THE IMPLEMENTATION AND ANALYSIS OF A TENDON-BASED STEWART-GOUGH-PLATFORM (SGP) FOR AN AUTOMATED STORAGE AND RETRIEVAL SYSTEM FOR MINI-LOAD

Von der Fakultät für Ingenieurwissenschaften, Abteilung Maschinenbau und Verfahrenstechnik der
Universität Duisburg-Essen
zur Erlangung des akademischen Grades

eines

Doktors der Ingenieurwissenschaften

Dr.-Ing.

genehmigte Dissertation

von

(Salah Bashir)
aus
(Hebron / Palästina)

Gutachter: Univ.-Prof. Dr.-Ing. Bernd Noche
Univ.-Prof. Dr.-Ing. Dieter Schramm
Tag der mündlichen Prüfung: 28.05.2013

Abstract

The Implementation and Analysis of a Tendon-Based Stewart-Gough-Platform (SGP) for an Automated Storage and Retrieval System for Mini-Load

Bashir Salah

The warehouse plays an important connecting role in the logistics network inside the company and between the various processes within the company. Its major role is to maintain a constant supply of the products, maintenance of products for a specific time period and control the supply requirement, the consumer requirement and the demand of the situation. Hence, a methodology to improve the efficiency of a new design of the Automated Storage/Retrieval System to increase the throughput performance of the system is strictly required.

Until now, all efforts to design Automated Storage and Retrieval Systems AS/RS have been carried out with Storage/Retrieval (S/R) machines. These have disadvantages of high investment value and restricted use due to the inflexibility of the physical layout. However, little attention has been paid so far to making use of the principles of the Stewart-Gough-Platform SGP on AS/RS.

To construct new designs, we set up a system under the name SGP-AS/RS. This system has attractive features such as high performance and scalability. An SGP is a kind of cable-driven platform with parallel manipulators using an octahedral assembly of struts which has six degrees of freedom (x, y and z).

Additionally, another analysis, which can help to obtain a methodology for estimating the single command and dual command cycle time of the SGP-AS/RS, is based on some assumptions. The resultant methodology depends on some parameter values, like dimensions of storage racks, location of the (I/O) points, maximum velocity consideration and acceleration/deceleration rate changes. These could also be used in future for selecting the right kind of (S/R) machine for this system. This tool was integrated with the main design tool, hence one could automatically evaluate the mid and maximum, single and dual command cycle time for the newly designed SGP-AS/RS.

An integrated storage system containing 5000 rack Bays has been presented, as well as the performance calculations of SGP-AS/RS with comparable storage and retrieval systems. At the same time, specified constraints were carried out. These calculations are based on the projected performance of the SGP-AS/RS. In contrast, the performance of comparable storage and retrieval systems are specified by the manufacturer.

Finally, the results of the designed SGP-AS/RS system are presented at the end of the dissertation, highlighting the important design parameters and the expected throughput from the system.

Kurzdarstellung

Eine Umsetzung und Analyse einer Seilgetriebenen Stewart-Plattform als Teil eines Automatisierten Regalbediengerätes für Automatische Kleinteilelager

Bashir Salah

Ziel dieser Arbeit ist die Untersuchung aller Aspekte und Rahmenbedingungen bei der Entwicklung des SGP-Regalbediengeräts, sodass dieses am Ende problemlos in die innerbetrieblichen Materialflusssysteme integriert werden kann. Von dem SGP-Regalbediengerät werden hohe Anforderungen wie hohe Durchsatzleistung und hohe Dynamik, Reduzierung der zu bewegenden Massen, hohe Energieeffizienz, Umweltschutz, hohe Wirtschaftlichkeit, Preisreduzierung im Unterschied zum anderen Konkurrenten etc. erwartet. Eine weitere Herausforderung ist, dass das SGP-Regalbediengerät auf einer neuartigen Technik beruht, die noch nie im Logistikbereich eingesetzt wurde, sondern bis jetzt nur im Robotikbereich angewendet wurde.

Im Rahmen dieser Arbeit werden ausschließlich automatische Kleinteilelager (AKL) betrachtet. Das AKL ist ein häufig in der Lager- und Kommissioniertechnik eingesetztes System. Das Regalbediengerät ist ein zentrales Element des AKLs.

Die aktuellen Forschungsarbeiten auf dem Gebiet der Regalbediengeräte konzentrieren sich im Wesentlichen auf die Verbesserung der bestehenden Komponenten. Untersucht wird der Einsatz neuer Werkstoffe für Teilbereiche der Regalbediengeräte und die Nutzung von energieeffizienten Betriebsverfahren. Die dabei zu erreichenden Leistungen sind an die Grenzen der Technik gestoßen.

Das SGP-Regalbediengerät beruht dagegen auf einer neuartigen Technik, die bis jetzt nicht im Logistikbereich eingesetzt wurde. Dabei wird das klassische Regalbediengerät durch eine Plattform, die an acht vorgespannten Seilen befestigt ist, ersetzt. Die Plattform wird mithilfe von acht Motoren, die unter Einsatz modernster Regelungsverfahren computergesteuert werden, bewegt. Dieser einfache Aufbau führt dazu, dass besonders niedrige Massen bewegt werden müssen. Außerdem werden Kunstfaserseile, die ein Vielfaches leichter als die konventionellen Stahlseile sind, verwendet. Dies führt dazu, dass die bereitgestellte Antriebsleistung weitgehend für die Bewegung der Nutzlast genutzt wird.

Mithilfe des Stewart-Gough-Plattform Regalbediengeräts werden höhere Geschwindigkeiten, Beschleunigungen und infolgedessen höhere Umschlagsleistungen erreicht. Außerdem spielt die Energieeffizienz und die zu bewegenden Masse eine große Rolle bei ihrer Entwicklung.

Im Rahmen dieser Arbeit wird eine Marktanalyse durchgeführt. Sowohl die Bedürfnisse eines Marktes als auch die Kompetenzen des Unternehmens sind jedoch dynamisch. Durch diese Marktanalyse werden die Kundenbedürfnisse, Kundennutzen und Einkaufsvolumina ermittelt. Im Rahmen der Marktanalyse werden sowohl sechs konventionelle, als auch andere Arten von Regalbediengeräten vorgestellt und mit dem SGP-RBG verglichen. Die Anzahl der gelieferten Regalbediengeräte wird in Deutschland und international analysiert. Schließlich werden die Umschlagsleistungen des SGP-RBGs berechnet und mit sechs anderen Konkurrenten verglichen. Dabei werden sowohl Einzelspiel- als auch Doppelspielzeiten für verschiedene Lagerabmessungen berechnet. Danach wird die Entwicklung des Systemsaufbaus im Laufe der Zeit näher erläutert. Hierbei werden auch die Systemkomponenten näher beschrieben.

Acknowledgment

In the name of Allah, the Most Gracious, the Most Merciful

Words can never describe my sense of gratitude towards Prof. Dr.-Ing. Bernd Noche. He helped me when I was down, depressed, and discouraged. He believed in me even when I had lost faith in myself. He was always there to guide me on technical and non-technical issues. He is the best teacher I ever had, and perhaps the best person I have ever known. These few sentences are not good enough for what I would like to say, but then nothing in words would ever be.

Special thanks to all academic and technical staff of Transport System and Logistic Institute for their helpful suggestions and administrative support.

I owe special gratitude to my parents, who pray for me all the time and from whom I always received psychological strength during my studies. Their wonderful care and endless patience enabled me to finish this dissertation.

Also, I wish to acknowledge my gratitude to my family, especially my beloved wife, my daughter and brothers, who encouraged me to continue at all times.

Last, but not least, I would like to thank all the friends with whom I spent precious time in Germany. Their kind friendship gives me confidence for a bright future and makes my life meaningful.

Duisburg, March 2013

Bashir Salah

Contents

List of Tables

List of Figures

Acronyms

A/D	Acceleration and Deceleration
ABC	Selective Inventory Control
AKL	Automated small load/parts warehouse
AS/RS	Automatic Storage /Retrieval System
ASS	Automatic Shelf System
CCM	Cable Cylinder Machine
CTT	Cycle Travel Time
DC	Dual Command
DCCM	Dual Command Cycle Module
DIN EN	German institute for standardization
DOF	Degree of Freedom
FCFS	First Come First Serve
FEM	European Federation Of Material Handling
FIFO	First in First out
FMEA	Failure Modes and Effects Analysis
FPL	Free Place List
HSR	High Storage Rack
Kg	Kilogram
LAM	Load carrying device
LHM	Containers for holding
LIFO	Last In First Out
P/D	Pickup and Deposit
PTC	Parametric Technology Corporation
RBG	Automatic Storage /Retrieval Machine
SC	Single Command
SGP	Stewart-Gaugh-Platform
SIT	Square in Time
TGW	TGW Logistics Group
VDI	The Association of German Engineer
VDMA	Verband Deutscher Maschinen- und Anlagenbau e.V
V_x, V_y	Maximum Velocity
WCL	Warehouse Current Filling List
WIhP	Work In handling Process
WMS	Warehouse Management System

List of Variables

$T_{c.t}$	Total Cycle Time
t_0	Dead Time
t_z	Time needed by S/R machine to Store or Retrieve the Pallets
$T_{SC/DC}$	Actual S/R machine traveling time either in Single command (SC) or Dual command (DC)
V_{pos}	Velocity(Position)
V_{max}	Maximum Speed
x_i ,y_i	Coordinates of the storage cell
T_i	Travel time to the storage cell
T_{single}	Single Command time
P_i	Probability of the SGP
N	Finite number
T_{sc}	Single Command Cycle Time
p, p'	Storage locations
T_{ij}	Travel Time between two storage points
T_{Dual}	Dual Command time
T_{DC}	Dual Command Cycle Time
L_{cons}	Constant value (calculated according to storage rack dimensions)
L_{max}	Maximum value
S_{total}	Maximum velocity
$T_{t/r}$	Time required to pick up and drop load to storage cell
$t_{F.Pos}$	Time required for the shuttle to position finely at I/O station
$T_{travel,E}$	Time required to travel from I/O station to the storage cell
$t_{T/R}$, $t_{F.Pos}$	Considered constant values
$t_{Esc.}$	Expected travel time for single command
t_{TB}	Time required by the shuttle to travel b/w two different storage cell
L_{speed},H_{speed}	Highlight length and height of the speed zones
F	Factor of total area
$X_{platform}$	Position of the platform in horizontal direction
$Y_{position}$	Position of the platform in vertical direction
α	Angle
P	Pressure
A	Contact area
F	Active force
OP_I	Path from I/O-Point to the storage location
P_IPo	Path from the storage shelf to outsourced location
P_O	Path from outsourced shelf to I/O-point

1 Analytical Tools

The designing and simulation work in this thesis was done using "MATLAB R2009a". Parametric Technology Corporation’s "Pro/ENGINEER Wildfire 5.0" is also utilized to comprehend the characteristics of a simulated warehouse. This chapter begins with a brief introduction of each of these softwares and their functions followed by defining the design parameters for the simulated warehouse.

Simulations are conducted taking into account modeling assumptions which are going to be discussed later in the next chapters. In addition, replications of these simulations were done by varying the distance between the I/O station and the designated cell of the storage rack with respect to the velocity of the shuttle.

The objective of this thesis is the efficient design of warehouse space for existing Warehouse Management Systems (WMS). The purpose is to improve the overall performance of Automated Storage and Retrieval Systems AS/RS using the principle of Stewart-Gaugh-Platform (SGP), which is called SGP-AS/RS. The approach involves first the creation of a three-dimensional model production and afterwards the creation of a prototype as well as a model analysis.

1.1 CAD

The Computer Aided Design (CAD) system is a well-known tool nowadays to aid the creation of two-dimensional drawings and 3D models.

Computer design is a collective term for all activities where the computer is used, directly or indirectly, in the context of development and construction activities. This refers to the graphical interactive production and manipulation of digital representation of an object in the strict sense, For instance, 2D drawings or 3D modeling [1].

This thesis uses two programs, CAD utilities Pro/E and AutoCAD, which are widely used in mechanical engineering. Whereas program Pro/E is used for 3D model formation, the program AutoCAD is used mainly for 2D drawing production.

1.1.1 Pro/E

Pro/ENGINEER is a parametric, integrated 3D CAD/CAM/CAE solution created by Parametric Technology Corporation (PTC). It was the first of its kind to be marketed with parametric, feature-based, associative solid modeling software. The application runs on Microsoft Windows and Unix platforms, providing solid modeling, assembly modeling and drafting, finite element analysis, and NC and tooling functionality for mechanical engineers [2].

The parametric modeling approach uses parameters, dimensions, features, and relationships to capture intended product behavior and to create a recipe which enables design automation and the optimization of design and product development processes. This powerful and rich design approach is used by companies whose product strategy is family-based or platform-driven, where a prescriptive design strategy is crucial to the success of the design process by embedding engineering constraints and relationships to quickly optimize the design, or where the resulting geometry may be complex or based upon equations. Pro/ENGINEER provides a complete set of design, analysis and manufacturing capabilities on one integral, scalable platform. These capabilities include Solid Modeling, Surfacing, Rendering, Data Interoperability, Routed Systems Design, Simulation, Tolerance Analysis, and NC and Tooling Design [2].

Free-body diagram of the shuttle with and without load are examined for this thesis using Pro/Engineer. The distribution of forces within the warehouse is also analyzed through this program. Besides this, it was of great help in the classification of zones based on the resultant forces and torque which affect the movement of the shuttle.

1.1.2 AutoCAD

AutoCAD is a vector-based drawing program. Technical drawings are created in AutoCAD. Nowadays, through development of the program, 3D functions of objects and special extension models can also be built in AutoCAD.

AutoCAD is a product of Autodesk AG and has been widely used in training, as well as in practice, and is an industry standard in a range of CAD software. AutoCAD is basically a vector-based drawing program that is based on simple objects such as lines, polylines, circles, arcs, and text, which in turn provide the basis for more complex 3D objects [1].

There are wide ranges of methods and tools in the AutoCAD program. It can be applied to deal effectively with design and documentation.

1.2 MATLAB

MATLAB is a high-level language and interactive environment that enables you to perform computationally intensive tasks faster than with traditional programming languages such as C, C++, and FORTRAN.

Matlab is a commercial "Matrix Laboratory" package which operates as an interactive programming environment. It is a mainstay of the Mathematics Department software lineup and is also available for PC's and Macintoshes and may be found on the CIRCA VAXes. Matlab is well adapted to numerical experiments since the underlying algorithms for Matlab's builtin functions and supplied m-files are based on the standard libraries LINPACK and EISPACK.

Matlab program and script files always have filenames ending with ".m"; the programming language is exceptionally straightforward since almost every data object is assumed to be an array. Graphical output is available to supplement numerical results [3].

1.3 Prototyping Process Model

Figure 1.1 illustrates the advantages and shortcomings of the major prototyping processes available to today's designer. In addition, it helps with the decision to select the best prototyping process for the product development process.

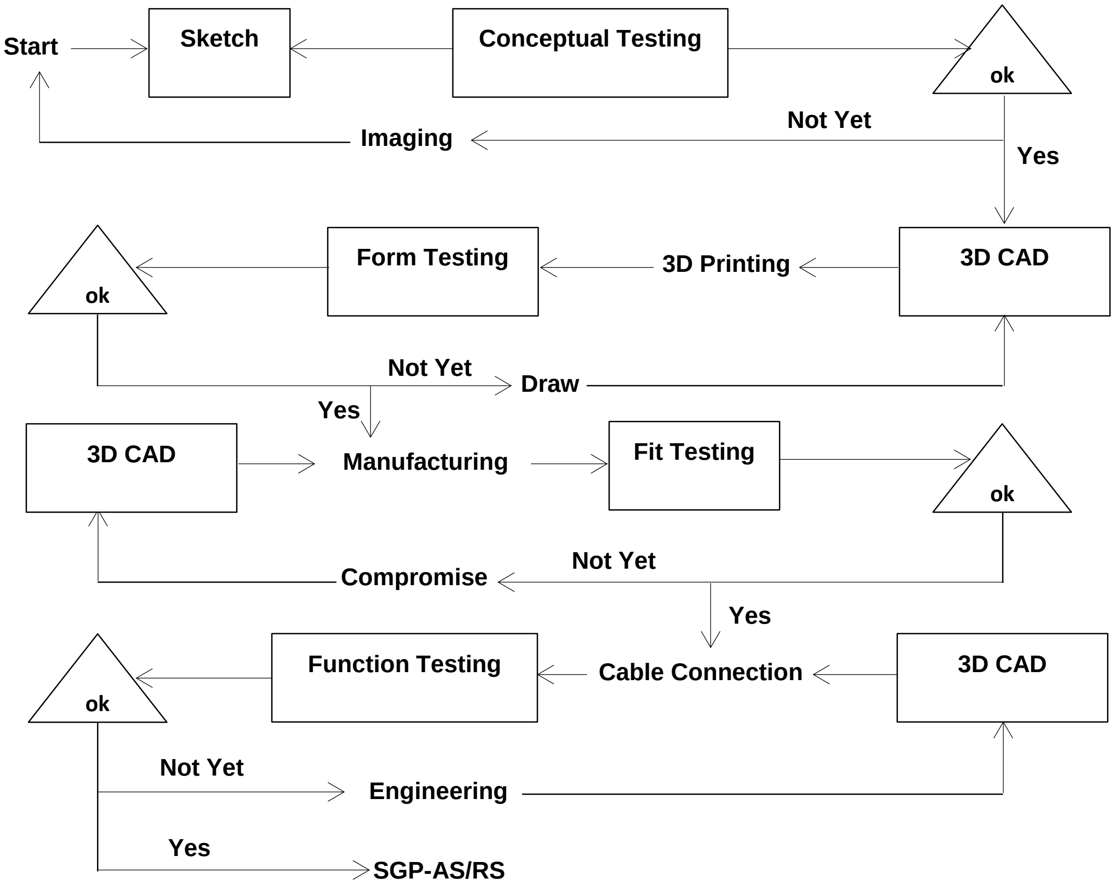


Figure 1.1: SGP Prototyping Process Model

2 Preface and Overview

2.1 Overview

In today's challenging competition in consumer goods, the manufacturers strive for their products to reach final customers before they turn their heads to the products of the rival. This challenge is influenced, for instance, by globalization, deregulation, new business commerce and convergence of the industries. The material handling process of re-engineering is now a critical issue for logistics and supply chain managers of airlines, shipping lines, terminal and warehousing enterprises around the world, although creating place and time utility, material handling is considered to be a non-value-added activity. Distance and time of material handling, times of re-handling, and the amount of Work In handling Process (WIhP) play a substantial role in the final cost of goods. Approximately 50% of the costs of goods are attributed to material handling and logistics [4].

Warehouses are facilities where goods or products are received, stored and transported. They are also known as distribution centers or order fulfillment centers. Firstly, goods are received from some sources. Then they are temporarily stored. Lastly, orders from customers are processed and fulfilled by retrieving (picking) these goods from their storage locations, packing them and finally transporting them to the customer.

Warehousing, which deals with all operations inside the facility, is an integral function of logistics, which include all distribution activities. Warehouses are basically used for storing raw materials and finished goods. They balance production schedule and demand, integrate products from several different manufacturers/suppliers in order to reduce inventory costs. They also attempt to ensure customer satisfaction by fulfilling orders and providing for a buffer for future customer orders by ensuring that supplies are available on hand to fill those orders. Distribution centers are important within the supply chain for the numerous reasons mentioned above.

There are various alternatives for storage and material handling within a warehouse which can be used. The primary criterion for choosing the type of storage and handling equipment in a warehouse is the unit load(s) being received, stored, picked or shipped. For instance, pallets and crates are used when receiving goods; cases and totes are used to store them; and cartons and boxes are used to ship them. Conveyors, fork trucks and Automated Storage and Retrieval Systems AS/RS are used to move materials around the warehouse. An automated storage/retrieval system can be defined as a storage system that performs storage and retrieval operations with speed and accuracy under a defined degree of automation [5].

Compared with the traditional approach of warehouses, Automated Storage and Retrieval Systems AS/RS have many promising advantages such as improved inventory management, high floor space efficiency, reduced labor costs, reduced costs of loss by theft, lower incidence of misplacement, increased reliability and reduced error rates [6-14]. Housman et al. [15] stated that the maximum benefits of such a system depend upon the optimal warehouse design and the optimal scheduling of pallet assignment, storage assignment and interleaving.

The type of storage assignment policy a warehouse employs generally governs the operations in the warehouse. A storage assignment policy serves to determine which products are assigned to which locations [16]. There are two decisions to be made for the storage of goods in a warehouse: flexibility (dedicated or flexible) and assignment (random, demand, or class-based) [14], [15].

If the warehouse uses the dedicated storage policy, goods are assigned and stored in fixed locations. If the warehouse is operating on the flexible storage policy, then items are not assigned to fixed, but to flexible locations i.e. randomly.

In random storage, goods are stored at the locations that happen to be available at any time the load is to be put away. This is the principle of the random-based storage assignment policy.

Items that have a high demand are assigned to convenient locations to facilitate the least possible picking time as opposed to items that have a low demand. These are stored in locations farther from locations with respect to (I/O) point of the warehouse. This is the principle of demand-based storage assignment policy. Class-based storage is a combination of random storage and demand (of the goods). Goods are assigned a class depending on their demand and then each class is assigned a fixed (dedicated) set of locations. Goods are stored randomly within each set of fixed locations. An effective class-based storage assignment policy can improve the performance of an AS/RS [6].

