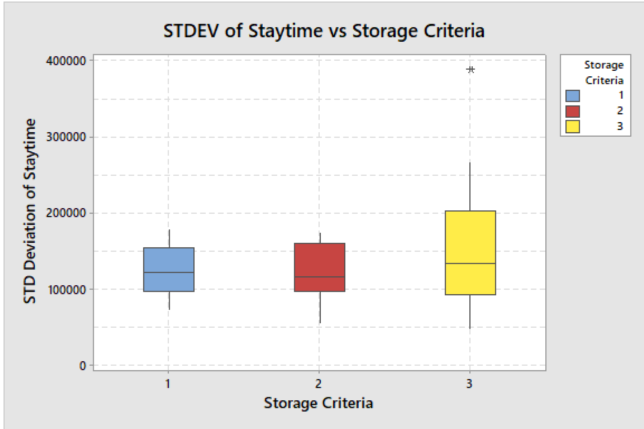


(d) Residual Plots

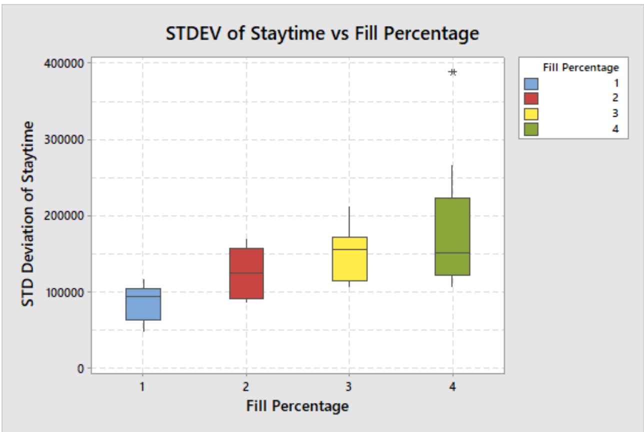
Figure 4.10: Average Staytime Boxplots & Residual Plots



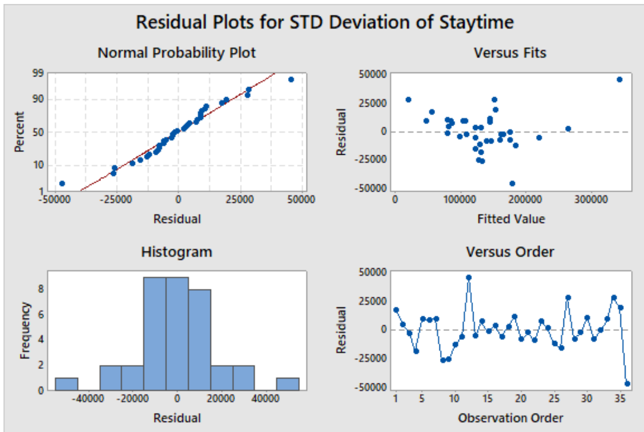
(a) Rack Layouts



(b) Storage Criteria



(c) Fill Percentages



(d) Residual Plots

Figure 4.11: Standard Deviation of Staytime Boxplots & Residual Plots

4.7 Results Summary & Discussion

The ANOVA test has been performed for each performance measure, however in order to interpret the ANOVA results; the model adequacy should be met, this has been verified via each of the residual plots as mentioned previously. The statistically significant interaction and main effects that have been obtained via the ANOVA are summarized in table (4.13) ("S" denotes the statistically significant and "I" denotes that no proof of statistical significance was found from the ANOVA analysis).