The vertical storage systems are important in the sense that less floor space is required to store a large number of goods [7]. Such storage systems are also called Non-Square-In-Time (NSIT). We say an AS/RS is Square-In-Time (SIT) if the time required for the mast to travel from the front to the back of the rack is the same as the time required for the carriage to travel from the bottom to the top of the mast [17].

2.2 AS/RS Components and Terminology

An AS/RS consists of one or more storage aisles that are serviced by a storage/retrieval (S/R) machine. The stored materials are held by a system of storage racks and aisles. The S/R machines are used to deliver and retrieve materials in and out of inventory. There are one or more input/output stations in each AS/RS aisle for delivering the material into the storage system or moving it out of the system. In AS/RS terminology, the input/output stations are called pickup-and-deposit (P&D) stations (see Figure 2.1) [16].

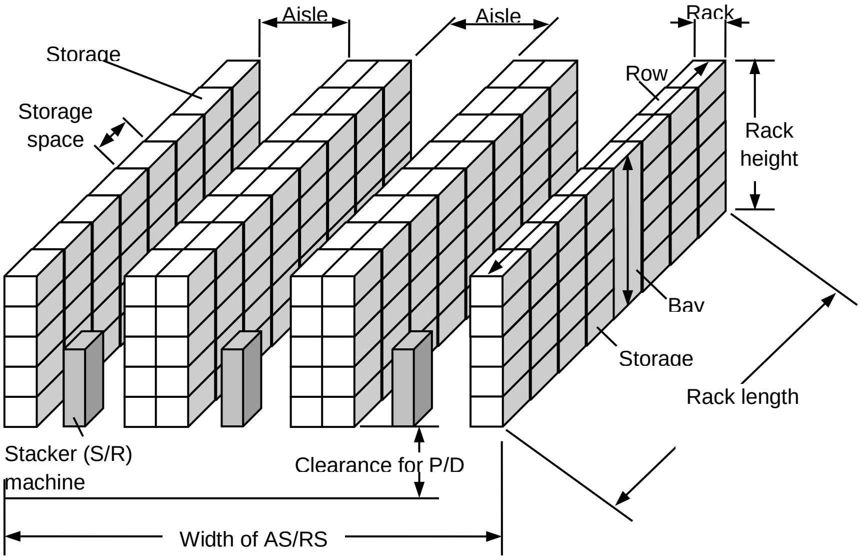


Figure 2.1: Generic structure of AS/RS [16]

2.3 AS/RS and Manufacturing Systems

Manufacturing Systems (MS) consist of automated machine tools, automated material handling, and an Automated Storage/Retrieval System AS/RS as essential components. Optimal performance of each element of this system would improve the productivity and efficiency of the total manufacturing system (see Figure 2.2) [62].

.

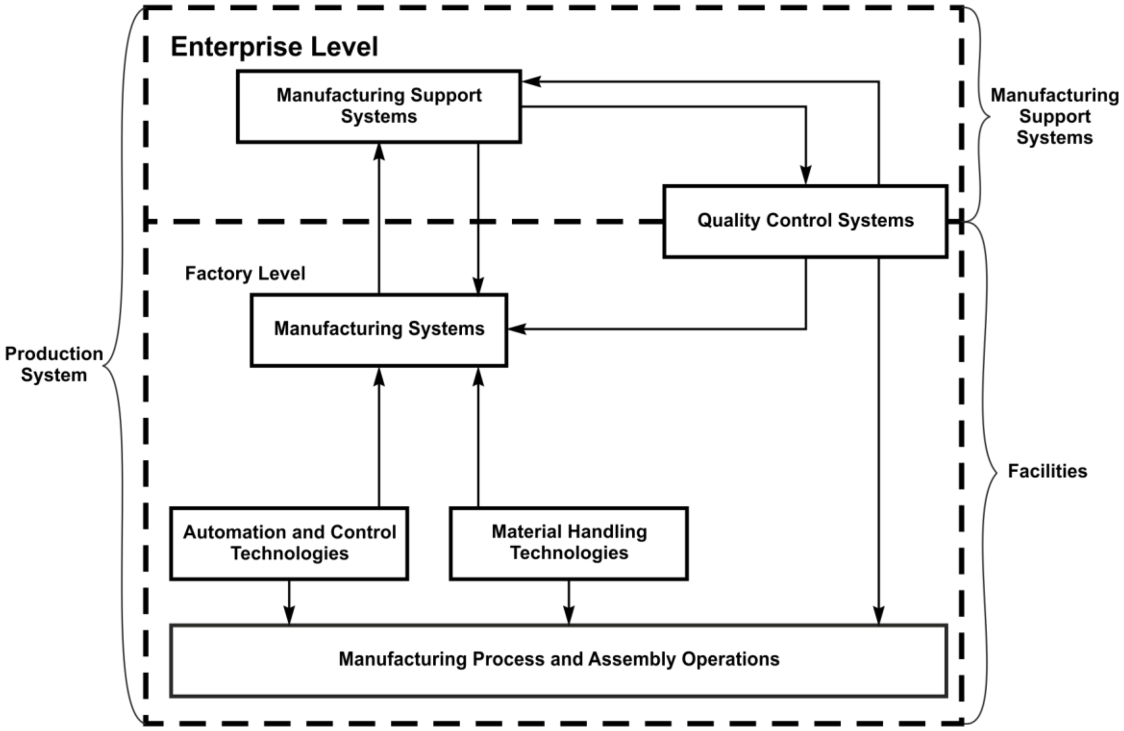


Figure 2.2: Material handling in the production system [5]

The increased demand for manufactured goods has increased the pressure on the manufacturing system, which in turn has motivated management to find new ways to increase productivity, considering the rarity of available resources. Improving the performance of each element of this system would increase the productivity and efficiency of the total manufacturing system [18].

[5] stated that AS/RS systems are custom-planned for each application, and they range in complexity from relatively small and manually controlled mechanized systems to very large computer-controlled systems fully integrated with factory and warehouse operations. There are several important categories of Automated Storage/Retrieval Systems which can be classified as follows:

2.3.1 Unit-load (AS/RS)

This is typically a large automated system designed to handle unit loads stored on pallets or in other standard containers. This system is computer controlled and (S/R) machines are full automated and designed to handle the unit load containers.

2.3.2 Mini-load (AS/RS)

This is used to handle small loads (individual parts or supplies) that are contained in bins or boxes within the storage system. The (S/R) machine is designed to retrieve the bin and deliver it to the input/output station located at the end of the aisle.

2.4 Man-on-board (AS/RS)

This represents an alternative approach to the problem of storing and retrieving individual items in the system. This offers an opportunity to reduce the total transaction time of the system.

2.5 Automated Item-retrieval System

This is also designed for retrieval of individual items or small unit loads such as the case of a product in a distribution warehouse. In this system, items are stored in single-file lanes instead of bins or drawers.

2.6 Deep-lane AS/RS

This is a high-density unit load storage system that is appropriate when large quantities are to be stored, but the number of separate types of material is relatively small.

2.7 General Benefits of AS/RS

The following points are some of the benefits of the AS/RS [19].

- **Space Saving**

(AS/RS) uses the vertical height of the building, to provide floor space savings. The footprint savings are greater with taller buildings. Hence, the extra space is available for manufacturing and value-added processes that generate revenue.

- **Increased Throughput**

An automated storage technology depends on (AS/RS), a technology which travels faster, thus increasing the throughput.

- **Reduced Labor Costs**

Automation frees manpower, dedicated to material handling, to perform more profitable value-added services.

- **Inventory Control and Security**

Integration with host systems means that inventory is tracked in real time from the moment it enters the system until its exit from the system.

- **Improved Ergonomics**

(AS/RS) can deliver parts to the operator at an ergonomically desirable height.

- **Hazardous or Hostile Working Environment**

(AS/RS) solutions in particular can operate in a hostile working environment, such as a freezer warehouse.

- **Improved Quality**

(AS/RS) improve the overall quality and consistency of order fulfillment processes. That is because the system tracks inventory in real-time and reduces the number of decisions an operator has to make.

2.8 SGP-AS/RSs Possible Areas of Application

The features of the new design of mini load SGP-AS/RS include high speed, high acceleration and light weight; thus enabling us to use it in very wide applications like apparel, automotives, beauty and cosmetics, libraries “book and publication distribution”, electronics, food and beverage, household appliances, pharmaceuticals and healthcare, retail, semiconductor, textiles or any application requiring inner pack or piece picking, some of these application areas are discussed below:

- **Libraries**

SGP-AS/RS as a high-density automated shelving system sorts bar-coded items by size and stores them in bins. The library’s SGP-AS/RS will shelf materials underground or behind by size rather than by library classification, in highly specific racks increasing the capacity of a conventional shelf.

All items selected for the SGP-AS/RS will have their barcodes scanned and will be placed in bar-coded bins that will be stored in the SGP-AS/RS.

Each item will be scanned whenever it is removed from, and returned to, the SGP-AS/RS, as will the new bin into which the item is deposited. This will allow the library's computerized systems to track the location of all materials stored in the SGP-AS/RS at all times, and will allow library patrons to request materials from any computer with an internet connection, via the library's catalogue or search engine.

Rare and archival materials from the Special Collections Research Centre will be stored in boxes that will be bar-coded. These boxes will be stored in special racks along with extremely large materials and retrieved in a similar manner. Upon request, automated (SGP) will retrieve materials stored in the SGP-AS/RS almost instantaneously.

Smaller AS/RS installations are currently in use or planned for only a handful of U.S. research libraries. The system will be applied at Sonoma State University [20].

HK Systems Company, which will construct the library's (AS/RS), has prepared a video which illustrates how the system will function. It begins with an overview of a concept of the ground level of the library and illustrates how the robotic crane retrieves materials from the storage system and brings them to the ground level, where library staff members will retrieve them from bins or racks and deliver them to library patrons [20].

- **Food and Beverage**
- **Apparel**
- **Decorative Products**
- **Electronic Components**

2.9 Problem Statement

Based on the discussion presented in the previous sections, the research problem which is now being studied is thus defined: How can a storage machine which uses (SGP) and which is consistent with optimization principles be designed? And how can this SGP-AS/RS be distinguished from other (AS/RSs)?

This study focuses on two major problems. Firstly the general design of the (SGP-AS/RS) machine which is more effective than conventional (S/R) machines and saves on investment costs and utilized area; while the conventional AS/RS uses large areas by building long racks, the utilization of the rack height instead of length will be discussed to minimize the used area in the warehouse. Secondly, besides the proposed general design, the access time of the platform due to the new design is important to know, because it is important to realize that the AS/RS is usually just one of many systems to be found in a warehouse. The true performance of the AS/RS is typically influenced by the other systems just as the performance of the other systems is influenced by the AS/RS. Therefore this calls for a decision to be made at this stage as to whether this new storage machine is effective or not. Hence, this thesis will provide an elaborate discussion on the travel times in single and dual command cases in addition to the performance analysis, throughput and utilization in order to prove the efficiency of the new design.

2.10 Research Objectives

Numerous related studies address AS/RS systems. Problems of interest in AS/RS include configuration problems such as determining the number of cranes; height and length of pick area, etc. Why is a study on SGP-AS/RS important? The design and scheduling of conventional AS/RS has been the subject of many research works. With AS/RS and (S/R) the machine’s travel time has been considered a major factor in finding the optimal design and schedule. The specification of an (S/R) machine for commercial usage usually includes the maximum of horizontal and vertical velocities, (A/D) rate, and (P/D) time. The (S/R) machines are used to deliver materials to the storage racks and to retrieve materials from a rack. These machines have three mechanical drives: a vertical drive, which raises and lowers the load carrying device; a horizontal drive, which moves the mini load back-and-forth along the aisle; and a shuttle drive, which transfers the mini load between the (S/R) machine carriage and both sides of the aisle. An (S/R) machine is mounted on rails along the top and bottom of each AS/RS storage aisle. The mast of the (S/R) machine moves horizontally along the aisle, while the load handling attachment (LAM) moves vertically up and down the mast. This leads to high investment value; moreover, we are confronted with movement restrictions due to the inflexibility of the physical layout and equipment.

To overcome the (S/R) machine’s restriction as well as higher investment costs, we can use the principles of (SGP) to construct a new design called SGPAS/RS which has attractive features such as ‘high performance’ and ‘scalability’. An (SGP) is a kind of cable-driven platform with parallel manipulators using an octahedral assembly of struts which has six degrees of freedom $(x, y,$ and $z)$. Using (SGP) principles, the shuttle can drive directly to any rack position using maximum velocities (V_x, V_y) and avoiding triangular drive which (S/R) machines currently produce for conventional Automated Storage and Retrieval Systems AS/RS.

Previous studies assumed the travel-time models for Automated Storage/Retrieval Systems AS/RS by considering the average uniform velocity for the (S/R) machine, ignoring the operating characteristics such as the acceleration/deceleration rate and the maximum velocity (V_{max}) [14], [15]. However, in the design problem, the average uniform velocity cannot be obtained without knowing the physical configuration of the rack (e.g. the length and height of the storage racks), which in turn requires information on the average uniform velocity. Hence, an optimal design and scheduling based on the average uniform velocity is far from optimal from a practical point of view. Recognizing these shortcomings of the previous models in this thesis, we propose travel-time models which integrate the operating characteristics of an (S/R) machine. Under the class-based turnover assignment rule, we propose travel-time models for SGP-AS/RS, for the cases of a single command cycle, a storage/retrieval is performed in a cycle, and a dual command cycle; both storage and retrieval are performed in each cycle.

This thesis will focus on improving the key variables of AS/RS performance (see Figure 2.3) by studying the impact of using (SGP) instead of (S/R) machines in the design of the new structure.

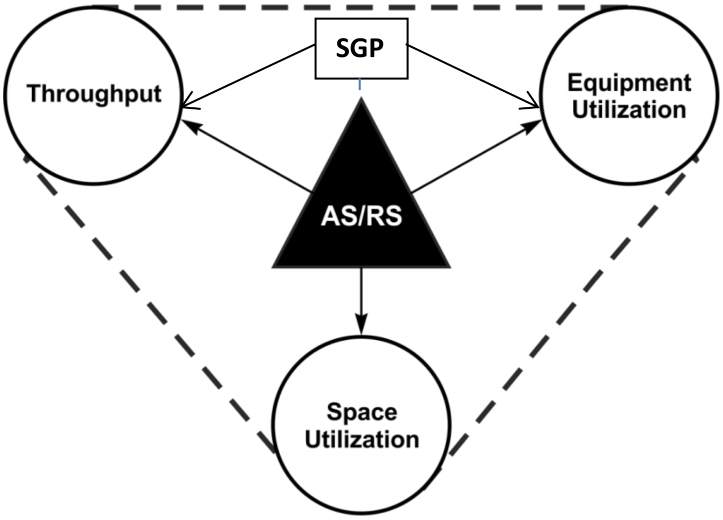


Figure 2.3: Key-variables for SGP-AS/RS performance evaluation.

2.11 Thesis outline

This Dissertation comprises nine chapters. Chapter one presents the analytical tools which are used in this thesis, while Chapter two introduces the motivation for this research and defines the logistic system, the warehouse management system, and some applications and uses of the SGP-AS/RS along with the problem statement and research objectives being defined. Chapter three introduces the literature review of related research work, which focuses on the simulation analysis of mini-load systems as well as the storage location assignment problem in mini-load systems. Chapter four illustrates the estimation of single and dual command cycle times for SGP-AS/RS using three different storage location assignments. Chapter five discusses the implementation of SGP-AS/RS to improvise warehouse management systems and presents the performance analysis, the throughput and utilization according to the shape factor of the rack. Chapter six shows the planning of a demonstrator of the SGP-AS/RS. For this reason, a template of a specification is created. This template can be filled by the customer to combine all the requirements of the SGP- AS/RS, and then a specification is created for the prototype. Based on this performance specification, a Demonstrator has been built up already at the University of Duisburg-Essen. Chapter seven introduces the marketing policies of the SGP-AS/RS machine and illustrates the potential role of the SGP machine in the intra-logistics systems. In Chapter eight, performance calculations of SGP-AS/RS with comparable storage and retrieval systems have been done at the same specified constraints. Therefore, the results obtained after simulation and modeling have been discussed and the average expected cycle-time for SGP- AS/RS, using the operating characteristics such as the acceleration/deceleration (A/D) rate and the maximum velocity (Vmax), have been presented. I then conclude my work and provide some suggestions for future work in Chapter nine.

3 Literature Review of Related Research Work

3.1 Introduction to the AS/RS

This chapter summarizes the current status of AS/RS development, highlighting the most recent research in this area, and then proceeds with a discussion of knowledge management and creation.

Automated Storage and Retrieval Systems (often referred to as ASRS or AS/RS) refers to a computerized robotic system that automates operations such as unloading, sorting, putting-away, storage, order-picking, staging and loading. The system typically consists of five main components: storage rack, (I/O) point, (S/R) machine, shuttle, and computer management system. Automated storage and retrieval systems were first introduced in the 1950s to eliminate the walking that accounted for 70 % of manual retrieval time [5]. An AS/RS is capable of handling pallets without involving an operator, thus the system is fully automated. There has been much advancement in AS/RS technology in the last forty years and it is predicted to grow rapidly in the next decade.

The use of (AS/RSs) has several advantages over non-automated systems. Examples are improved inventory management, high floor space efficiency, reduced labor costs, reduced costs of loss by theft, lower incidence of misplacement, increased reliability and reduced error rates, improved material flow and inventory control [21-28]. Apparent disadvantages are high: investments costs, less flexibility and higher investments in control systems [29].

A recent application of AS/RS is in the automobile industry. After car bodies have been painted, they are moved into storage in an AS/RS to coordinate the production schedule with the number of bodies painted in a specific color. The selected bodies are then retrieved and returned to production [30].

When it comes to the subject of knowledge creation, countries are now marketing themselves as having a knowledge-based economy. What, exactly, does this mean? There are many definitions, but an (OECD) report, “The Knowledge-Based Economy” [22], defines them as economies which are directly based on the production, distribution and use of knowledge and information, leading towards growth in high-technology investments, high-technology industries, more highly skilled labor and associated productivity gains.

3.2 Stewart-Gough-Platform

From a technical point of view, the Stewart platform is one of the popular parallel manipulators. It is a six-degree-of-freedom (DOF) positioning system that consists of top plate, bottom plate and six extensible legs, which connects the top plate to the bottom plate. A general Stewart platform is shown in Figure 3.1.

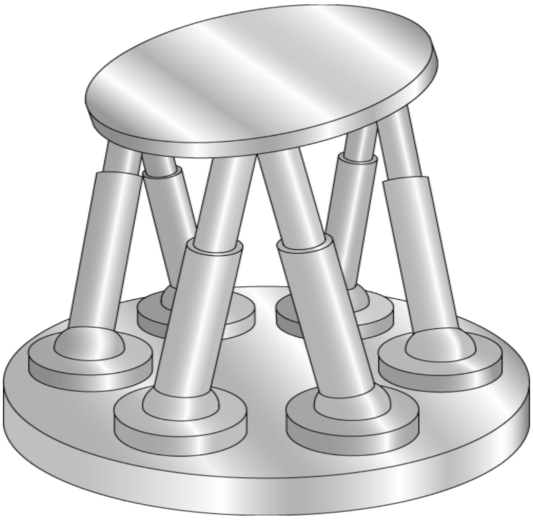


Figure 3.1: General Stewart platform [31]

The Stewart Platform was originally designed in 1965 as a flight simulator, and it is still commonly used for that purpose. Since then, a wide variety of applications have benefited from this design. A few of the industries using the Stewart Platform design include aerospace and defense, automotive, transportation, and machine tool technology, who use the platform to perform flight simulation, handle vehicle maintenance, and design crane hoist mechanisms. The Stewart Platform design is also used for the positioning of satellite communication dishes and telescopes and in applications such as shipbuilding, bridge construction, transportation, and as a drilling platform on the Lunar Rover [31].

At the University of Duisburg-Essen in the department of Mechatronics, a research project under the name of SEGESTA ARTIST is being carried out. It is a specialized platform driven by cables and with working space in this platform. This is called The Segesta cable robot, as shown in Figure 3.2.

Figure 3.2: The Segesta Cable Robot [32].

The (S/R) machines are used to transfer materials to the storage racks and to retrieve materials from a rack. These machines have three mechanical drives: a vertical drive, which raises and lowers the mini load; a horizontal drive, which moves the mini load back-and-forth along the aisle; and a shuttle drive, which transfers a mini load between the (S/R) machine carriage and both sides of the aisle. An (S/R) machine is mounted on rails along the top and bottom of each AS/RS storage aisle. The mast of the (S/R) machines moves horizontally along the aisle, while a carriage moves vertically up and down the mast.

To overcome the (S/R) machine's restriction and higher investment costs as well, we can use the principles of the Stewart-Gaugh-Platform to construct a new design called SGPAS/RS, which has attractive features such as 'high performance' and 'scalability'. Using (SGP) principles, the shuttle can drive directly to any rack position using maximum velocities (Vx, Vy) and avoiding triangular drive, which (S/R) machines at present make for conventional Automated Storage and Retrieval Systems AS/RS. SGP-AS/RSs are clearly capable of high speeds and accelerations. In our (SGP-AS/RS), the horizontal and vertical drives operate simultaneously to reduce the travel time.

3.3 Automated Storage and Retrieval System

Numerous related studies address AS/RS systems. Problems of interest in AS/RS include configuration problems such as determining the number of cranes; height and length of pick area, etc. The design of AS/RS end-of-aisle order picking system is addressed by [33]. The authors develop a mathematical model to analyze the performance of AS/RS end-of-aisle order picking system and the present a design algorithm to determine the minimum number of aisles required to meet a given throughput requirement.

3.4 Performance Analysis of Unit-Load AS/RS

There are several works of research which give us an overview of the status of the Automated Storage/Retrieval System. Travel time models for the (S/R) machine in the AS/RS under randomized storage were proposed [33], which considered both single and dual command cycles, alternative (I/O) points, and various dwell-point strategies for the (S/R) machines. Subsequently [25] proposed a framework for the dual command cycle travel time model under an n-class-based storage policy. In calculating the travel time, previous studies in travel-time models assumed a constant (S/R) machine velocity. Hwang and Lee [27] have presented travel time models, which considered the operating characteristics of the (S/R) machine, including a constant acceleration and deceleration rate, and the maximum velocity restriction.

The Shape Factor is the ratio of the maximum vertical travel time to the horizontal travel time, if maximum horizontal travel time is greater than maximum vertical travel time. Otherwise, it is the ratio of the maximum horizontal travel time to maximum vertical travel time [8].

When (shape factor) b = 1, the rack is said to be square-in-time (SIT); otherwise, the rack is simply referred to as rectangle-in-time. Since the motors have significantly different speeds, a square-in-time rack will not be physically square [39]. Empirical experience indicates that the optimal design for AS/RS is frequently not square in time. Furthermore, many systems that have been installed are not square in time. For this reason, it is desirable to determine the expected travel time for a rack that is not necessarily square in time [8].

It is shown that significant reductions in crane travel time (and distance) are obtainable from turnover-based rules. These improvements can, under certain circumstances, be directly translated into increased throughput capacity for the existing system, and can be used to alter the design (e.g., size and number of racks, speed of cranes, etc.) of proposed systems in order to achieve a more desirable system balance between throughput and storage capacity [15]. Based on that, we have concentrated on finding the optimal design of the AS/RS having a Stewart-Gough-Platform as the load carrying unit. The distinctive feature of this SGP is that it significantly reduces the travel time between (S/R) operations. It is held in position by cables which are driven by multiple motors at the four corners of the aisle. Furthermore, we would like to explore the relationship between system design parameters and performance metrics.

A number of performance optimization procedures or algorithms for the (S/R) machines have been published [34], which attempted to optimize the position of the (S/R) machine, when it becomes idle (also known as the ‘‘dwell point’’ of the S/R machine)

The design optimization is done initially by developing a design tool based on conventional formulations. Separately, a tool to estimate the single and dual command cycles based on FEM 9.851 standard [35] is integrated with the design tool, and from the resultant design, specifications of AS/RS system, along with the obtained single and dual command cycle time, the minimum and expected throughput of the system were obtained. A variation of the input parameters led to obtaining an optimal height for the given specific load dimensions, ultimately providing us with an optimal design solution for the given input and load specifications.

A number of papers in literature focus primarily on the AS/RS design. Some of these design-focused papers are concerned with the (S/R) machine. For instance, a large majority of unit-load AS/RS papers assume a single-shuttle (S/R) machine, which implies that the (S/R) machine can move only one unit-load at a time. In addition, a travel time model for a new type of (S/R) machine with one vertical platform and N horizontal platforms (to serve N tiers of the rack) is presented [36].

3.5 Simulation Analysis of Mini-Load Systems

Simulation models have been developed by Lynn and Wysk (Linn and Wysk 1984) and by Medeiros, Enscore, and Smith (Mederirus, Ensore and Smith 1986) for mini-load systems. These models can be used to determine the average travel time of the (S/R) machine and the number of container retrievals performed by a mini-load system per cycle.

[37] has developed a general simulation model in order to test the performance of various storage assignment policies of a mini-load warehouse system. Even though the system concept was relatively simple, the simulation model became quite complex. This is because there are numerous factors in the design and operation of even a simple, single aisle system which influences performance. This inherent complexity has contributed to the difficulty in anticipating the performance of large, automated, warehouses.

[38] has developed a model to predict system parameters such as dual cycles per hour, crane and operator utilization and distance traveled by the crane. One can use the model to help design a mini-load system.

3.6 Summary

Research effort of this thesis aims at studying design issues that are mainly technical and logistical in nature. Indeed, the main focus of study is to work on these design issues by comparing different alternative classical automated storage machines. At the same time, this research focuses on the strategic level of design decisions in terms of a mini-load system.

4 Estimation of Single and Dual Command Cycle Times for (SGP-AS/RS)

1.1 Introduction

Performance analysis of an Automated Storage and Retrieval System AS/RS is a complex analysis, with the throughput of SGP-AS/RS playing an important role in determining the efficiency of the system. It is necessary to calculate the system throughput; but the throughput is further dependent upon a major scale on the Cycle Travel Time of transactions, namely the single and dual command cycle transactions. Therefore, the main objective in this study is to determine the time taken in performing the single and dual command cycles, which helps to investigate the performance characteristics of the Stewart Gough Platform Automated Storage and Retrieval System (SGP-AS/RS). The function of a product cycle planner by the conception of an automatic warehouse system takes two important parameters into consideration:

- Storage capacity (storage space).
- System throughput (both single and dual command cycles).

Generally, a work cycle is one in which the same operation is performed in repeated cycles. Here, in this case of warehouse configuration, it is the automatic feeder performing the single and dual command cycles in which the unit loads are transferred from one point to another. When the storage and retrieval operations are performed one by one or independently of each other, then the operation is called Single Command Storage Cycle (SC) or Single Command Retrieval Cycle. However, when the storage and retrieval operations are performed simultaneously, then it is termed as Dual Command Cycle (DC) or Combined Cycle. In this case, the (S/R) machine traveling between two points is an empty travel [28].

4.1 Operating Procedure of (SGP- AS/RS)

Computer-directed warehousing systems using the storage rack (SGP) system are revolutionizing the design and operation of large-capacity and high-volume storage facilities, which leads to a reduction of labor costs, high floor–space utilization, improved material flow, improved inventory control, and lower incidence of misplacement or theft [40]. The system's operating procedure is described in Figure 4.1.

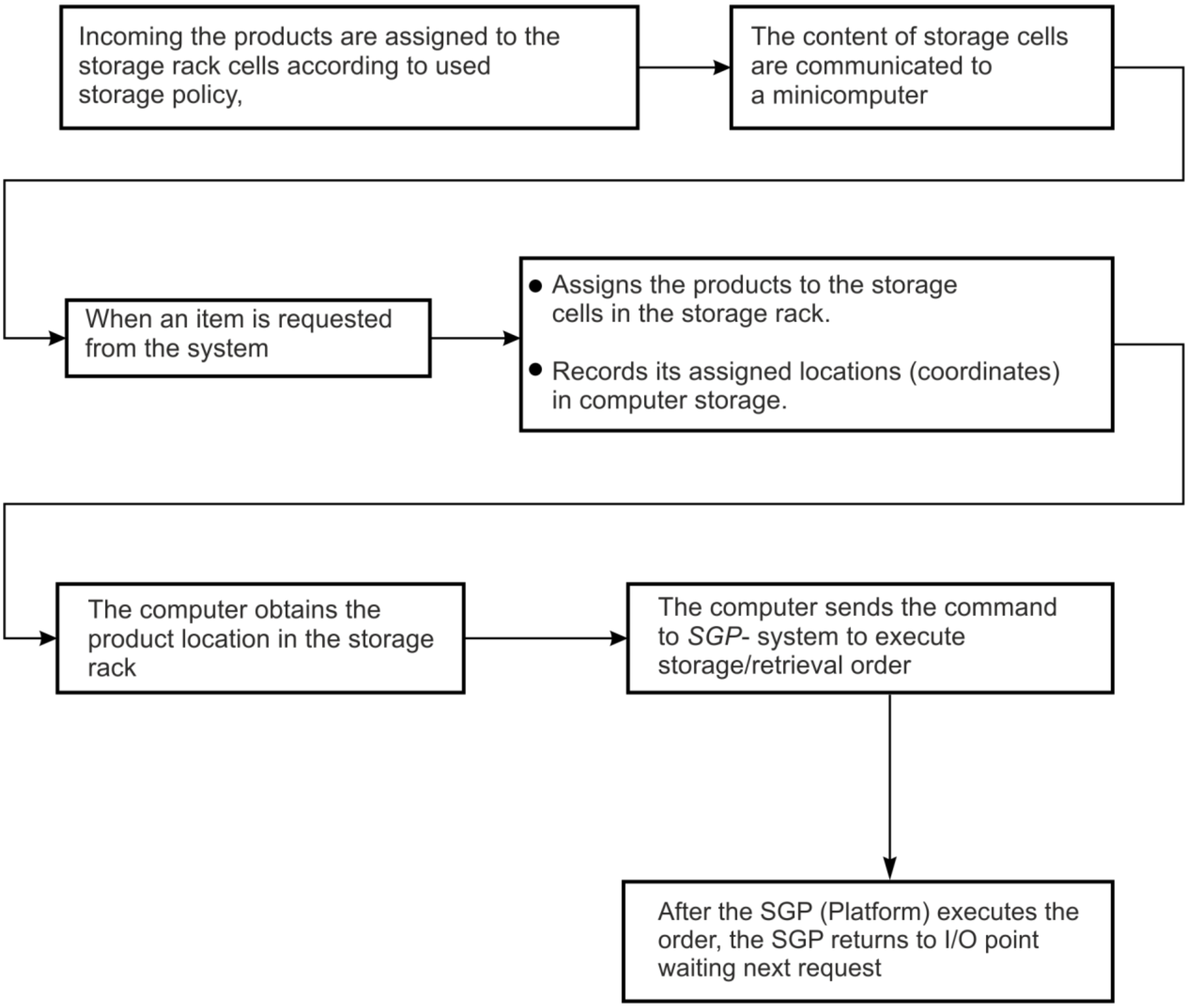


Figure 4.1: Operating procedure of SGP-AS/RS.

4.2 Single Command Cycle (SC)

An operation or cycle in which the (SGP), after picking up the load at (I/O) point, travels to the storage/retrieval location after performing the storage/retrieval operation, then returns to (I/O) point, is called a Single Command Cycle (SC), and the time taken to perform such an operation or to complete one such a cycle is called the Single Command Cycle Time (T_{sc}). The operating cycle of single command is described in Figure 4.2.

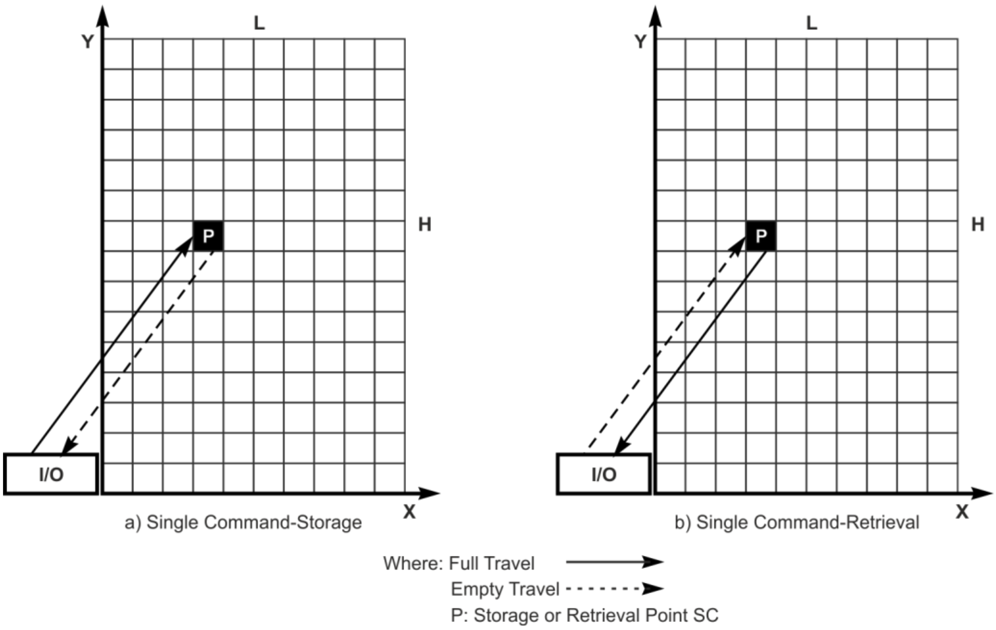


Figure 4.2: Storage /Retrieval operation in case of SC.

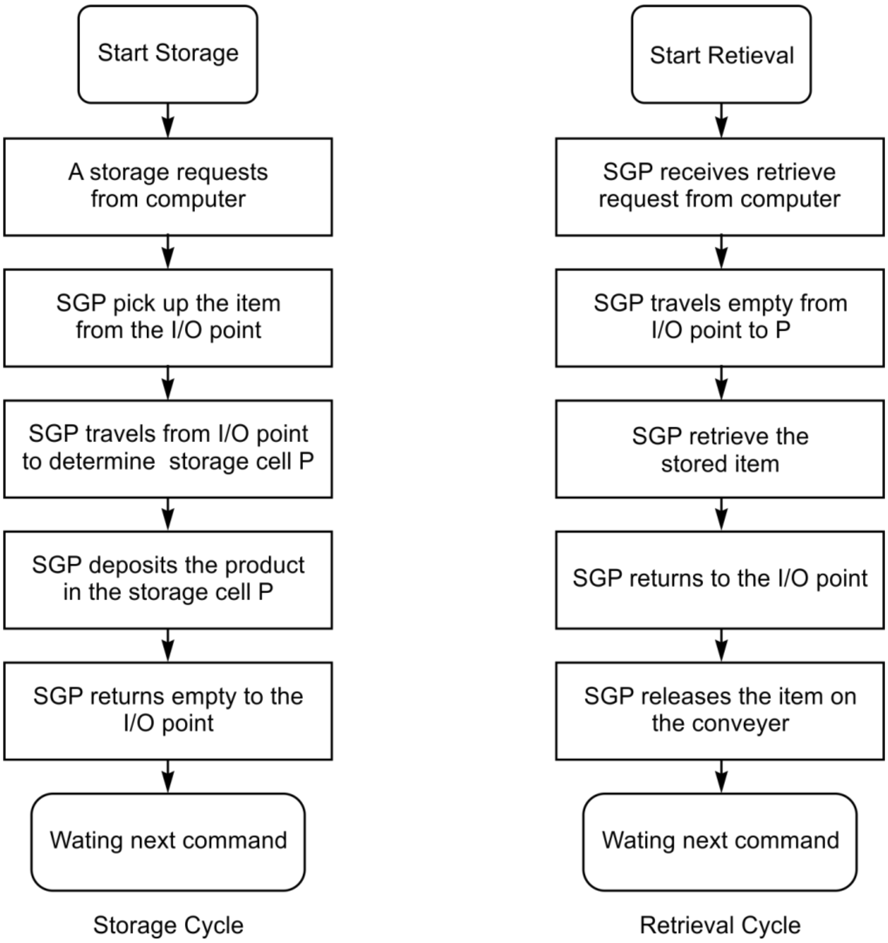


Figure 4.3: Operating procedure of Single Command Cycle.

4.3 Dual Command Cycle

Dual command includes both storage and retrieval, which is more effective than single command and saves more time and effort in the warehouse system. An operation or cycle, in which the (SGP) after picking up the load, travels to the storage location, deposits the load, and then travels to the retrieval location, performs the retrieval operation, finally travels back to the (I/O) point and deposits the retrieved load, is termed Dual command (DC) cycle operation, and, when it is repeated, it is termed Dual Command Cycle. The time taken in order to perform such an operation or complete one cycle is termed Dual command cycle time(T_{DC}), dual command process is represented in Figure 4.4 and Figure 4.5

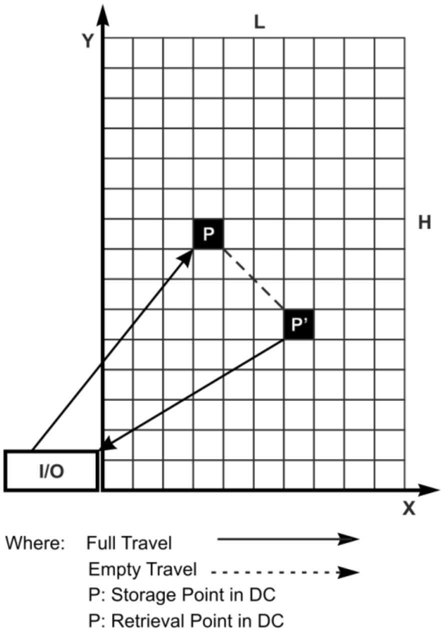


Figure 4.4 The storage and retrieval process in case of DC.

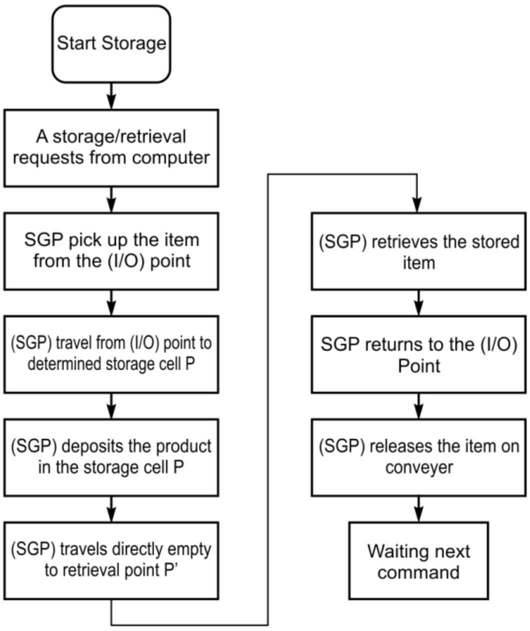


Figure 4.5 : Operating procedure of Dual Command Cycle

4.4 Storage Assignment

The decision made at this stage is the allocation of storage locations for all items, which require storage for a certain period during production. There are different rules for storing items in (AS/RS), based on turnover frequency and the number of items to be stored. [41], [42], [43] present the following Storage Location Assignment Rules:

4.4.1 Dedicated Storage Assignment

In this rule, each product type is assigned a fixed location. Replenishments of that product always occur at this same location. The main disadvantages of dedicated storage are its high space requirements and, consequently, low utilization of space. This is due to the fact that locations are reserved even for products that are out of stock. Furthermore, for each product type sufficient space must be reserved in order to accommodate the maximum inventory level that may occur. Most advantages of dedicated storage, such as locating heavy products at the bottom or matching the layout of stores, are related to non-automated order-picking areas and are of little interest for (AS/RSs).

4.4.2 Random Storage Assignment (RANDOM)

With this method, it is equally likely for any pallet to be stored in any of the vacant "n" rack locations. A location is randomly picked and assigned to the pallet on which it is to be stored if it is empty. Otherwise, another location will be picked. This is an approximation to the closest open location rule where the storage location for a given pallet is selected from a list of open rack locations. Among them, the one closest in time to the (I/O) point is selected. The pallet is stored in this location, regardless of its turnover.

4.4.3 Turnover rate Based Zone Assignment (ZONE)

The storage rack is partitioned into a number of zones, which are equal in number to the number of product groups that were grouped according to their demand curve. The zone closest to (I/O) is assigned to store pallets with the highest turnover rates. When searching for an empty location, if one cannot be found in its own zone, the next lowest turnover zone will be searched. The storage racks are partitioned into a number of classes depending upon turnover rates. This is also called class-based turnover assignment.

4.5 Estimation the Cycle Travel Time

To determine the performance of (SGP-AS/RS), which mainly depends on the total cycle time, the total cycle travel time of storage and retrieval (SGP) is calculated according to the following equation:

$$T_{c.t} = t_0 + (2_{Sc}\ or\ 4_{DC}).t_z + T_{SC/DC} - - - - General\ formula\ [44]$$

Where:

$T_{c.t}$: Total cycle time in seconds.

t_0 : Dead time, e.g. response times, switching times, sensor response, etc. (it is a constant for all travel commands).

t_z : Time needed by (S/R) machine to store or retrieve the pallets in the storage cell (it is a constant for all travel commands).

$T_{SC/DC}$: Actual (S/R) machine traveling time either in Single command (SC) or Dual command (DC) [44].

- **Assumptions**

In order to estimate the traveling time of the (SGP) in both single and dual commands, the following assumptions are made [62]:

- (SGP) holds just one item per route.
- (I/O) point is located in lower-left corner of the storage rack.
- Storage Rack has N storage locations (storage cells), all storage cells are equal in size, and each cell holds only one type of item.
- Each (SGP) is capable of simultaneously moving both vertically and horizontally and directly to any cell in the rack (the Trajectory of (SGP) is straight line).
- (SGP) system operates on both single and dual commands.
- Initial rack length and height, as well as the speed and acceleration/deceleration profiles of the (SGP) are known.
- Demand, or turnover frequency, of each item is constant and known.
- (P/D) times associated with load handling are constants.

4.5.1 SGP's Movements Stages

The (SGP's) movements have to be known. This helps to obtain the formulas and to obtain a correct travel time equation. Therefore, Figure 4.6 describes the moving stages of the (SGP) between two points (i.e. between (I/O) point and any storage cell in case of (SC)). The steps are:

1. Start-up time and picking the product after receiving the storage request.
2. Start-up and moving to the predetermined storage cell.
3. Moving with constant speed.
4. Brakes.
5. Move to "crawl speed" on the determined storage cell.
6. Stop.

These steps represent the (SGP's) movements in case of Single command in Figure 4.6, whereas the (SGP's) movements in case of dual command will be presented later in this section. In the returning stroke, the same steps (1-6) are repeated with varying speed directions and time shares for all movements [44].