Effects	Lift Utilization	Shuttle Utilization	Satellite Utilization	Input per hour (UL/h)	Output per hour (UL/h)	Average Storage Cycle Time	Standard Deviation of Storage Cycle Time	Average Retrieval Cycle Time	Standard Deviation of Retrieval Cycle Time	Average Staytime	Standard Deviation of Staytime
Layout	S	S	S	S	S	S	S	S	I	S	I
Storage Criteria	S	S	S	S	S	S	S	S	S	S	S
Fill Percentage	S	S	S	S	S	S	S	S	S	S	S
Layout * Storage Criteria	I	S	S	S	S	S	I	S	I	S	S
Layout * Fill Percentage	S	I	I	S	S	I	I	I	I	I	I
Storage Criteria * Fill Percentage	S	S	I	S	S	S	S	S	S	S	S

Table 4.13: Summary of ANOVA Tests

From the results of the ANOVA tests the following can be elucidated:

- We can assume that all main factors have a significant effect on the utilization of all three vehicles, with the storage criteria being the most significant factor affecting the responses of the Lift & satellite, this is because the F-value of the storage criteria is the highest among the other F-values, this variation due to storage criteria can be seen in figure(4.12). However for the shuttle; the Layout factor is the most dominant with an F-value of 125,49. This can also be be verified graphically in figure (4.13).
- The Interaction effect "Layout*Storage Criteria" is significant for all three vehicles, with the Lift & shuttle having an additional significant two-way interaction of "Storage Criteria*Fill percentage".
- A summary of the vehicle utilizations is shown in figure (4.14), this figure shows the average Utilization of each vehicle for each simulation run with the descending order of lift utilization. It can be shown that the Lift utilization exhibits high variability with respect to the other two vehicles. By examining the higher values of the graph for lift utilization (left part of the graph); it can be seen that the Lift is more utilized when using the storage criteria CC (closest channel), this is expected due to the fact that the lift will need to travel more to the higher levels when using this storage criteria.