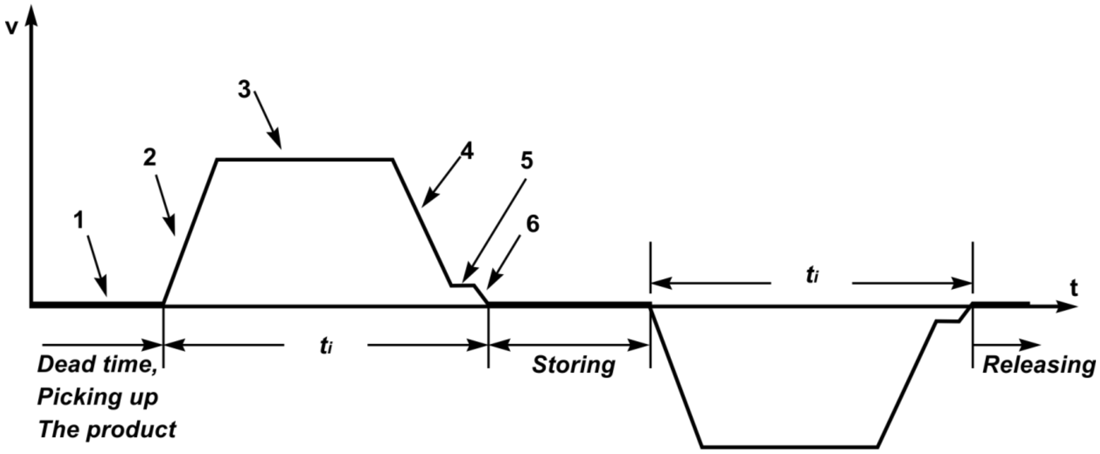


Figure 4.6: The behavior of the AS/RS movements between (I/O) and storage cell I in (SC) [44]

4.5.2 Travel Time Curve

As shown in Figure 4.6, t_l is the time period which describes the actual travel time that the (SGP) moves from (I/O) point to any storage cell I, therefore Figure 4.7 accurately illustrates this time period.

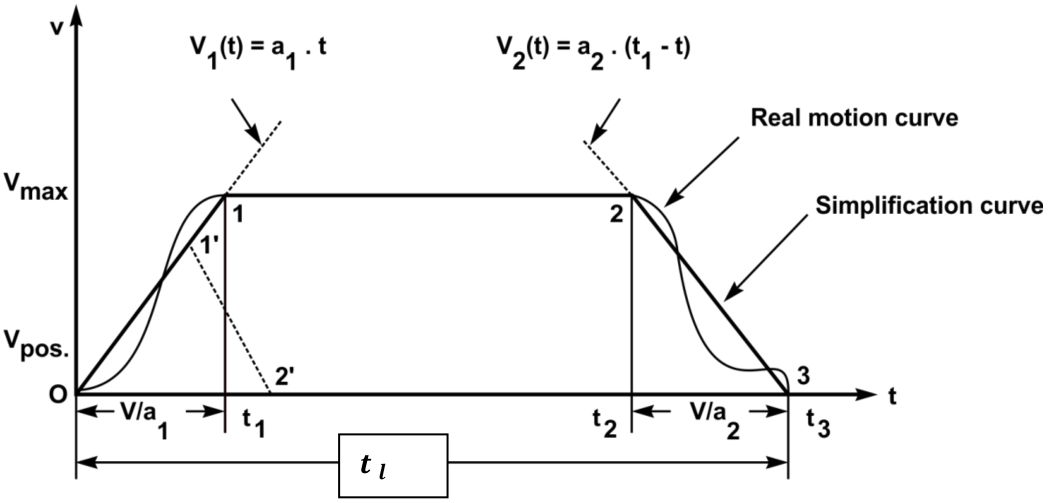


Figure 4.7: Speed-time curve of the (ASRS) motion [44].

The time t_l to reach the storage cell is calculated with the help of the speed–time curve, which is a representation of (SGP) motion, and where time is directly proportional to the speed of (SGP).

After simplification of the real motion process defined as $V = f(t)$ to speed curves for the acceleration, the braking phase becomes linear, and the creep at the deceleration $V_{pos.}$ during the positioning process is neglected. So, this yields the trapeze $0,1,2,3$ $v - t$ characteristics. And for further simplification it is considered that acceleration and deceleration are the same by taking the average value of both of them:

$$a_1 = a_2 = a = \frac{2|a_1 a_2|}{a_1 + |a_2|} \text{ [44].} \qquad (4-1)$$

The travel distance during the t_l after simplification is the area under the trapeze as $0,1,2,3$ $v - t$ curve; therefore, the distance L is equal to the integration value of speed equation up to the point of time as below.

$$l = \int_0^{t_l} v(t)dt = Vt_l - \frac{v^2}{a} \qquad (4-2)$$

With $V = V_{max.}$ therefore, travel time to any point in the storage rack is:

$$t_l = \frac{v}{a} + \frac{l}{v} \qquad for\; l \geq \frac{v^2}{a} \qquad (4-3)$$

l : is a traveling distance from (I/O) point to the storage cell and vice versa in case of (SC) ,or between two storage cells and the time between (TB) in case of (DC) [44].

Where l is calculated according to direct motion of (SGP) to the storage cells and by using Pythagoras theory:

$$l_i = \sqrt{{x_i}^2 + {y_i}^2} \qquad (4-4)$$

where : (x_i) and (y_i) are the coordinates of the storage cell.

In equation (4-3), $V = V_{max.}$ =constant, and a =constant so, $\frac{\mathrm{v}}{\mathrm{a}}$ is a constant value for time when starting and braking while $\frac{L}{V}$ is a dependent variable for time.

But, in the case of $l \leq \frac{v^2}{a}$, as in the trapezoidal represented by $0,1,2,3$ points under the $v - t$ characteristics in Figure 4.3 as an example with plotted points $0', 1', 2'$,this speed–time curve characterizes the travel between two adjacent points, if the travel cycle only starts (accelerate) and brakes (decelerate) where $V_{max.}$ is not yet reached, then the travel distance is:

$$l = a\left(\frac{t_l}{2}\right)^2 \qquad (4-5)$$

Therefore t_l :

$$t_l = 2\sqrt{\frac{l}{a}} \qquad (4-6)$$

Although equations (4-3) and (4-6) are employed to estimate the travel time in both cases (SC) and (DC), one prefers to use equation (4-3) with existing negligible errors due to the moving triangle under the $v-t$ curve , because t_1 is for long distance.

4.5.3 Expected Cycle Travel Time in Single Command

To calculate expected travel time, two alternative storage assignment policies assumed are as follows:

4.5.3.1 Random Storage Assignment in Single Command

The cycle travel time in case of single command as shown in (Figure 4.2 a and b) can be estimated, depending on the travel distance L_i between (I/O) point and storage cell(x_i, y_i); therefore, the expected travel time is generally:

$$E(T_{single}) = E(T_i) = 2 \times \sum_{i=0}^{N} T_i\, P_i \qquad (4-7)$$

To ensure that the expected travel time can be numerically calculated by discrete coordinate of (x_i, y_i).

Where T_i : The travel time to the storage cells and vice versa

P_i : The probability of the (SGP) to go to cell I from total storage cells.

And for all $i = 1, 2, 3 \ldots\ldots N$

According to equation (4-3), $t_l = T_i$ however, since the stored products are assigned randomly to the storage cells in the storage rack, equation (4-7) becomes:

$$E(T_{single}) = 2 \times \sum_{i=0}^{N} (\frac{v}{a} + \frac{l_i}{v}) \times \frac{1}{N} \qquad (4-8)$$

An analytical solution is replaced with $P_i = \frac{1}{N} = constant$, then

$$\frac{1}{N} = \frac{\Delta x . \Delta y}{\sum_i^N \Delta x . \Delta y} = \frac{\Delta x . \Delta y}{area\ of\ the\ rack} \qquad (4-9)$$

As can be seen in Figure 4.8, the cells are represented by $(\Delta x, \Delta y)$, while the area of storage rack is represented by the sum of areas of all cells, which is equal to $(L.H)$, all storage cells have the same probability as in equation (4-9).

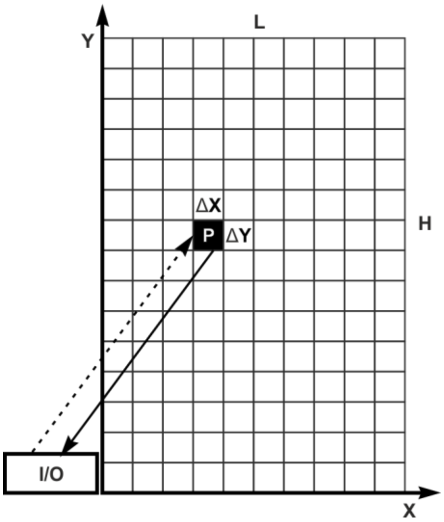


Figure 4.8: storage rack cell dimensions.

$$By\ using\ (Infinitesimals\ Contemplation\ ):N\rightarrow\infty,\quad \Delta x\rightarrow dx,\quad \Delta\rightarrow dy \qquad (4-10)$$

The discrete model of storage rack with a finite number of N storage places is transferred into a continuous model with an infinite, infinitesimally small storage space. According to this assumption, in equation (4-8), integration will be carried out instead of summation, and we finally obtain the following equation:

$$E\left(T_{single}\right)=2\frac{1}{(LH)}\int_{0}^{H}\int_{0}^{L}(\frac{v}{a}+\frac{L}{v})\ dx\,dy \qquad (4-11)$$

And by substituting $L=\sqrt{x^2+y^2}$, equation (4-11) becomes:

$$E\left(T_{single}\right)=2\frac{1}{(LH)}\int_{0}^{H}\int_{0}^{L}(\frac{v}{a}+\frac{\sqrt{x^2+y^2}}{v})\ \ dx\,dy \qquad (4-12)$$

And by using the “trigonometric substitutions” as integration techniques, we obtain the final *unbounded formula* to find expected cycle travel time in case of single command without partitions (class-based storage):

$$E\left(T_{single}\right)=\frac{2}{(LH)}\times\left[\frac{vLH}{a}+\left[\frac{1}{2v}\left[\begin{array}{c}-\frac{H^3}{9}+\frac{2}{3}LH\sqrt{L^2+H^2}\\ +\frac{1}{3}L^3\,log\left(2\left(\sqrt{L^2+H^2}+H\right)\right)\\ +\frac{1}{3}H^3\,log\left(2\left(\sqrt{L^2+H^2}+H\right)\right)\end{array}\right]\right]\right] \qquad (4-13)$$

4.5.3.2 Class–Based Storage Assignment in Single Command

Equation (4-13) represents the (SC) cycle travel time, but this formula does not represent the storage rack in case the storage policy depends on the market demand of the products. Different demands of stored products, which will affect the (S/R) frequency of the stored products, lead to dividing the storage rack into parts to reduce the cycle travel time by assigning the high storage/retrieval frequency products in the part which is closest to the (I/O) point (i.e. highest - turnover products assigned to the highest turnover class, which is located in the closest - location to (I/O) point), and this policy is called “class–based storage policy”. This policy can be applied by using the (ABC) storage analysis to minimize the total cycle travel time for long run, which leads to an improvement of the inventory control system [15].

(ABC) analysis ranking all products in the inventory system by their contribution to the total demand, with “A” items representing the high-volume products “B” the medium-volume products, “C” the low-volume products, and it is typical to find that the small percentage of the products represents the large percentage of the total demand [15]..

Consider a system comprising three classes as in Figure 4.9, class A, B, C and L_A, L_B, L_C, $H_{A,}$ $H_{B,}$ H_C are the symbols representing the borders of the classes respectively, where class A is the closest class to the (I/O) point, and it contains the highest turnover products with a lower storage area, the products which are assigned to classes will be assigned *randomly* inside the class itself, it is unrealistic to assume that the turnover of every product to be stored in the system will be known or constant over time [15]. Moreover, the exact shapes of optimal boundaries between classes are quite difficult to specify [44], therefore, in our case the class boundary shape is considered to be an L-square shape because the L-square shape has the symmetry property about the line from the (I/O) point to the opposite corner of the unit rack [44].

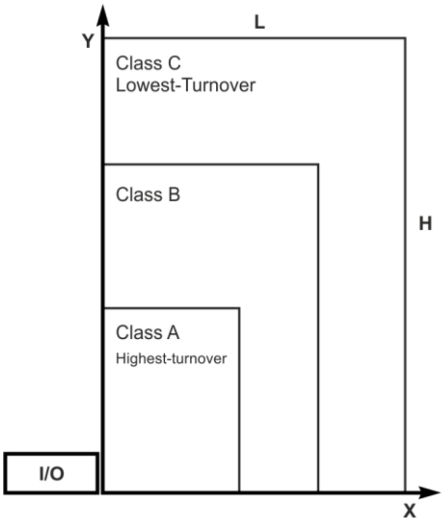


Figure 4.9: Three Classes-Storage rack

According to the partitions above, each partition has N storage places (i.e. N_A, N_B, N_C). These numbers are related to the products–turnover and the (ABC) cumulative demand curve, the L-shape of the classes assumed according to the [44].

The expected cycle travel time of a *classed–based storage* system in single command process is estimated as normal storage rack with a difference in probability P_i of the products according to the turnover percentage, therefore equation (4-7) becomes:

$$E(T_{single}) = 2 \times \sum_{i=0}^{N} T_i \; P(I = i) \qquad (4-14)$$

$P(I = i)$ can be calculated using what is known in probability theory as "*Bayes Formula*" Involving *conditional probability* and by using the analytical solution as in equation (4-9), the probabilities of selected storage cell in each class are:

$$P_A(I = i) = P((I = i|I \in A)P(I \in A) = \frac{P(I \in A)}{N_A} = \frac{P(I \in A) \times \Delta x \Delta y}{Area\ A} \qquad (4-15a)$$

$$P_B(I = i) = P((I = i|I \in B)P(I \in B) = \frac{P(I \in B)}{N_B} = \frac{P(I \in B) \times \Delta x \Delta y}{Area\ B} \qquad (4-15b)$$

$$P_C(I = i) = P((I = i|I \in C)P(I \in C) = \frac{P(I \in C)}{N_C} = \frac{P(I \in C) \times \Delta x \Delta y}{Area\ C} \qquad (4-15c)$$

where $P(I \in class\ (A\ or\ B\ or\ C))$ represents the turnover value (storage/retrieval frequency value) of the class (i.e. class A).

But in order to differentiate the classes with respect to the (I/O) point, it is necessary to define the closeness of the class from (I/O) point (i.e. storage cells in class A are the closest coordinates to the (I/O) point), therefore equation 14 becomes:

$$E(T_{single}) = 2 \times \left[\sum_{i=0}^{N_A} T_{iA} \times P_A(I = i) + \sum_{i=0}^{N_B} T_{iB} \times P_B(I = i) + \sum_{i=0}^{N_C} T_{iC} \times P_C(I = i) \right] \qquad (4-16)$$

By substituting the values of T_i, L_i and $P(I = i)$, the formula becomes:

$$E(T_{single}) = 2 \times \left[\begin{array}{l} \sum_{i=0}^{N_A} (\frac{v}{a} + \frac{\sqrt{x^2 + y^2}}{v}) \times \frac{P(I \in A) \times \Delta x \Delta y}{Area\ A} \\ + \sum_{i=0}^{N_B} (\frac{v}{a} + \frac{\sqrt{x^2 + y^2}}{v}) \times \frac{P(I \in B) \times \Delta x \Delta y}{Area\ B} \\ \sum_{i=0}^{N_C} (\frac{v}{a} + \frac{\sqrt{x^2 + y^2}}{v}) \times \frac{P(I \in C) \times \Delta x \Delta y}{Area\ C} \end{array} \right] \qquad (3-17)$$

$$By\ using\ (Infinitesimals\ Contemplation): N \to \infty, \quad \Delta x \to dx, \quad \Delta \to dy \qquad (4-18)$$

Finally, the expected cycle travel time $E(T_{single})$ will be calculated according to the following equation:

$$E\left(T_{single}\right) = 2 \times \left[\begin{array}{l} \left[\int_{0}^{H_A} \int_{0}^{L_A} \left(\frac{v}{a} + \frac{\sqrt{x^2+y^2}}{v}\right) dx\, dy \ \times \frac{P(I \in A)}{Area\ A} \right] \\ + \left[\int_{H_A}^{H_B} \int_{L_A}^{L_B} \left(\frac{v}{a} + \frac{\sqrt{x^2+y^2}}{v}\right) dx\, dy \times \frac{P(I \in B)}{Area\ B} \right] \\ + \left[\int_{H_B}^{H_C} \int_{L_B}^{L_C} \left(\frac{v}{a} + \frac{\sqrt{x^2+y^2}}{v}\right) dx\, dy \times \frac{P(I \in C)}{Area\ C} \right] \end{array} \right] \qquad (4-19)$$

Due to the complexity of this kind of integration, some computer mathematical software like *Mathmatica* or *Matlab* has to be used, in our case *Mathmatica* software has been used to solve this kind of integration, where *Mathmatica* is a computational software program used in scientific, engineering, and mathematical fields and other areas of technical computing. The unbounded solution of equation 19 is shown below in equation (4-20).

$$E\left(T_{single}\right) =$$

$$2 \times [\ [\ \frac{\nu L_A H_A}{a} + \frac{1}{2}[- \frac{H_{A^3}}{9} + \frac{2}{3}\ L_A H_A \sqrt{{L_A}^2 + {H_A}^2} + \frac{1}{3}\ {L_A}^3\, log\left(2\left(\sqrt{{L_A}^2 + {H_A}^2} + H_A\right)\right)$$
$$+ \frac{1}{3}\ {H_A}^3\, log\left(2\left(\sqrt{{L_A}^2 + {H_A}^2} + L_A\right)\right)\ ] \times \frac{P(1 \in A)}{Area\ A}\ \ ]$$

$$+[[\ [\ \frac{\nu L_s H_s}{a} + \frac{1}{2}[- \frac{H_{s^3}}{9} + \frac{2}{3}\ L_s H_s \sqrt{{L_s}^2 + {H_s}^2}\ H_S$$
$$+ \frac{1}{3}\ {L_s}^3\, log\left(2\left(\sqrt{{L_s}^2 + {H_s}^2 + H_s} \ + H_s\right)\right) \frac{1}{3}\ {H_s}^3\, log\left(2\left(\sqrt{{L_s}^2 + {H_s}^2} \ + L_s\ \right)\right)\ ]\ ]$$

$$-[[\ [\ \frac{\nu L_A H_A}{a} + \frac{1}{2}[- \frac{H_{A^3}}{9} + \frac{2}{3}\ L_A H_A \sqrt{{L_A}^2 + {H_A}^2}$$
$$+ \frac{1}{3}\ {L_A}^3\, log\left(2\left(\sqrt{{L_A}^2 + {H_A}^2} \ + H_A\ \right)\right) + \frac{1}{3}\ {H_A}^3\, log\left(2\left(\sqrt{{L_A}^2 + {H_A}^2} \ + L_A\ \right)\right)\ ]\ ]$$
$$\times \frac{P(1 \in B)}{Area\ B}\ \ ]$$

$$+[[\ [\ \frac{\nu L_C H_C}{a} + \frac{1}{2}[- \frac{H_{C^3}}{9} + \frac{2}{3}\ L_C H_C \sqrt{{L_C}^2 + {H_C}^2} \ + \frac{1}{3}\ {L_C}^3\, log\left(2\left(\sqrt{{L_C}^2 + {H_C}^2} + H_C\ \right)\right)$$
$$+ \frac{1}{3}\ {H_C}^3\, log\left(2\left(\sqrt{{L_C}^2 + {H_C}^2} \ + L_C\ \right)\right)\ ]\ ]$$

$$-[[\ [\ \frac{\nu L_S H_S}{a} + \frac{1}{2}[- \frac{H_{S^3}}{9} + \frac{2}{3}\ L_S H_S \sqrt{{L_S}^2 + {H_S}^2} \ +$$
$$\frac{1}{3}\ {L_S}^3\, log\left(2\left(\sqrt{{L_S}^2 + {H_S}^2} \ + H_S\ \right)\right) + \frac{1}{3}\ {H_S}^3\, log\left(2\left(\sqrt{{L_S}^2 + {H_S}^2} \ + L_S\ \right)\right)\ ]\ ]\ ] \times \frac{P(1 \in C)}{Area\ C}\ \ ]\ ] \qquad (4-20)$$

4.5.4 The Expected Cycle Travel Time in Dual Command

Dual command, sometimes called “interleaving system“, is capable of visiting two rack storage locations (P, P') between successive returns to the (I/O) point, so after completing a given storage request, the (SGP) can travel directly to the next retrieval location without returning to the (I/O) point. No doubt a dual command storage system permits potentially higher throughput than a single command storage system. However, a maximum throughput of dual command system may only be obtained from an optimal combined storage/retrieval assignment. In this section, I will examine two alternative storage policies in dual command as before [44].

The following Figure 4.10 explains the AS/RS travel movements in dual command cycle time.