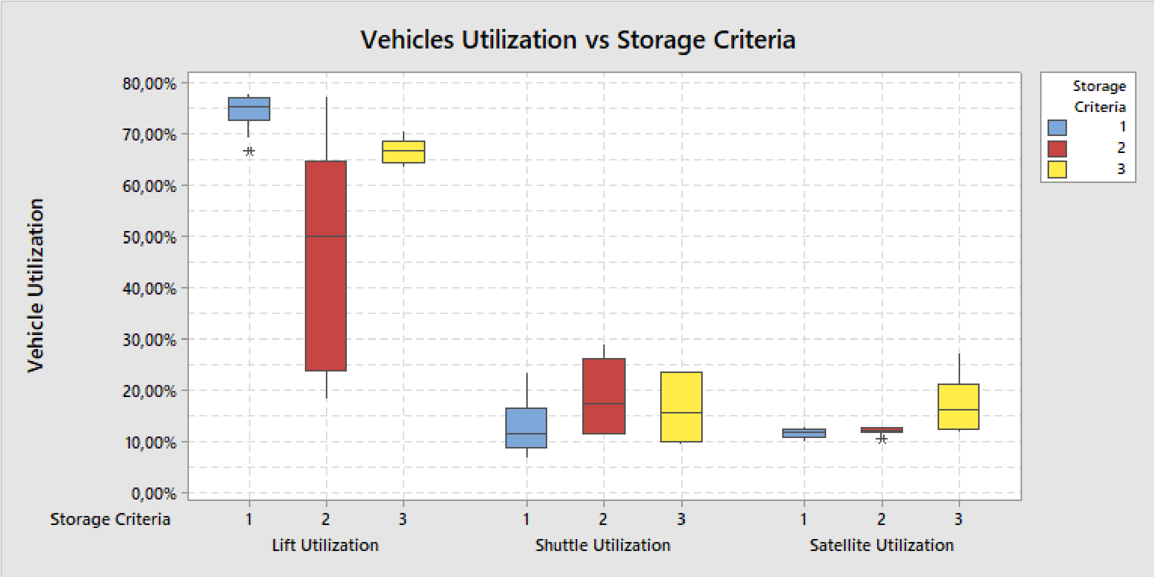


Figure 4.12: Boxplot of Vehicles Utilization with respect to Storage Criteria

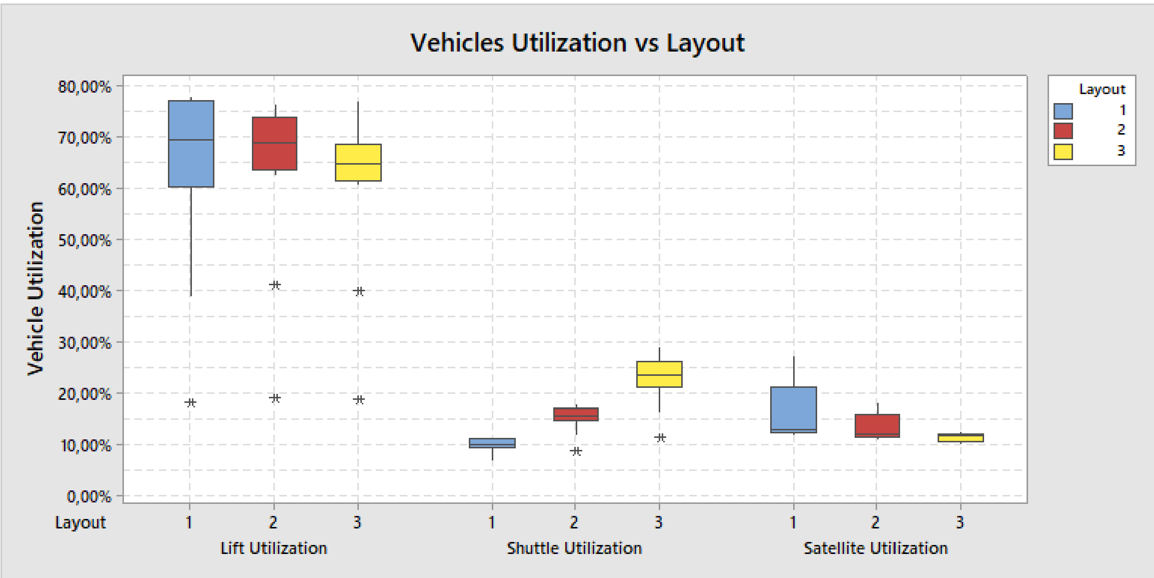


Figure 4.13: Boxplot of Vehicles Utilization with respect to Rack Layout

- In regards to the Rack throughput (UL/h); All main & effects and interactions have a significant impact. The storage criteria here is also the most significant factor with the highest F-value for both Inputs per hour & Outputs per hour, Figure (4.15) shows this variation of rack throughput with respect to the storage criteria employed.

- The ANOVA tests for storage cycle indicated that all the main factors have significant impact with the storage criteria being the most significant for both the average value and standard deviation of the storage cycle. Some Interaction effects are also significant with "Storage criteria* Fill percentage" occurring in both ANOVA tables.

- The Results for the retrieval cycle indicate a similar behavior to the storage cycle results,