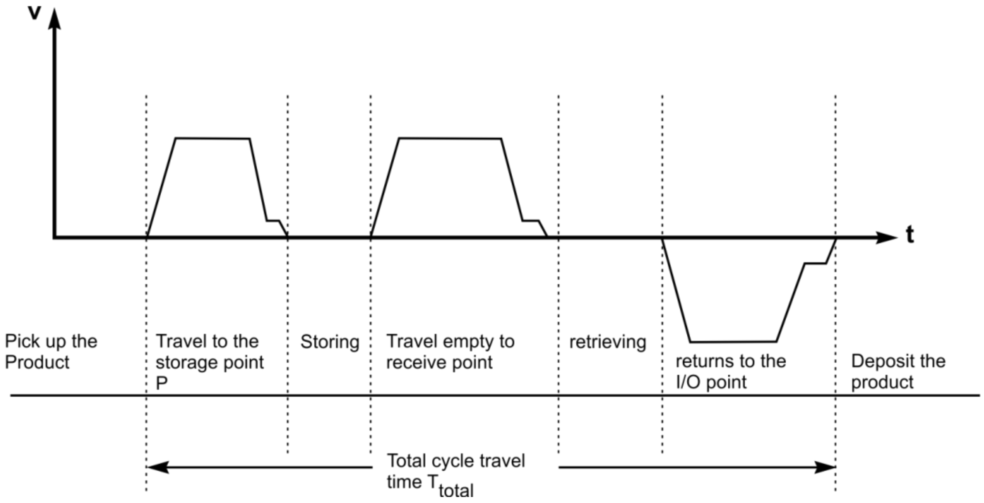


Figure 4.10: The behavior of the AS/RS movements in dual command [44].

As mentioned before, each dual command cycle involves two random locations (P, P'), the first one represents the storage cell, while the second represents the retrieval cell, and the products are assigned randomly to these storage locations.

As single command, two alternative storage assignment policies were assumed to estimate dual command cycle time as following:

4.5.4.1 Random Storage Assignment in Dual Command:

The expected cycle travel time of dual command can be calculated by the following general formula (4-21):

$$E(T_{Dual}) = E\left(T_{(0-i-j-0)}\right) = T_{0i} + T_{ij} + T_{j0} \qquad (4-21)$$

In fact $T_{0i} = T_{j0}$, which is equal to single command cycle travel time (SC), where T_{ij} is the time between two storage points (P, P'), and it is already called the time between (TB). Therefore, the above equation becomes:

$$E(T_{Dual}) = E(SC) + E(TB) \qquad (4-22)$$

As we assumed before, the products are assigned randomly to the storage cells, so the expected cycle travel time in dual command calculated under the assumption that the storage place P and retrieval place P' are selected randomly from the storage rack, therefore the probabilities for P and P' are:

$$P(I = i) = \frac{1}{N} \qquad (4-23a)$$

$$P(J = j) = \frac{1}{N-1} \qquad (4-23b)$$

Where: $i\,, j = 1, 2, 3, \dots \dots . . N\,. For\ i \neq j$

$E(SC)$ has been calculated in 3.6.3-A, and in the next analysis the expected time between $E(TB)$ will be calculated according to the assumptions above:

$$E(TB) = E(T_{ij}) = \sum_{J=0}^{N-1} \sum_{i=1}^{N} T_{ij} \times P(I = i, J = j) \qquad (4-24)$$

where T_{ij} : is the travel time between two storage points (P, P'), and it is same as in equation (4-3), and the travel movements will be the same as the travel movements between (I/O) point and any storage cell, but there are some differences in the probabilities and the travel distance measures as below :

$$P(I = i, J = j) = \frac{1}{N(N-1)} = Constant \qquad (4-25a)$$

$$L_{ij} = \sqrt{(x - x')^2 + (y - y')^2} \qquad (4-25b)$$

where the storage place P coordinates are represented by (x, y) while P' coordinates are represented by(x', y').

From a practical point of view $(\Delta x . \Delta y) \ll (\text{area of the rack})$ then the probability becomes:

$$\frac{1}{N(N-1)} \cong \frac{\Delta x . \Delta y . \Delta x' . \Delta y'}{(rack's\ area)^2} \qquad (4-26)$$

Therefore, equation (4-24) becomes:

$$E(TB) = E(T_{ij}) = \sum_{J=0}^{N} \sum_{i=1}^{N} \frac{v}{a} + \frac{\sqrt{(x - x')^2 + (y - y')^2}}{v} \times \frac{\Delta x . \Delta y . \Delta x' . \Delta y'}{(rack's\ area)^{\,2}} \qquad (4-\ 27)$$

By using “infinitesimal contemplation”:

$$N \to \infty, \quad \Delta x \to dx, \quad \Delta y \to dy\,, \qquad \Delta x' \to dx', \qquad \Delta y' \to dy' \qquad (4-28)$$

Under this assumption, instead of the summation in equation (4-27) integration will be performed as in equation (4-11):

$$E(TB) = E\left(T_{ij}\right) = \frac{1}{(LH)^2} \int_0^H \int_0^L \int_0^H \int_0^L \frac{v}{a} + \frac{\sqrt{(x-x')^2 + (y-y')^2}}{v} \; dx.dy.dx'.dy' \qquad (4-29)$$

By inserting the values of this equation in equation (4-22), we will obtain the expected cycle travel time of the (SGP) in the case of random storage assignment in dual command, but actually the integration solution of equation (4-29) is not practical. In order to solve this kind of problem, we have to perform approximation, instead of integration by using one of the following two practical methods:

1. Assuming the worst case by taking the average of the maximum distance between the farthest two storage cells in the rack as $L_{cons.}$, which becomes constant, not variable, or
2. Carry out the integration without square root of distance.

The first method of approximation has been chosen to solve this kind of mathematical problem as below:

$$L_{cons.} = \frac{L_{Max.(P-P')}}{2} = \frac{\sqrt{(x-x')^2 + (y-y')^2}}{2} \qquad (4-30)$$

where $L_{cons.}$ is a constant value, which is calculated according to the storage rack dimensions, and will be substituted as a constant value in equation (4-31).

Finally, the average travel time between P and P' is:

$$E(TB) = E\left(T_{ij}\right) = \frac{v}{a} + \frac{L_{Max.(P-P')}}{2v} \qquad (4-31)$$

The total expected cycle travel time in dual command “randomly storage assigned” is obtained by substituting equations (4-31) and (4-13) in equation (4-22).

4.5.4.2 Class-Based Storage Assignment in Dual Command

In the previous case we discussed the random storage assignment without classes, but when the storage rack is class-based, then the expected cycle travel time is different. It is conceptually similar to the case discussed in 4.6.3.2, but with different probability values for each class. The dual command case is shown in Figure 4.11, where there are nine travel possibilities of (SGP) from P to P', each with a different probability value.

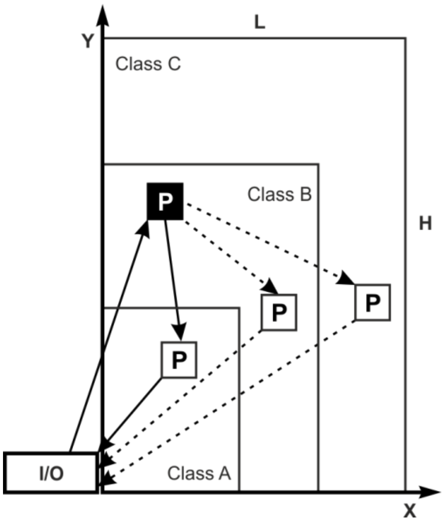


Figure 4.11: The classed –based dual command storage system.

The nine travel possibilities are $T_{A-A}, T_{A-B}, T_{A-C}, T_{B-B}, T_{B-A}, T_{B-C}, T_{C-C}, T_{C-A}, T_{C-B},$

The expected travel time is calculated as in equation 22 → $E(T_{Dual}) = E(SC) + E(TB)$,where the value of $E(SC)$ is taken from the result of equation (4-20) and the $E(TB)$ value is calculated by taking each of the two classes as individual cycle travel and finally summing the nine cases together as follows:

$$E(TB) = E\left(T_{ij}\right) = \begin{bmatrix} \displaystyle\sum_{j-0}^{N_A}\sum_{i=0}^{N_A} T_{ij} \times P(I = i, J = j) \\ \displaystyle + \sum_{j=0}^{N_B}\sum_{i=0}^{N_A} T_{ij} \times P(I = i, J = j) \\ \displaystyle + \ldots + \sum_{j=0}^{N_B}\sum_{i=0}^{N_C} T_{ij} \times P(I = i, J = j) \end{bmatrix} \qquad (4-32)$$

By using Bayes Formula but involving conditional probability, the probability of each travel possibility is:

$$P_{A-A}, P_{A-B}, P_{A-C}, P_{B-B}, P_{B-A}, P_{B-C}, P_{C-C}, P_{C-A}, P_{C-B} \qquad (4-32a)$$

$$P_{A-\boldsymbol{A}}(I = i, J = j) = P((I = i, J = j | I \in A, J \in A) P(I \in A) P(J \in A) = \frac{P(I \in A)\, P(J \in A)}{{N_A}^2}$$
$$= \frac{P(I \in A)\, P(J \in A) \times \Delta x . \Delta y . \Delta x' . \Delta y'}{(Area\ A)^2} \qquad (4-32b)$$

$$P_{A-\boldsymbol{B}}(I = i, J = j) = P((I = i, J = j | I \in A, J \in B) P(I \in A) P(J \in B) = \frac{P(I \in A)\, P(J \in B)}{N_A \times N_B}$$
$$= \frac{P(I \in A)\, P(J \in B) \times \Delta x . \Delta y . \Delta x' . \Delta y'}{(area\ A) \times (area\ B)} \qquad (4-32c)$$

$$P_{A-\boldsymbol{C}}(I=i,J=j)=P((I=i,J=j|I\in A,J\in C)P(I\in A)P(J\in C)=\frac{P(I\in A)\,P(J\in C)}{N_A*N_C}$$

$$=\frac{P(I\in A)\,P(J\in C)*\ \Delta x.\Delta y.\Delta x'.\Delta y'}{(area\ A)*(area\ C)} \qquad (4-32d)$$

$$P_{B-\boldsymbol{B}}(I=i,J=j)=P((I=i,J=j|I\in B,J\in B)P(I\in B)P(J\in B)=\frac{P(I\in B)\,P(J\in B)}{{N_B}^2}$$

$$=\frac{P(I\in B)\,P(J\in B)\times\Delta x.\Delta y.\Delta x'.\Delta y'}{(Area\ B)^2} \qquad (4-32e)$$

$$P_{B-\boldsymbol{A}}(I=i,J=j)=P((I=i,J=j|I\in B,J\in A)P(I\in B)P(J\in A)=\frac{P(I\in B)\,P(J\in A)}{N_B\times N_A}$$

$$=\frac{P(I\in B)\,P(J\in A)\times\ \Delta x.\Delta y.\Delta x'.\Delta y'}{(area\ B)\times(area\ A)} \qquad (4-32f)$$

$\Big\downarrow$ until

$$P_{C-\boldsymbol{B}}(I=i,J=j)=P((I=i,J=j|I\in C,J\in B)P(I\in C)P(J\in B)=\frac{P(I\in C)\,P(J\in B)}{(N_C)\times(N_B)}$$

$$=\frac{P(I\in C)\,P(J\in B)\times\ \Delta x.\Delta y.\Delta x'.\Delta y'}{(area\ C)\times(area\ B)} \qquad (4-32g)$$

By using “infinitesimal contemplation”:

$$N\to\infty,\quad \Delta x\to dx,\quad \Delta y\to dy\,,\qquad \Delta x'\to dx',\qquad \Delta y'\to dy' \qquad (4-33)$$

As before, converting the summation to integration taking into consideration the right integral limits as follows:

$$(TB)=E(T_{ij)}=$$

$$\int_0^{H_A}\int_0^{L_A}\int_0^{H_A}\int_0^{L_A}(\frac{v}{a}+\frac{\sqrt{(x-x')^2+(y-y')^2}}{v})\,dx.dy.dx'.dy'\times\frac{P(I\ \in A)P(J\ \in A)}{(area\ A)^2}$$

$$+\int_{H_A}^{H_A}\int_{L_A}^{L_A}\int_0^{H_A}\int_0^{L_A}(\frac{v}{a}+\frac{\sqrt{(x-x')^2+(y-y')^2}}{v})\,dx.dy.dx'.dy'\times\frac{P(I\ \in A)P(J\ \in B)}{(area\ A)(area\ B)}$$

$$+\int_{H_A}^{H_B}\int_{H_A}^{L_B}\int_0^{H_A}\int_0^{L_A}(\frac{v}{a}+\frac{\sqrt{(x-x')^2+(y-y')^2}}{v})\,dx.dy.dx'.dy'\times\frac{P(I\ \in A)P(J\ \in C)}{(area\ A)(area\ C)}$$

$$+\int_{H_A}^{H_B}\int_{L_A}^{L_B}\int_0^{H_A}\int_0^{L_A}(\frac{v}{a}+\frac{\sqrt{(x-x')^2+(y-y')^2}}{v})\,dx.dy.dx'.dy'\times\frac{P(I\ \in B)P(J\ \in B)}{(area\ B)^2}$$

$$+\int_{H_A}^{H_B}\int_{L_A}^{L_B}\int_{0}^{H_A}\int_{0}^{L_A}(\frac{v}{a}+\frac{\sqrt{(x-x')^2+(y-y')^2}}{v})\,dx.dy.dx'.dy'\times\frac{P(I\in B)P(J\in A)}{(area\ B)(area\ A)}$$

$$\Big\downarrow\text{Until}$$

$$+\int_{H_A}^{H_B}\int_{L_A}^{L_B}\int_{0}^{H_A}\int_{0}^{L_A}(\frac{v}{a}+\frac{\sqrt{(x-x')^2+(y-y')^2}}{v})\,dx.dy.dx'.dy'\times\frac{P(I\in C)P(J\in B)}{(area\ C)(area\ B)}$$

$$(4-34)$$

Similar to equation (4-29), the result of equation (4-34) is not practical, thus we have to approximate the integration as in equation (4-30), taking the average maximum possible travel distance between the farthest two storage points in the same class and in two different classes (P, P'). The final equation which approximates the integration in equation (4-34) is written as:

$$E(TB)=E(T_{ij)}=\sum\frac{v}{a}+\frac{L_{max.(P-P')}}{2v}\quad\times P(I=i,J=j)\qquad(4-35)$$

Therefore, by estimating the average maximum distance between the farthest two storage cells in nine travel possibilities, the value of each possibility is multiplied by its assigned probabilities.

Finally, the average expected cycle travel time is calculated by substituting the following equation in equation (4-22):

$$E(TB)=E(T_{ij)}=\begin{bmatrix}\left(\frac{v}{a}+\frac{L_{A-A}}{2v}\times P(I\in A,J\in A)\right)\\+\left(\frac{v}{a}+\frac{L_{A-B}}{2v}\times P(I\in A,J\in B)\right)\\+\left(\frac{v}{a}+\frac{L_{A-C}}{2v}\times P(I\in A,J\in C)\right)\\+\ldots+\left(\frac{v}{a}+\frac{L_{C-B}}{2v}\times P(I\in C,J\in B)\right)\end{bmatrix}\qquad(4-36)$$

4.6 The Impact of (I/O) Location and Class Boundaries on the Cycle Travel Time

In the previous sections, the cycle travel time of (SGP) was calculated assuming that (I/O) point is located in the lower left corner of the rack. However if the (I/O) point is located in the lower-middle of the rack, some improvement could be expected in the throughput of the storage system. Therefore, we will examine the cycle travel time according to (I/O) point related to the storage rack in the class–based storage system (SC).

As is shown in the following Figure 4.12, the (I/O) point is located in the lower-middle of the storage rack, and it is considered to be the reference point $(0, 0)$:

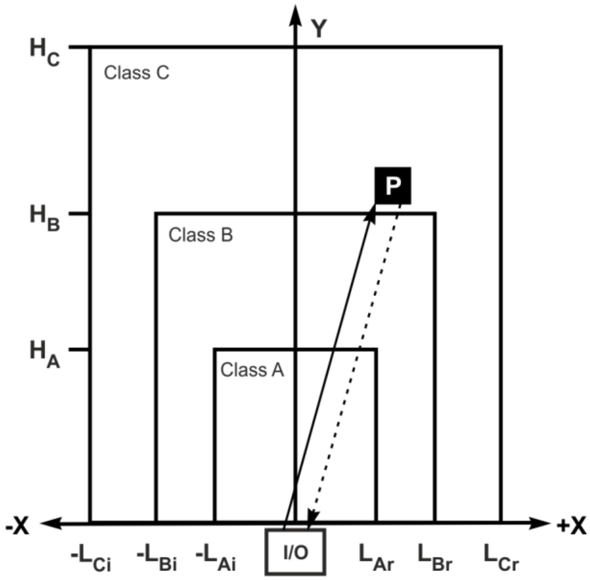


Figure 4.12: the I/O point is located in the lower-middle of the storage rack.

In order to calculate the expected cycle travel time based on the new location of (I/O) point, the (I/O) point is assumed to be the reference point to (0.0), and similar to the previous cases, the formula remains the same, but with some modifications in the integral limits in equation (4-19) as shown below:

$$E\left(T_{single}\right) = 2 \times \left[\begin{array}{l} \left(\int_{0}^{H_A} \int_{-L_{Al}}^{L_{Ar}} \left(\frac{v}{a} + \frac{\sqrt{x^2+y^2}}{v}\right) dx\,dy \right) \times \frac{P(I \in A)}{area\ A} \\ + \left(\int_{0}^{H_B} \int_{-L_{Bl}}^{L_{Br}} \left(\frac{v}{a} + \frac{\sqrt{x^2+y^2}}{v}\right) dx\,dy - \int_{0}^{H_A} \int_{-L_{Al}}^{L_{Ar}} \left(\frac{v}{a} + \frac{\sqrt{x^2+y^2}}{v}\right) dx\,dy \right) \times \frac{P(I \in B)}{area\ B} \\ + \left(\int_{0}^{H_C} \int_{-L_{Cl}}^{L_{Cr}} \left(\frac{v}{a} + \frac{\sqrt{x^2+y^2}}{v}\right) dx\,dy - \int_{0}^{H_B} \int_{-L_{Bl}}^{L_{Br}} \left(\frac{v}{a} + \frac{\sqrt{x^2+y^2}}{v}\right) dx\,dy \right) \times \frac{P(I \in C)}{area\ C} \end{array} \right] \qquad (4-37)$$

Equation (4-37) will be solved like equation (4-19), L and H values are substituted. In that case the boundaries of the classes are changed with (I/O) point still remaining in the lower-middle of (S/R) as in Figure 4.13.

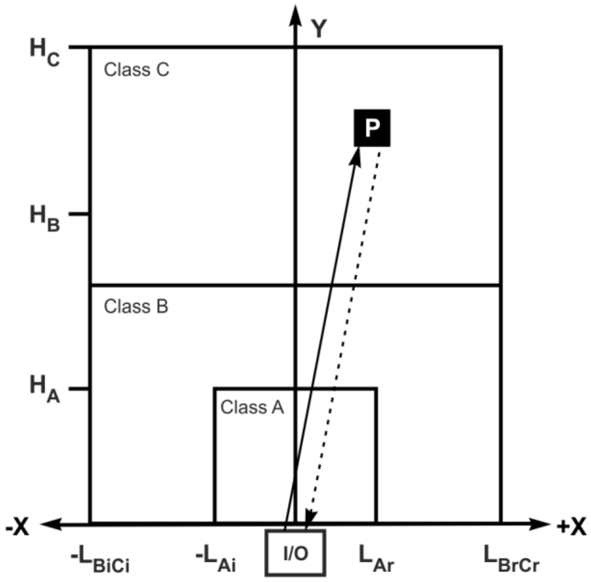


Figure 4.13: The new shape of the classes.

The new formula to calculate the expected cycle travel time in single command is the modification of the last part in equation (4-37) as below:

$$E\left(\mathrm{T_{single}}\right) =$$

$$2 \times \left[\begin{array}{c} \left(\int_{0}^{H_A}\int_{-L_{Al}}^{L_{Ar}} \frac{v}{a}+\frac{\sqrt{x^2+y^2}}{v}\,dx\,dy\right)\times\frac{P(I\in A)}{area\ A} \\ +\left(\int_{0}^{H_B}\int_{-L_{Bl}}^{L_{Br}} \frac{v}{a}+\frac{\sqrt{x^2+y^2}}{v}dx\,dy-\int_{0}^{H_A}\int_{-L_{Al}}^{L_{Ar}} \frac{v}{a}+\frac{\sqrt{x^2+y^2}}{v}dx\,dy\right)\times\frac{P(I\in B)}{area\ B} \\ +\left(\int_{H_B}^{H_C}\int_{-L_{Cl}}^{L_{Cr}} \frac{v}{a}+\frac{\sqrt{x^2+y^2}}{v}\,dx\,dy\right)\times\frac{P(I\in C)}{area\ C} \end{array}\right] \qquad (4-38)$$

4.7 Numerical Results:

In order to prove the efficiency of SGP-AS/RS design and operations, we have to prove that by the following numerical example [62]

If we have a storage rack with the following Parameters:

- Length = 20 m
- Height = 40 m
- The SGP liner speed = 6 m/s
- The SGP acceleration/deceleration = 5 m/s²
- The input /output point is located in the lower-left corner of the storage rack.

4.7.1 The Cycle Travel Time of the SGP-AS/RS

1- Random Storage Assignment in Single Command:

The single command cycle time in case of random storage assignment according to equation 4.12 is:

$$E(Tsingle) \ = 2 \ \frac{1}{(20\ .\ 40)} \int_0^{40} \int_0^{20} \frac{6}{5} + \frac{\sqrt{x^2+y^2}}{6} dx\, dy$$

By using the Mathematica software the integration of term $\sqrt{\mathrm{x}^2+\mathrm{y}^2}$ is:

$$\int_0^{40} \int_0^{20} \sqrt{x^2+y^2} = \frac{4000}{3} \left[4\sqrt{5} \ + 8 * ArcCsch(2) + ArcSinh(2)\right] = 21239{,}3$$

Therefore the Single command cycle time in case of random storage is:

$$E(Tsingle) = 2 * \left[\frac{1}{(20 * 40)} \left[\frac{6 * 20 * 40}{5} + 21239\frac{3}{6}\right]\right] = 11{,}24\ sec.$$

2- Classed –Based Storage Assignment in Single Command:

In class –based case the dimensions of the class have to be known in order to substitute the limits of the integration in equation 4.19, therefore, the dimensions of the classes are calculated according to the storage rack area = 800 m², and the assumption that the $\frac{\mathrm{Li}}{\mathrm{Hi}} = \frac{1}{2}$,the dimensions are represented in the table 4.1 :

Classes i	Percentage of class space (area)	Length (m)	Height (m)	Real class area (m²)	Percentage of activity = P(I ∈ class i)
Class A	30% = 240 m²	LA ≅ 11 m	HA ≅ 22 m	242 m²	80 %
Class B	30% = 240 m²	LB ≅ 15.5 m	HB ≅ 31 m	238.5 m²	15 %
Class C	40 % = 320 m²	LC ≅ 20 m	HC ≅ 40 m	319.5 m²	5 %

Table 4.1: The dimensions of classes according to “ABC storage policy”.

Relating to the dimensions of the classes, and by using equation 4.19, the cycle travel time is:

$$E(Tsingle) = 2 * \left[\left[\int_0^{22}\int_0^{11} (\frac{v}{a} + \frac{\sqrt{x^2+y^2}}{v} dx\, dy\right] * \frac{P(I \in A)}{Area\ A}\right]$$
$$+ \left[\int_{22}^{31}\int_{11}^{15,5} (\frac{v}{a} + \frac{\sqrt{x^2+y^2}}{v} dx\, dy\right]$$

Finally, the Single command cycle time is:

$$E(Tsingle) = \ 2 \ * \ \Bigg[\Big[[\frac{6}{5} * (11 * 22) \ + 3533\ \frac{7}{6}\Big] * \frac{0,8}{242}\Bigg]$$
$$+ \left[\left[\frac{6}{5} * [(15,5 * 31) - (11 * 22)] + \left[1201.\frac{78}{6}\right]\right] * \frac{15,5}{238}\right]$$
$$+ \left[\left[\frac{6}{5} * [(40 * 20) - (15,5 * 31)] + \left[.\frac{78}{6}\right]\right] * \frac{0,15}{238}\right]$$

3- Random Storage Assignment in Dual Command:

As the equation 4.22 (TDual) = E (SC) + E (TB), the value of the first term is already known from part (A) which equal to 11.24 second.

And the value of second term is calculated according to equation 4.31:

$$E(TB) = E(T0,0 - 20,40) = \frac{6}{5} + \frac{LMax(0,0 - 20,40)}{2 * 6} = 1,2 + 44.\frac{721}{12} = 4,93\ sec.$$

Thus, the Dual command cycle time in case of random storage without class is:

$$E(TDual) = 11,24 + 4,93 = 16,17\ sec.$$

4- Classed-Based Storage Assignment in Dual Command:

As above, by equation 4.22 the first term is known from part (B) which is equal to 6.6738 sec., and the second term $\mathrm{E(TB)}$ can be calculated by equation 4.36 as below:

$$E(TB) = \left[\frac{6}{5} + \frac{L(0{,}0 - 11{,}22)}{12} * (0{,}8 * 0{,}8)\right] + \left[\frac{6}{5} + \frac{L(0{,}0 - 15{,}5.31)}{12} * (0{,}8 * 0{,}15)\right] + \left[\frac{6}{5} + \frac{L(0{,}0 - 20{,}40)}{12} * (0{,}8 * 0{,}..)\right] =$$

So the Dual command cycle time in case of classed –based is:

$$E(TDual) = 6{,}636 + 3{,}56212 = 10{,}19812\ sec.$$

5- Changing the I/O point Location:

Under the same conditions, but the I/O point is located in the lower- middle of the storage rack and it's considered to be the reference point (0, 0), equation 4.37 is used to calculate the Single command cycle travel time as below:

$$E(Tsingle) = 2 * \left[\left[\int_0^{22}\int_{-5{,}5}^{5{,}5} (\frac{6}{5} + \frac{\sqrt{x^2+y^2}}{6} dx\, dy\right] * \frac{0{,}8}{242}\right] + \left[\int_0^{31}\int_{-7{,}75}^{7{,}75} (\frac{6}{5} + \frac{\sqrt{x^2+y^2}}{6} dx\, dy\right]$$

6- Change the classes shape and boundaries:

In case of changing the boundaries of the classes as figure 4.9, the single travel time can be calculated by using equation 4.38, with changing in the integration limits as below:

$$E(Tsingle) = 2 * \left[\left[\int_0^{22}\int_{-5{,}5}^{5{,}5} (\frac{6}{5} + \frac{\sqrt{x^2+y^2}}{6} dx\, dy\right] * \frac{0{,}8}{242}\right] + \left[\int_0^{24}\int_{-10}^{10} (\frac{6}{5} + \frac{\sqrt{x^2+y^2}}{6} dx\, dy\right]$$

7- Calculation for Conventional AS/RS:

In order to prove SGP-AS/RS it has to compared with conventional AS/RS ,we have to examine one system under the same conditions , therefore ,the following system represents a technical system which is exist in the market ,and I will calculate the cycle travel time according to the given equations :

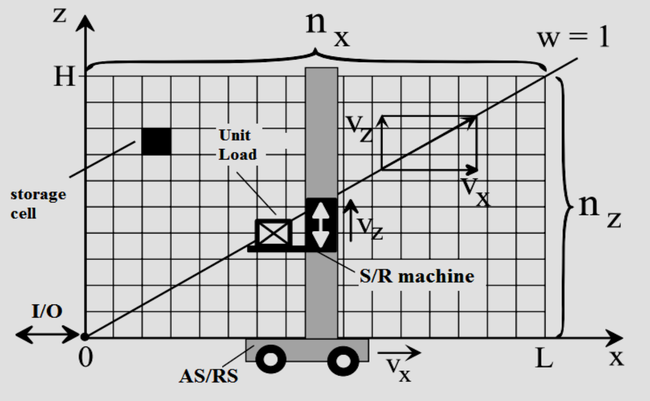


Figure 4.14: The movement of the AS/RS machine [44]

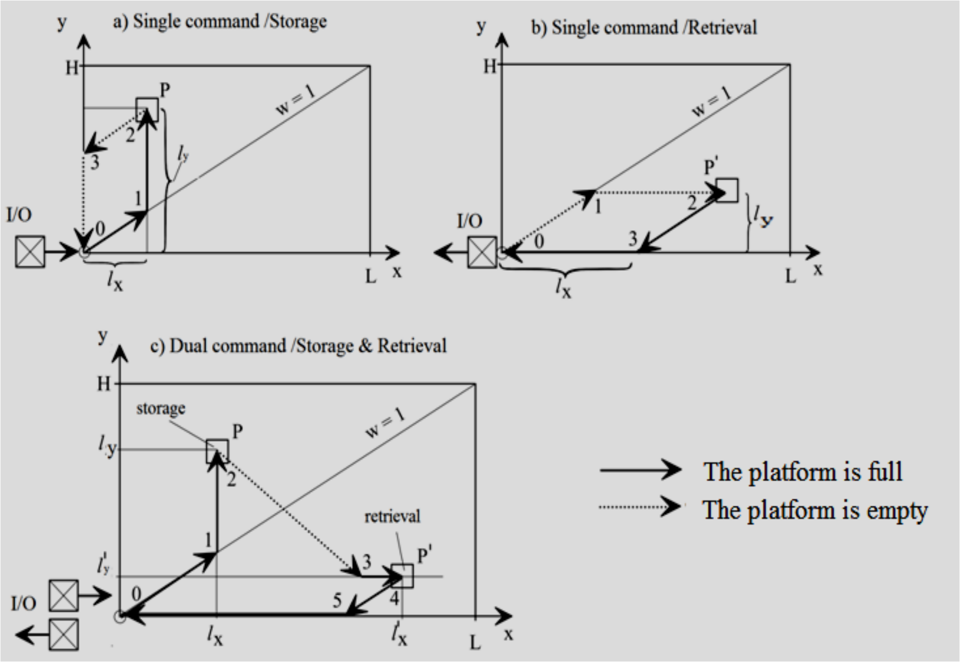


Figure 4.15: An example for S/R machine movements in single and dual command [44]

Where: p is storge place

p´ is retrieval place

Shape factor: $w=\frac{Vx}{Vy}\cdot\frac{H}{L}$

The equation to calculate the Single Command cycle time for S/R machine is: [44]

$$E(T)=2*\left[\left[1-\frac{w}{2}\right]\frac{Vx}{ax}+\frac{w}{2}\frac{Vy}{ay}+\frac{L}{Vx}\left[\frac{1}{2}+\frac{1}{6}w^{2}\right]\right], if\ w\ \le 4---39$$

$$E(T)=2*\left[\frac{1}{2w}\frac{Vx}{ax}+\left[1-\frac{1}{2w}\right]\frac{Vy}{ay}+\frac{L}{Vx}\left[\frac{w}{2}+\frac{1}{6w}\right]\right], if\ w\ \ge 4---40$$

These two equations describe the S/R machine movements in case of random storage without class- based policy, taking into consideration the shape factor (w).

For comparing this system with our system it should be examine it under the same conditions so the parameters are:

- H =40 meter
- L = 20 meter
- V=6 $\mathrm{m/s}$
- Vx = 5 $\mathrm{m/s}$ (assumption)
- Vy = 3,32 $\mathrm{m/s}$

- a= 5 $\mathrm{m/s^2}$
- ax = 4 $\mathrm{m/s^2}$ (assumption)
- ay = 3 $\mathrm{m/s^2}$

Therefore the single command cycle time in random storage policy is estimated as following:

$$w = \frac{5}{4} * 32 * \frac{40}{20} = 3 \ \leq 1, \qquad use\ equation\ 4.40$$

Thus, the cycle travel time for the S/R machine in case of random storage without class-based assignment.

$$E(T) = 2\left[\frac{1}{2\,.\,3} * \frac{5}{4} + \left[1 - \frac{1}{2\,.\,3}\right] 3 * \frac{32}{3} + \frac{20}{5}\left[\frac{3}{2} + \frac{1}{6\,.\,3}\right]\right] = 2 * [7{,}353] = 14{,}71\ sec.$$

Case Nr.	Case description	Cycle Travel time (sec.)
1	Random storage assignment in single command	11.24
2	Classed –based storage assignment in single command	6.64
3	Random storage assignment in dual command	16.17
4	Classed-based storage assignment in dual command	10.20
5	Classed –based storage assignment in single command (I/O in lower-left corner of storage rack).	6.11
6	Classed –based storage assignment in single command (I/O in lower-left corner of storage rack and shape of class is different).	5.41
7	Random storage assignment in single command without direct travel of S/R machine.	14.71

Table 4.2: Summarize the results of the different cases.

According to the above results of cycle travel time, it seems that SGP-AS/RS is more effective and has high performance than the conventional AS/RS machine, the following figure summarize the results.

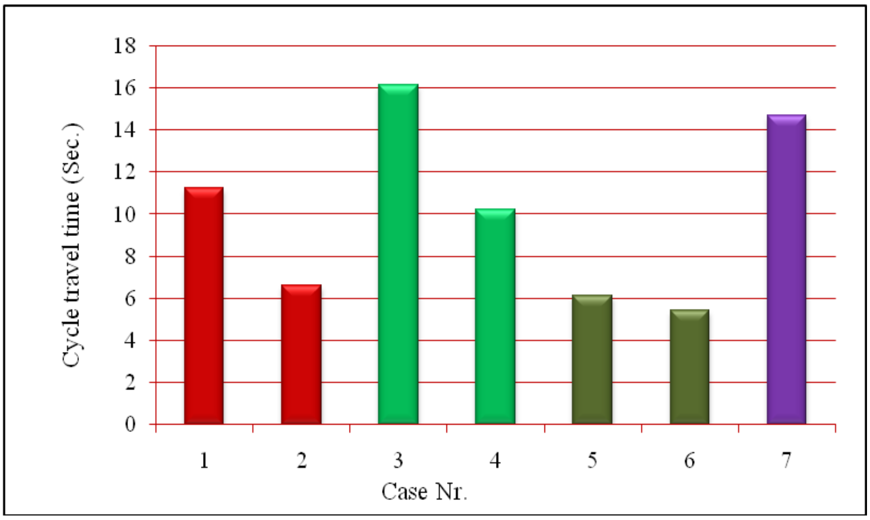


Figure 4.16: The results of cycle travel time for the different cases in numerical example

4.7.2 The Impact of Demand Changing:

This section shows the impact of changing the working percentages (demand) on cycle travel time in case of using the policy “Classed –based assignment in single command”. And keeping on the dimensions of the classes in storage rack for all cases where the percentages are changed as table 4.3.

Classes	Percentage of class space (area)	Length (m)	Height (m)	Real class area (m²)	Parameters : L =20m H= 40 m v =6 m/s a= 5 m/s²
Class A	30% = 240 m²	LA ≅ 11 m	HA ≅ 22 m	242 m²	
Class B	30% = 240 m²	LB ≅ 15.5 m	HB ≅ 31 m	238.5 m²	
Class C	40 % = 320 m²	LC ≅ 20 m	HC ≅ 40 m	319.5 m²	

Table 4.3: The dimensions of storage rack and the parameters of storage process

The change happens just in the substitution of the probabilities values in equation 4.19, because the dimensions still the same, the results are shown in table 4.4.

Case Nr.	1	2	3	4	5	6	7
ABC curve*	20% 60% 30% 30% 50%10%	20%65% 30%25% 50%10%	20%70% 30%20 50%10	20%75% 30%20% 50%5%	20%80% 30%15% 50%5%	20%85% 30%10 50%5%	20%90% 30%7% 50%3%
CTT in (SC)	5.992	6.1515	6.311	6.470	6.63	6.789	6.949

Table 4.4: Show’s the class –based assignment in single command cycle travel time (CTT) with different working frequency (demand rate) with keeping the same classes dimensions.

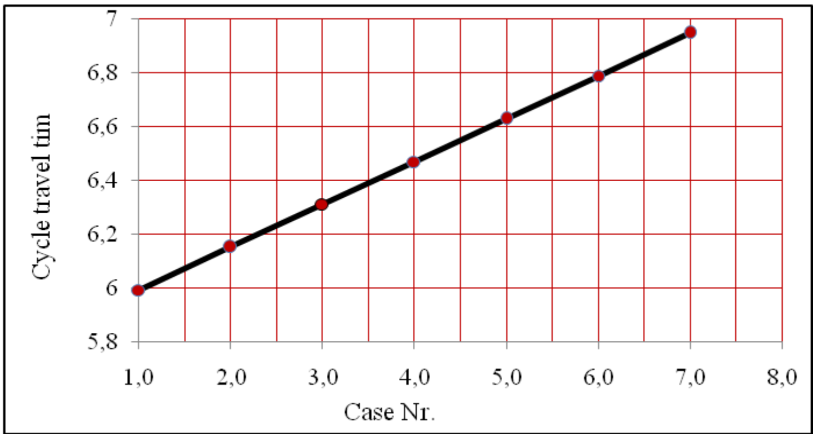


Figure 4.17: The changing of cycle travel time according to changing of working percentage.

4.7.3 The Impact of Changing the Storage Rack Dimensions

This section shows the changing in cycle travel time according to changing in the length and height of the storage rack with constant storage area .the calculation done in case of *classed- based assignment with single command*, the table below shows the dimensions of rack and the classes which have constant space fraction according to the rack length and height. The cycle travel time will be calculated by using equation 4.19 as before with substation different parameters values for each time:

	Rack dim. With cons. area = 800 m^2	Classes fractions: Class A =30% Class B =30% Class C= 40%		Cycle travel time sec.
		Classes Length(m)	Classes height (m)	
1	L = 60 m H=13.33	LA = 32.87 ≅ 33 LB = 46.51 ≅ 47 LC = 60	HA = 7.3 ≅ 7 HB = 10.32 ≅ 10 HC = 13.33 ≅ 13	6.574sec.
2	L= 55m H=14.55m	LA = 30.13 ≅ 30 LB = 42.6 ≅ 43 LC = 55	HA = 7.97 ≅ 8 HB = 11.27 ≅ 11 HC = 14.55 ≅ 15	5.737
3	L=50m H=16m	LA = 27.4 ≅ 27 LB = 38.75 ≅ 43 LC = 50	HA = 8.76 ≅ 9 HB = 12.4 ≅ 12 HC = 16	5.993
4	L=45m H=17.78m	LA = 24.64 ≅ 25 LB = 34.84 ≅ 35 LC = 45	HA = 9.74 ≅ 10 HB = 13.77 ≅ 14 HC = 17.78 ≅ 18	6.38
5	L=40m H=20m	LA = 22 LB = 31 LC = 40	HA = 11 HB = 15.50 ≅ 16 HC = 20.78	6.59
6	L=35m H=22.86m	LA = 19.20 ≅ 19 LB = 27.10 ≅ 27 LC = 35	HA = 12.52 ≅ 13 HB = 17.70 ≅ 18 HC = 22.86 ≅ 23	5.53
7	L=30m H=26.67m	LA = 16.40 ≅ 16 LB = 23.20 ≅ 23 LC = 30	HA = 14.64≅ 15 HB = 20.70 ≅ 21 HC = 26.67 ≅ 27	5.47
8	L=25m	LA = 13.70 ≅ 14	HA = 17.53≅ 18	5.94

	H=32m	LB = 19.37 ≅ 19 LC = 25	HB = 24.79 ≅ 25 HC = 32	
9	L=20m H=40m	LA = 11 LB = 15.5 ≅ 16 LC = 20	HA = 22 HB = 31 HC = 40	6.64
10	L=15m H=53.33m	LA = 8.2 ≅ 8 LB = 11.59 ≅ 12 LC = 15	HA = 29.3≅ 29 HB = 41.4 ≅ 41 HC = 53.33 ≅ 53	6.249
11	L=13.33m H=60m	LA = 7.3 ≅ 7 LB = 10.33 ≅ 10 LC = 13.33 ≅ 13	HA = 32.86≅ 33 HB = 46.48 ≅ 46 HC = 60	7.378

Table 4.5: The results of cycle travel time with different classes' dimensions.

Sample calculation for the first parameter:

$$E(T) = 2 * \left[\int_{0}^{7}\int_{0}^{33}(\frac{6}{5} + \frac{\sqrt{x^2+y^2}}{6}dx\,dy * \frac{0,8}{Area\ A} + \int_{7}^{10}\int_{33}^{47}(\frac{6}{5} + \frac{\sqrt{x^2+y^2}}{6}dx\,dy * \frac{0,15}{Area\ B}\right.$$

$$\left. + \int_{10}^{13}\int_{47}^{60}(\frac{6}{5} + \frac{\sqrt{x^2+y^2}}{6}dx\,dy * \frac{0,}{Area\ C}\right]$$

The following figure shows the impact of changing the rack dimensions (length &height) with fixed area in the cycle travel time, under the perfect conditions the cycle travel has to be straight line, but in figure 4.18 it's not exactly linear because the calculations were done with some numerical approximation in the dimensions of classes in table 4.5.

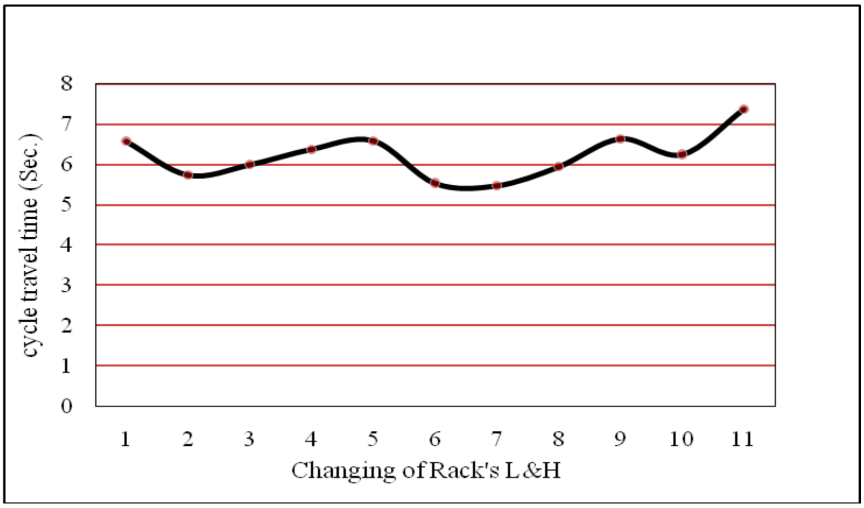


Figure 4.18: The relation between cycle travel times vs. changing the class's dimensions

In case of comparing between conventional AS/RS machine and the SGP-AS/RS machine in impact of dimensions changing in the cycle travel time as above, the comparing must be under the same conditions, therefore the comparing will done between case 1 & 7 as below, the comparing will be in case random storage assignment without classes.