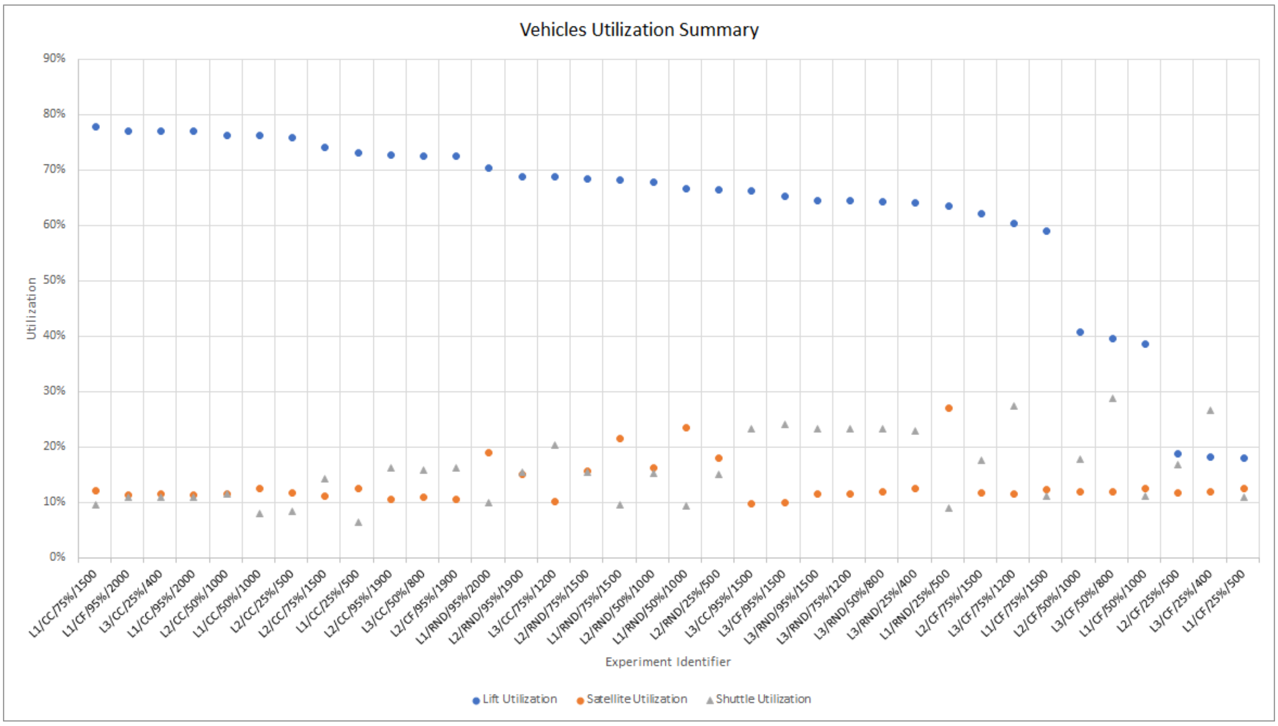


Figure 4.14: Graph of Vehicles Utilization

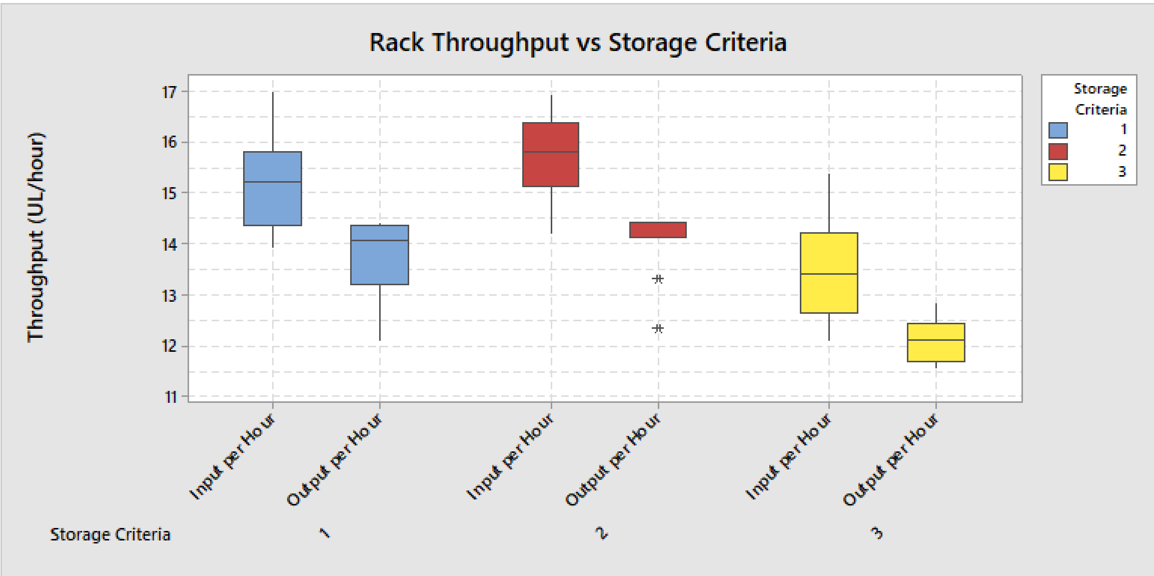


Figure 4.15: Boxplot of Rack Throughputs

the major difference is that the retrieval cycle standard deviation is not affected by the Layout main effect.