The equation of SGP- AS/RS machine:

$$E(T) = 2 * \frac{1}{20 * 40} * \int_0^{40} \int_0^{20} \frac{6}{5} + \frac{\sqrt{x^2 + y^2}}{6} dx\, dy$$

The equation for traditional AS/RS machine:

$$E(T) = 2 * \left[\left[1 - \frac{w}{2}\right] \frac{Vx}{ax} + \frac{w}{2} \frac{Vy}{ay} + \frac{L}{Vx} \left[\frac{1}{2} + \frac{1}{6} w^2\right] \right], if\ w\ \leq 1$$

$$E(T) = 2 * \left[\frac{1}{2w} \frac{Vx}{ax} + \left[1 - \frac{1}{2w}\right] \frac{Vy}{ay} + \frac{L}{Vx} \left[\frac{w}{2} + \frac{1}{6w}\right] \right], if\ w\ \geq 1$$

	Rack dim. With cons. area = 800 m²	Parameters of conventional machine: - Vx = 5 m/s - Vy = 3,32 m/s - ax = 4 m/s^2 - ay = 3 m/s^2	Parameters of SGP-AS/RS machine : - v =6 m/s - a= 5 m/s^2
		Cycle travel time	Cycle travel time
1	L = 60 m H=13.33	14.9	12.9
2	L= 55m H=14.55m	14	12.18
3	L=50m H=16m	13.21	11.5
4	L=45m H=17.78m	12.47337	10.86
5	L=40m H=20m	11.912	11.25
6	L=35m H=22.86m	11.63	9.88
7	L=30m H=26.67m	11.64	9.64
8	L=25m H=32m	12.6	9.7
9	L=20m H=40m	14.6	11.25
10	L=15m H=53.33m	18.32	11.94
11	L=13.33m H=60m	20.8	12.9
12	L=10 H=80m	26.27	11.8

Table 4.6: Cycle travel time for both machines in case of single command

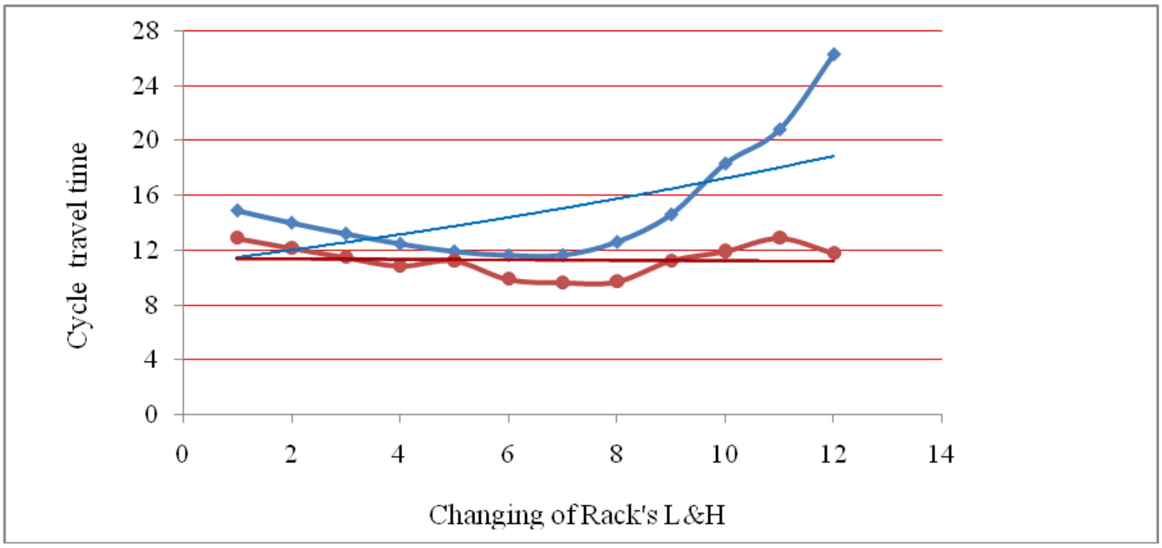


Figure 4.19: The impact of changing rack's dimensions on Cycle travel time for both AS/RS and SGP-AS/RS.

As can be seen in figure 4.19 which describe the impact of rack dimensions changes on the cycle travel time for both machine which implies that the SGP-AS/RS machine in red color have approximately constant cycle travel time with changing of Length and height, but the conventional AS/RS machine in blue line shows that the cycle travel time increase rapidly after shape factor (w) become more than one, due to relation between Length and height.

According to above results we can also generalize those results for single command with based-classed policy and also dual command with based classed policy, which is practically more effective than the single command without classes.

Finally, it seems form the above results that the SGP-AS/RS machine is more effective than conventional AS/RS machines where the travel to the storage cells is not direct.

5 Implementation of SGP-AS/RS to Improvise (WMS)

5.1 Overview of New Design for Logistics Warehouse Based on (SGP-AS/RS)

Several strategies exist in literature for zone positioning, varying from optimal solutions for single command scheduling to rules of thumb for dual command scheduling. [15] proved that a L-shaped configuration with square in time (SIT) boundaries for classes A, B and C is optimal when single command scheduling is applied in square in time racks. [47] also study dual command scheduling and compare three different zones shapes. Their conclusion is that the performance of each of the proposed shapes depends on their location of the I/O station and that none is superior to the others.

Previous studies assumed the travel time models for (AS/RS's) systems by considering the average uniform velocity for the (S/R) machine, ignoring the operating characteristics such as the acceleration/deceleration (A/D) rate and maximum velocity (V_{max})[40,and 41].

In this work we have proposed travel time models for SGP-AS/RS, in cases of single and dual command cycles under class-based storage assignment rules, which integrates the operating characteristics of electric motors used. This model has been simulated in "Interactive Physics", and can be used by designers as a tool for quickly evaluating alternative layout configurations to design the warehouse space with respect to the cycle time in (SGP-AS/RS) of electric motors (machines).

Our new design of SGP-AS/RS employs simple movement in two dimensions along the warehouse space (storage rack) as shown in Figure 5.1. The platform of the SGP-AS/RS is driven by eight cables, which are attached at the edges of the platform; the automated small platform can carry a maximum load of 25 kg.

In addition to improving the quality and efficiency of research in the field of SGP-AS/RS, the development of an accurate and optimal design model would be highly appreciated, while a first academic demonstrator has already been built up at the University of Duisburg-Essen.

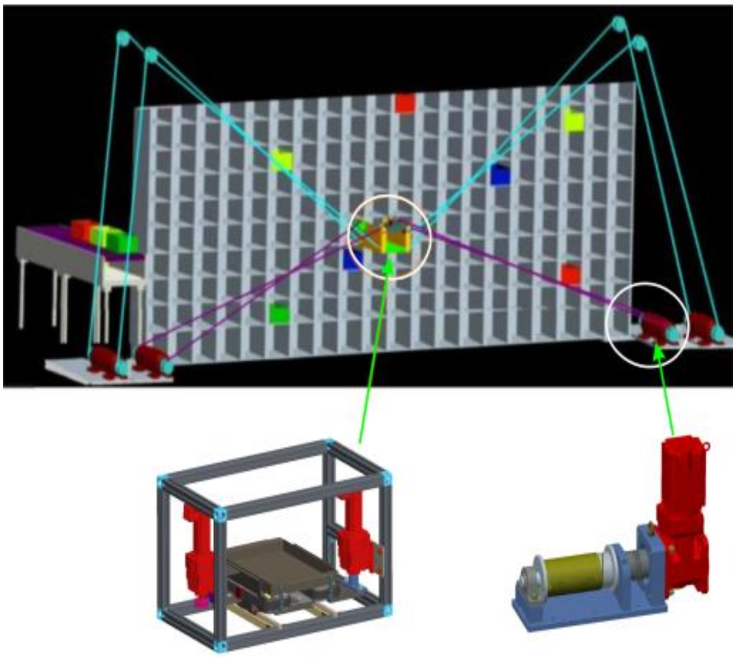


Figure 5.1: Logistics warehouse using (SGP- AS/RS)

5.2 Logistics Warehouse Analysis

As we have mentioned before, travel time models of (SGP-AS/RS), that are used in logistics warehouse must be analyzed by considering an optimal design and scheduling based on the average uniform velocity, in cases of single and dual command storage assignments.

5.3 Simulation Analysis and Results

In this section, we describe our simulation experiment, which evaluates the relative performance of 2D modeling of SGP-AS/RS. The SGP-AS/RS under study is a single aisle and one-sided rack system served by eight motors mounted on the four corners of storage rack. Each corner has two motors, which drive the transport platform through cables. Experimental settings are [64].

: Warehouse space structure*:* warehouse system is rectangular in time.

- (I/O) point position: (I/O) point is at the lower left-hand corner of the warehouse system as shown in Figure 5.2.
- SGP-AS/RS machines operation: SGP-AS/RS machines operate either on a single- or dual-command basis.
- SGP-AS/RS machines specification: maximum velocity in the horizontal and vertical directions and (A/D) rate, as well as the rack length and height are known.
- SGP-AS/RS Type: symmetrical mini-loads with identical items.

- Storage Assignment Policy: items are allocated to storage location according to class-based storage strategy.
- Maximum Velocity Restriction: rack length and height are long enough for the machines used in SGP-AS/RS to reach maximum velocity from the (I/O) point.
- (A/D) Effects: Acceleration/Deceleration effects are considered when designing the zoning of the warehouse.
- Rows and Columns: 50 rows and 25 columns of equally sized storage locations in a rack. Each location has height, width and length of one meter.
- Items Selection: items are selected for storage according to first come, first served (FCFS) rule.
- Size of (SGP-AS/RS):
    - Capacity = (50x25) = 1250 storage compartments
    - Width = 1 x (80 cm + 20 cm) = 1 m,
    - Length = 25 x (90 cm + 10 cm) = 25 m
    - Height = 50 x (90 cm + 10 cm) = 50 m
- Mini-load Dimensions:
    - Width = 80 cm
    - Length= 90 cm
    - Height = 90 cm

With the above SGP-AS/RS specifications, we initially gathered the maximum travel distances of transport platform for given warehouse dimensions. When considering that the transport platform is loaded with a 200 kg mass, the distribution of forces have been calculated and diagrammatically presented in Figure 5.3. We tend to design a warehouse with the already mentioned parameters. Considering the design of our warehouse, we have changed the (I/O) point in three different positions to obtain the resultant zones, respectively illustrated in (Figure 5.4, Figure 5.5 and Figure 5.6).

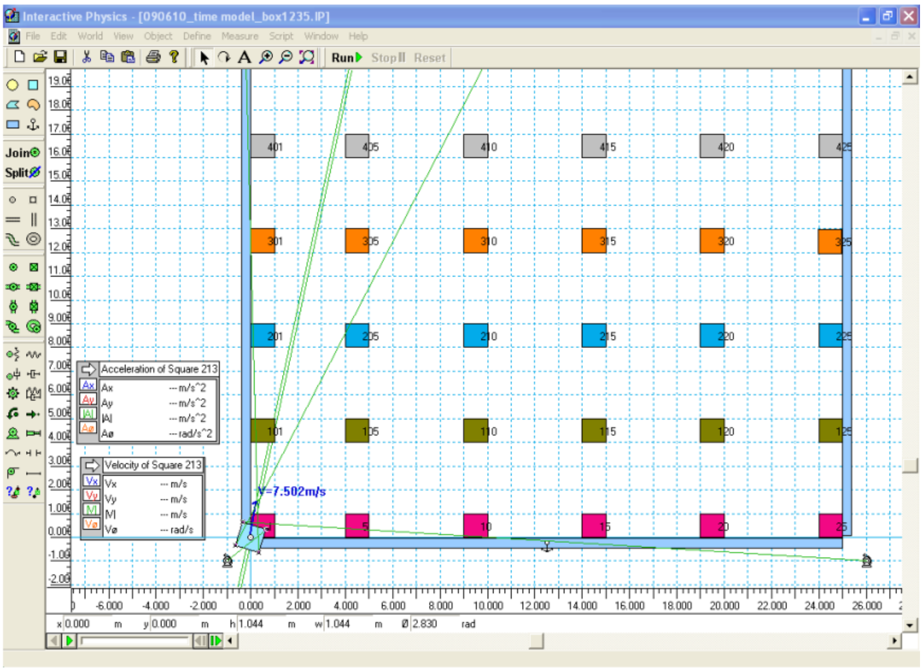


Figure 5.2: (I/O) station position at (x=0, y=0).

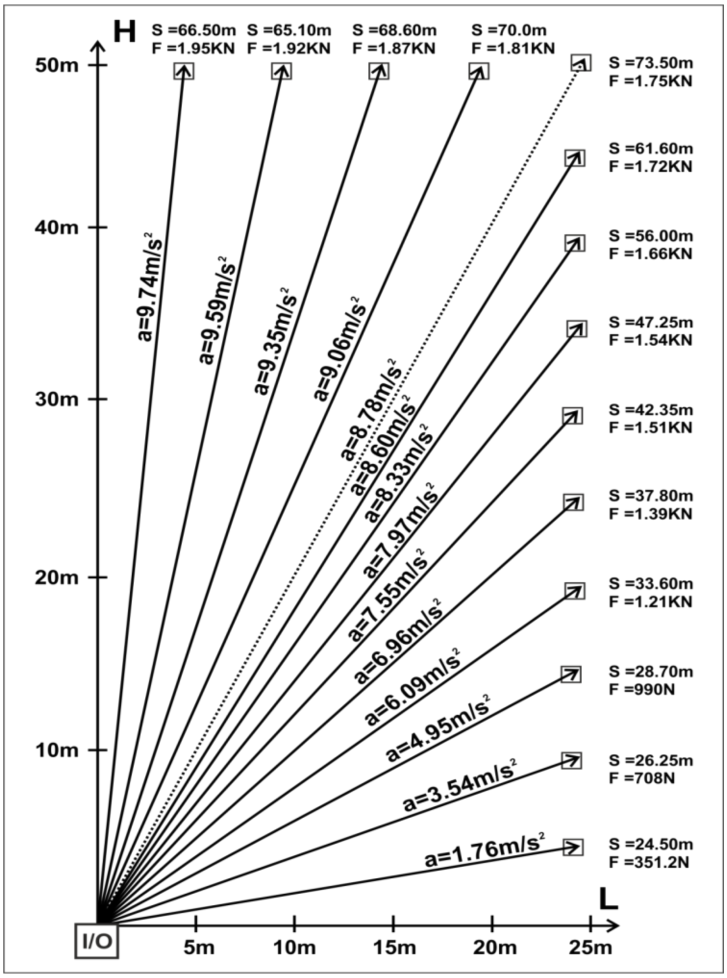


Figure 5.3: Forces & distances with (I/O) station at left-hand corner.

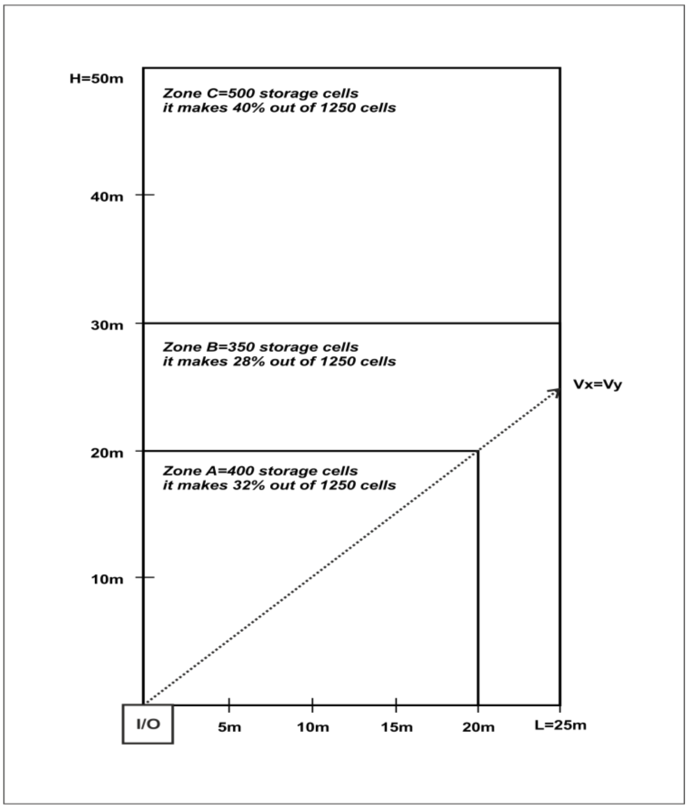


Figure 5.4: Zoning in altitudinous warehouse, (I/O) station at left-hand corner.

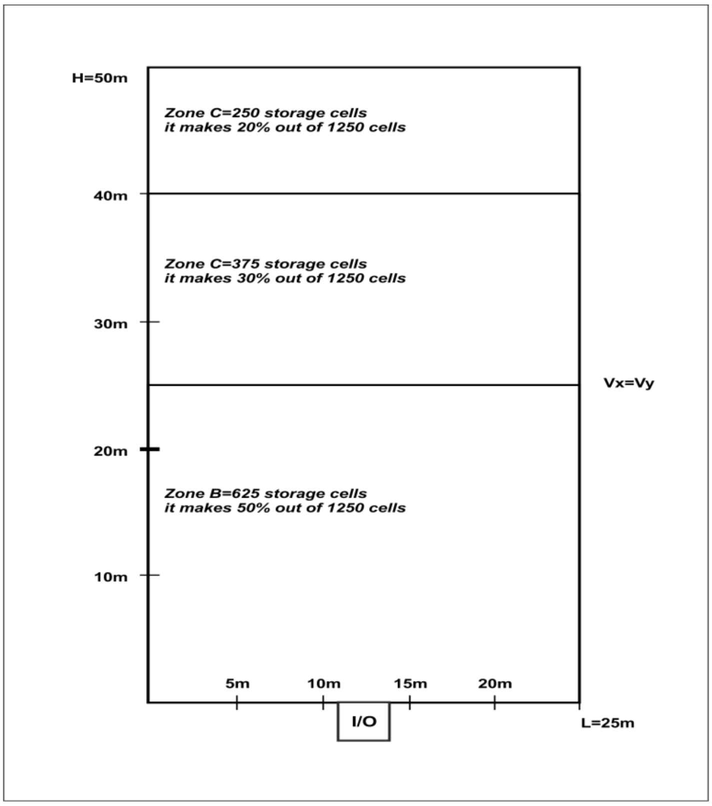


Figure 5.5: Zoning in altitudinous warehouse, (I/O) station at horizontal center.

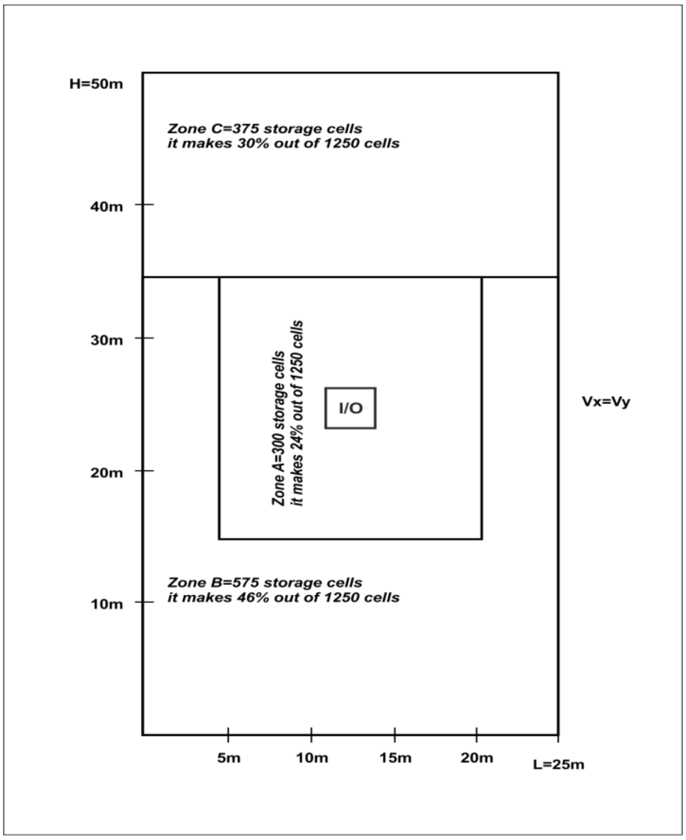


Figure 5.6: Zoning in altitudinous warehouse, (I/O) station at center of warehouse.

5.3.1 Discussion of Results

The role of the electric motor is very significant in the system performance of SGP-AS/RS. For instance, the number of storage and retrieval requests handled per unit time mainly depends on the capabilities of the electric motor. Among the specifications of the electric motors, the A/D rate and maximum velocities in the horizontal and vertical directions are three important elements.

With the available research and development in this field it makes it possible for further improvement of S/R unit. The S/R with Stewart-Gough-Platform has definitely a bigger advantage in comparing the available S/R units in the market, with its high efficient output and easy system makes it more suitable for small and middle size company.

Considering these three elements which describe the capabilities of the electric motors, we developed analytical and dynamic expressions for the travel time of the motors in an SGP-AS/RS. Through the evaluation on a discrete rack, it is confirmed that the proposed model performs satisfactorily. We hope that the proposed Demonstrator will be a practical and useful tool for designing an optimal SGP-AS/RS.

6 Prototyping Process

In this chapter, we will discuss some important aspects concerning the construction elements of our prototype in order to confirm that the design is in accordance with its specifications and its goals, that is, that the product development has to be fast and it should be compatible with the original specifications.

6.1 Properties of Prototype Components

6.1.1 Cable Cylinder Machine (CCM)

Cable Cylinder Machine (CCM) is an important part of the Automatic Shelf System (ASS) there are eight cable cylinder machines presented in (SGP-AS/RS). Each cable is connected at one side with its corresponding cable cylinder, and at the other side with one of the eight frame clips at the Push-Pull-Platform (Figure 6.1).