- Figure (4.16) summarizes the Averages & standard deviations for both cycles (storage & retrieval); The plot is drawn in increasing order of storage cycle times with the lowest achieved storage cycles on the left. It can be noticed that the best performance with respect to cycle times is achieved when using the storage criteria CF (closest floor) as shown on the left part of the figure. However as shown also by the ANOVA tests this is not always true as other factors have an effect on the cycle time, this justifies the existence of a high cycle time while using the storage criteria CF (L3/CF/95%/1500) on the right part of the figure.

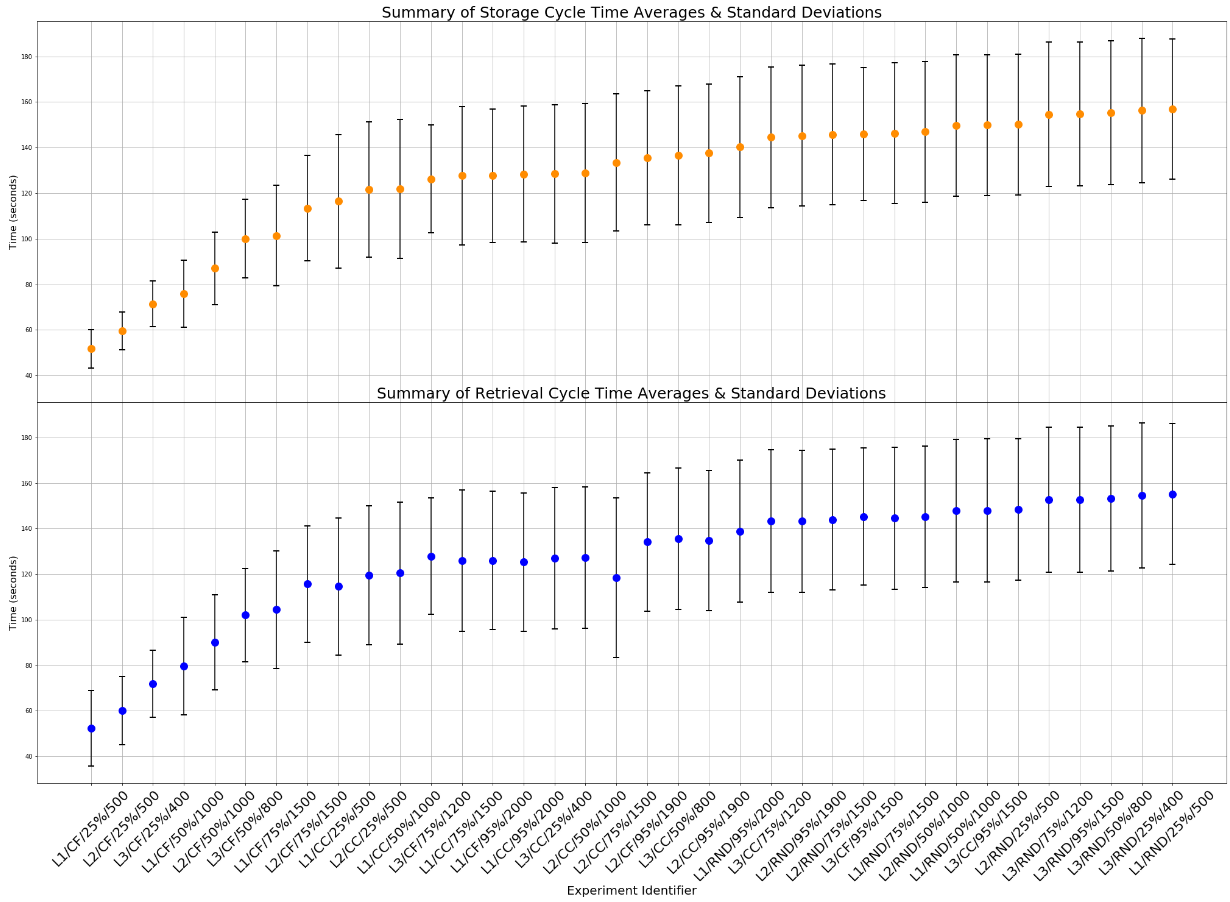


Figure 4.16: Graph of Averages & Standard Deviations of Cycle times

- One can also deduce from the results that using a random storage criteria does not yield a good performance with respect to other allocation methods tested, this is evident in figure (4.16) as most of the simulation runs that lay on the right side of the figure used the storage criteria RND (random allocation).

Chapter 5

Conclusion and Future Work

5.1 Conclusion

In this work, a meta-model for simulating autonomous vehicle storage and retrieval systems was developed, the objective was to provide an efficient model that can assist designers in evaluating the performance of their systems and to enable them to test different designs & system behaviors. The main characteristics of the developed model are summarized as follows:

- The flexibility of the model allows the remodeling for different rack configurations & topologies (from single lane to deep lane storage, variable number of bays, levels & cell capacity).
- The vehicles speed, acceleration and dimensions can also be varied.
- Auto-generating object functionality allows the setup of simulation experiment in a brief amount of time and saves the user from the long model building process prior to simulation.
- Different storage allocation policies can be used.
- The simulation model provides a visually accurate portrayal of the actual system.
- The Ability of the model to simulate months of warehouse operation in less than 10 minutes, this can be very useful in testing many realistic design scenarios in a short timespan.

In the second part of the thesis a set of experiments where planned and conducted on the meta-model to investigate factors that affect the performance of AVS/RSs, the factors that where taken into consideration that could have an effect on the system performance are: the storage allocation criteria of the items, the layout of the rack and the fill ratio of the rack at startup.

Eight performance measures have been presented and an ANOVA analysis test has been conducted for each measure. It has been verified that the statistical model fits the data collected from the simulation with an R^2 & an adjusted R^2 value above 93% for all but one performance measure tested. Furthermore the model assumptions have been verified using residual plots. From the ANOVA tests the following can be concluded:

- All main effects have a significant impact on all the performance measures except for the standard deviation of the retrieval cycle time & the staytime (where the rack rack layout has been found to be an insignificant factor in these two measures).
- The storage criteria used has been found to be the most significant factor affecting most of the performance measures.
- Significant interaction effects have been found in the ANOVA analysis for all responses.

Therefore from the analysis it is safe to conclude that Storage Criteria, Rack layout & Initial Fill of the rack have a significant impact on the performance of the AVS/RS system and must been taken into consideration when evaluating such systems.

5.2 Future Work & Recommendations

Further Work needs to be done to improve the meta-model, some challenges must be addressed and solved to insure the reliability and functionality of the model, the following suggestions are proposed:

- Extending the model to incorporate more vehicles instead of the current: one lift, one shuttle and one satellite system.
- The addition of multiple item types where items of the same type are grouped together.
- Introducing a zoning policy in the model where each set of vehicles is assigned a specific zone.
- The addition of double-command cycles, and taking into consideration the capability of the shuttle and the satellite to simultaneously perform different tasks.
- Inclusion of an easy to use and efficient GUI for the model that allows smoother control of the system parameters and easier model usage.
- Linking the model to an external database in order to save the data acquired in the simulations and to insure no data loss occurs at the end of every simulation run.
- Incorporating simulation based optimization algorithms in the model.
- Including the cost of the different system parts in the analysis and integrating the energy features of the AVS/RS to estimate the energy consumption (which affects the total cost) of the overall system.

- Performing further analysis after the ANOVA test (eg: tukey test) to find to find out the statistically significant levels of the factors which provide the best values for the response variables which in turn leads to finding the best experiment that gives the optimum performance measures.

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