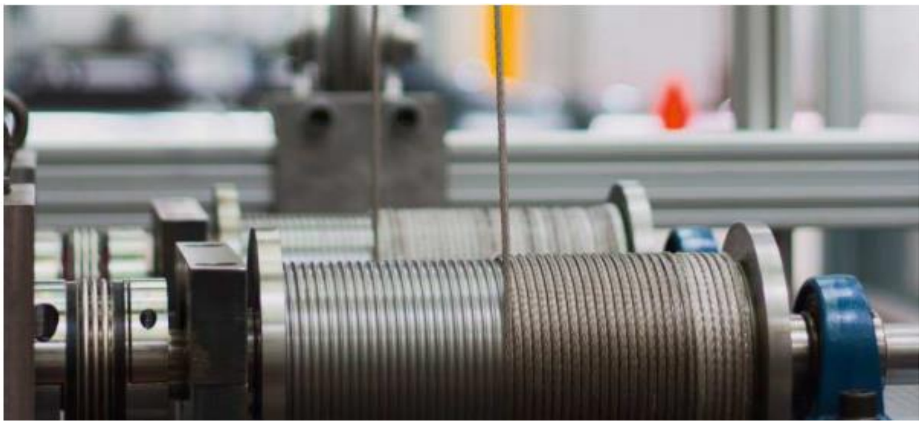


Figure 6.1: Cable Cylinder Machine [48].

6.2 Installation of the Cable-Cylinder Machine

At the beginning, the pedestal bearing is used on the fixed bearing cabinet stand, and then the cylinder cabinet is used between the pedestal bearing and the moving bearing cabinet. After that, the upper top of the moving bearing cabinet is mounted with the cylinder cabinet. A metal ball coupling is used on the shaft. Lastly, the servo-motor is attached to the motor flange cabinet, so that they are firmly bound together (see Figure 6.2).

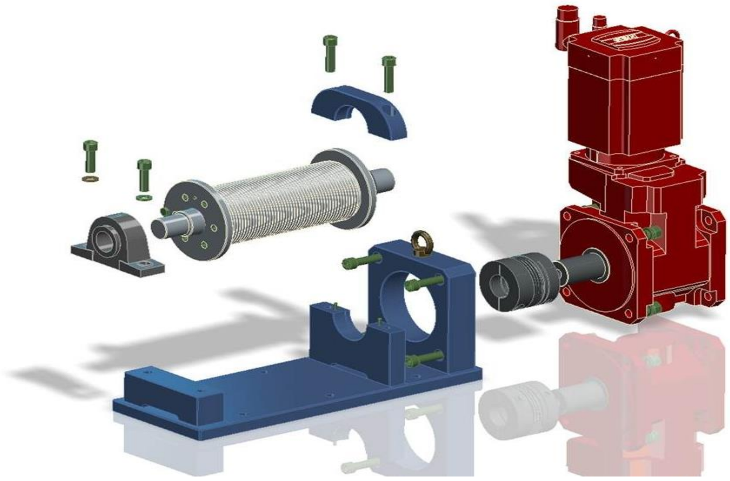


Figure 6.2: Installation of the Cable Cylinder Machine with motor [48].

6.2.1 The Shelves

The shelf is a major component of the (SGP-AS/RS). There are different types of racks available in the market. Shelves are usually used for storage of products, container tray, cardboard storage tray, long goods, and stages.

For the SGP-AS/RS demonstrator, ground-level shelves have been used (see Figure 6.3), because it has many advantages. The ground-level shelves ensure the storage of goods in large product ranges with small to medium-sized quantities. The ground-level shelves also possess high-rack facilities. Although the shelves are intended only for small parts, bulky parts with or without pallets (for different industries) can also be stored. In addition, a number of construction components and accessories allow customizing the shelf system to the specifications in the existing room.

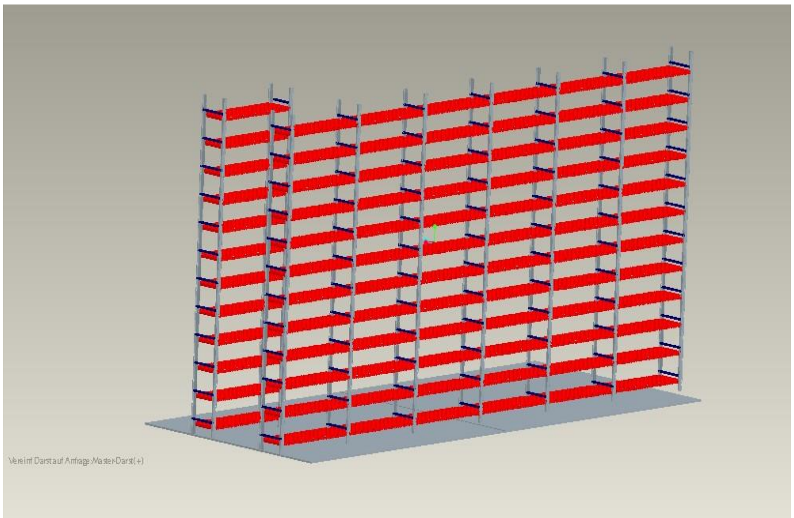


Figure 6.3 : The Simulation of a Shelf System

6.3 Structure of the Hall

The hall consists of two floors. These floors are separated by an I-beam. One floor is concrete in nature (represented by a dark yellow color in Pro/E). However, the other floor exhibits a grid depicted as a dark grey color. On the right wall, control devices are placed. Before the left wall, there is a niche. (see Figure 6.4).

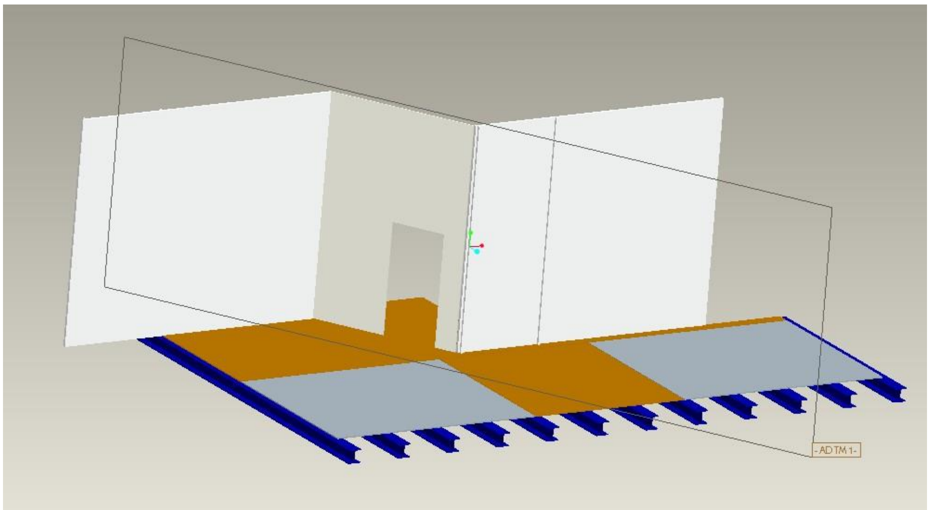


Figure 6.4: Floor Structure of the Hall

6.3.1 Position of the Shelf System

Racks are typically metal structures with locations that can accommodate loads (e.g. pallets) that need to be stored. An AS/RS rack structure is composed of a set of columns referred to as bays, and a set of rows referred to as tiers. Commonly, all bays have the same width; bays in the same tier have the same height. The intersection of bays and tiers are referred to as cells. A typical AS/RS structure module consists of single-deep stored unit loads in two parallel long narrow racks and an aisle between them. Storage racks interface with the storage and retrieval machine and require very tight tolerances.

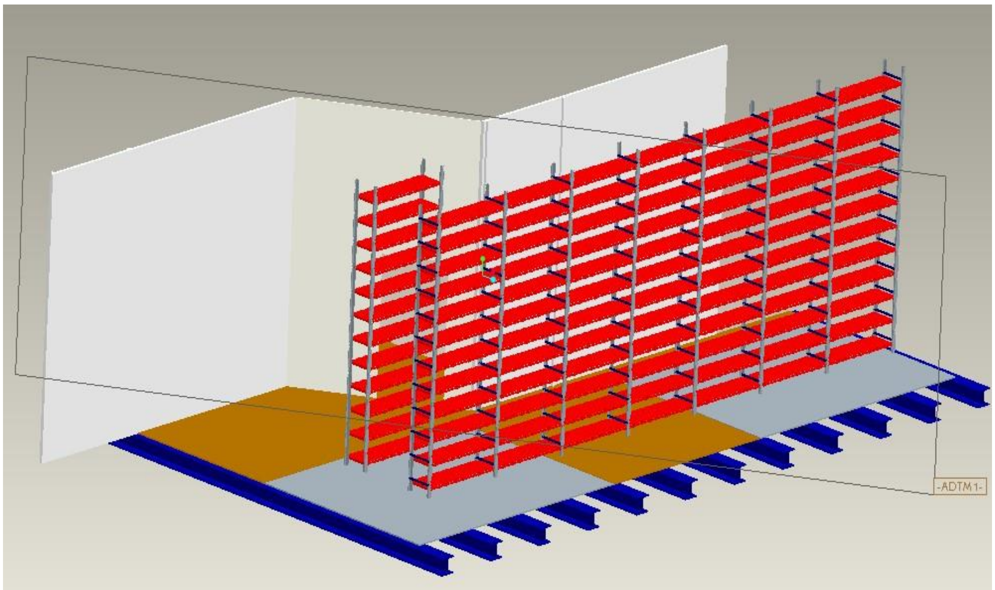


Figure 6.5: Position of the Shelf System

A good balance between rack height and length can help to reduce travel times. Often racks have equally sized storage cells. However, to meet highly varying customer’s demand, it is also interesting to allow the storage of differently shaped loads within a single rack.

6.4 Functional Specifications for Prototype Testing

After defining the specifications, all defined system components are purchased. These are fitted in accordance with the work plan, which is located in the functional specification document. Thus, the test facility will be realized. The condition is that the SGP-AS/RS meets all the requirements, such as functionality, high speed and acceleration, high handling capacity, low energy consumption, safe operation, etc.

6.4.1 Background

6.4.1.1 General Purpose/Application

The decisive criterion for purchasing a rack feeder is not only the handling capacity, but also the investment and operating costs (energy consumption, maintenance costs, spare parts, etc.). Handling the capacity is defined in accordance with VDI-2516 as the "number of storage and retrieval of transactions per unit of time" [49]. To increase this value, higher Acceleration /Deceleration (A/D) values and higher speed are required.

The most efficient, available stacker cranes in the market today have A/D values of 3.5 m/s^2 as well as a speed of up to 6 m/s. These values are attributed to its slim design. These values may already favor a development of vibrations of the structure, which will be transferred to the related equipment. Likewise, effects, especially during the braking and acceleration process, the inertia of the mast, are detrimental to the stability of the stacker crane, which makes the use of an auxiliary drive control essential. With SGP-AS/RS, these problems are avoided, as the mast and the lifting device can be replaced by a single platform. This platform is connected with eight cables and is moved with the help of eight-controlled motors.

A test facility for the SGP-AS/RS has already been built at the University of Duisburg-Essen in Duisburg and the interaction of the whole system has been verified as well. Foremost attention is paid to the functionality of the mechanics and the control of the system. The theoretical values for handling the capacity can be tested experimentally. From this experimental plant experiences are collected to verify the feasibility of the SGP-AS/RSs and to optimize the system if necessary.

A. Principle

The new SGP stacker crane consists of a platform, the loading device (Platform). The containers are brought through the conveyer belt at the I/O point; here the containers are carefully transferred to the transport platform. With the help of cables, the platform is transferred to the desired position for unloading. The whole process is controlled through mechatronically controlled drives and other elements.

B. Reducing the Weight of the Moving Masses

Conventional stacker cranes have a mass up to 2000 kg (chassis, mast, hoist, lift trucks) which are moved to transport a payload of 50 kg. The total moving mass in SGP-AS/RS should not exceed 100 kg.

6.4.1.2 Prototype Components

A. Transport Platform (Shuttle)

The platform is moved by means of eight pre-controlled motors. On the platform, there is the load carrying equipment. The distance between the shelf and the platform is about 5 cm. For reasons of weight reduction, the platform should be built using a light material. (Figure 6.6).

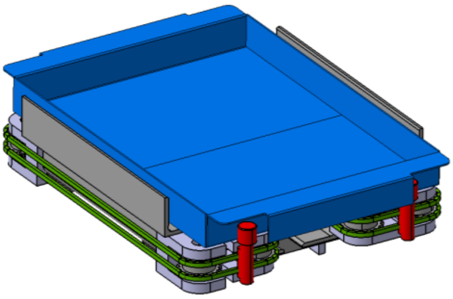


Figure 6.6: Pusher for Trays with a maximum weight of 20 kg of load unit [51]

B. Cage for Transport Platform (Shuttle)

The S/R machine moves in X and Y directions, while the shuttle moves in Z direction. Pick-up and delivery in storage cells and I/O stands are accomplished via a specially designed shuttle mounted on the SGP. When the SGP is fine positioned both in horizontal and vertical direction with the cell or the I/O stand, the shuttle starts to move in the direction perpendicular to the movement plane of storage retrieval machine.

The cage (Figure 6.7) is 840 mm in length, 480 mm wide and 550 mm in height. The aluminum profiles are produced from Al-Mg-Si alloy by Bosch-Rexroth AG.

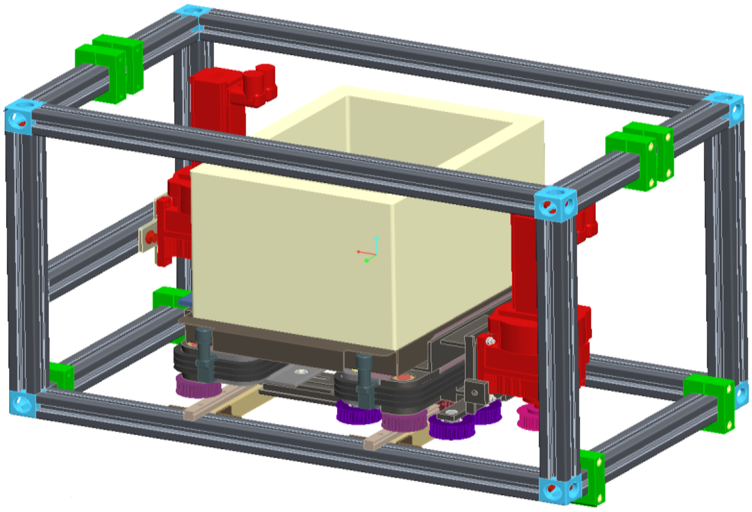


Figure 6.7: Transport Platform (Shuttle) Principle [51]

C. Motors for Moving the Platform

For the cable-cylinder machine a Servo drive motor is required. The Servo drive is produced by SEW company. It consists of two parts. The upper part is an engine and the lower part is a Servo bevel gear (also known as: Bevel Servo Flange)

D. Ropes

In this demonstrator “Liros D-Pro Heat-Stretch” cables with a diameter of 5 mm are applied [52]. “Liros D-Pro Heat-Stretch is a plastic phase cable produced by the Liros Company. LIROS is recognized as a world leader in the manufacture of Hi-Tec yachting ropes, kite surf cords, paragliding lines and a wide range of industrial cordage. The material, “Liros D-Pro Heat-Stretch” has an extremely high breaking strength. This material is very light, with a density lower than the density of the water. In addition, this is water resistant and is confirmed to be extremely resistant to acids and alkalis.

i. Initial situation:

- The rope diameter should be as small as possible. The required cable diameter is 5 mm.
- The cable has the longest possible life cycle.
- The construction of the cables can be recognized based on the system design.
- The safety factor should be at least five.
- A total of eight ropes are needed. Four cables must be at least 17 m long, the other four cables at least 11.2 m.
- The indoor temperature and operating temperature should not exceed 70° C.

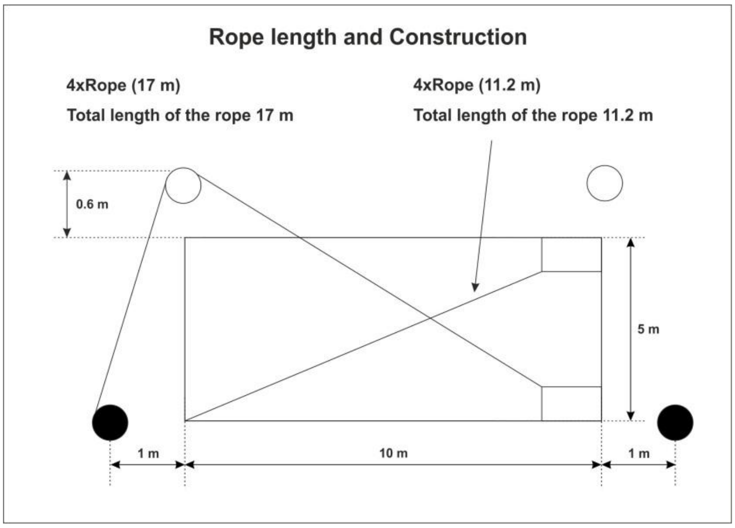


Figure 6.8: Rope Length calculation.

7 The Functional Viewpoint of Marketing

7.1 Marketing Criteria

While marketing something, the priority is to check the important characteristics, that it can be grasped and measured. In this way, similar products of the competition, which are, in general, available in a buyer’s market, can be compared in order to expose one’s own potentials against those of the competition. In this case, the potential of new SGP-AS/RS in a matrix on the basis of the function of Flexibility and Transport is demonstrated below:

7.1.1 Flexibility

Since 1950, the concept of flexibility has been used in terms of manufacturing systems. Originally it was defined as “adaptability, re-arrangement capability and flexibility of firm” and has since then changed little. Being employed in the complex engineering field, the single term, however, is hardly sufficient. It can be further divided into operational and strategic flexibility along with the basis of flexibility and enhanced flexibility, as well as adaptability, which has been discussed. If flexibility is to be evaluated by material flow systems, the complexity should be distinguished in types of flexibility. As no single description has come forward, an example of possible classification criteria set out in (REFA-90) [53] is highlighted below:

- Product flexibility
- Manufacturing Redundancy
- Amount of flexibility
- Adaptive flexibility
- Expansion flexibility

According to [53] "changeability similar to the definition of flexibility in fulfillment of the requirements" can be specified in the following ways:

- Transport material flexibility.
- Layout flexibility.
- Throughput flexibility.

A product meeting the above mentioned criteria of 100 % would no longer be economical. Therefore, a realistic middle ground can be found, which will later be applied to the conventional and the newly designed (SGP) and then compared afterwards. The terms related to flexibility are explained below:

7.1.2 Flexibility of Transport Material

This means that the system will be able to transport a wide variety of products regardless of their size, dimensions or weight. This is necessary for changes in the product portfolio to be backed up.

7.1.3 Layout Flexibility

The ability of a layout to respond to known and future product mixes. It considers the most flexible layout to be the one with the lowest material handling cost over a number of demand scenarios.

7.1.4 Throughput Flexibility

It is caused by the production of power changes, which, for instance, in case of increased demand, adapts to the system.

7.1.5 Changeable Potential

This surrounds extensions of the existing system, if the flexibility potential is either not sufficient or does not exist or if a new system should be integrated.

7.2 Transport

The referred criteria of flexibility can be described concretely on the basis of key performance indicators; otherwise, generally, a valid description is very difficult. This is to be determined here as an example of the function "transportation" which occupies the major role in a material flow system. The transport can be used to create a more precise differentiation and the matrix is further broken down into the following points:

1. Means of transport:
    - Increase in number.
    - Increase in speed.
2. Transport Process:
    - Change the road ways.
    - Adding new transfer location.
3. Transport Unit:
    - Varying the number and type of transport units.
    - Replacement of lifting.

7.3 Marketing Matrix

The marketing matrix integrates all relevant information on markets. The information is condensed into strategic indicators, based on their importance for business success and performance and comparison tables, which are important to implement the plan efficiently. The advantage of this is to give a clear, logical and straightforward package, according to criteria described in the previous section, [53] derives the following matrix represented in Table 7.1.

Measurement	**Flexibility-art** / **Value**	**Layout Flexibility**	**Throughput, flexibility**	**Transport Material Flexibility**
Mode of Transport	Increase of the number			
	Speed increase			
Transport Process	Alteration of infrastructure			
	Adding new passing places			
Transport Unit	Varying the number and type of transport units			
	Replacing the load-carrying			
Changeable Potential				

Table 7.1: Matrix for assessing the potential marketing of materials handling systems [53]

In this work the main focus lies on the internal flow material which is presented in Table 7.1 which can be filled with one of the three values corresponding to the estimated potential of the material flow system:

- $Value\ 0\ =$ no influence.
- $Value\ 1\ =$ indirect influence.
- $Value\ 2\ =$ direct influence.

The column layout flexibility, throughput flexibility and Transport material flexibility can be multiplied by the value set multipliers and summed up, as shown in Table 7.2.

7.4 Marketing Proposal

Table 7.2 and Table 7.3 are compared using a conventional stacker crane with the (SGP). The numbers are not measured, but were roughly estimated by an expert team from the Department of Transport Systems and Logistics; therefore, these are only partly representative.

Conventional (AS/RS):

Measurement	Flexibility-art Value	Layout Flexibility	Throughput, flexibility	Transport Material Flexibility
Mode of Transport	Increase of the number (0)	0	2	1
	Speed Increase (2)	0	2	0
Transport Process	Alteration of infrastructure (3)	2	1	0
	Adding new passing places (3)	2	2	2
Transport Unit	Varying the number and type of transport units (3)	0	2	2
	Replacing the load-carrying (0)	0	2	2
Changeable Potential		12	19	12

Table 7.2: Matrix for the Marketing Potential of Estimating a conventional stacker crane

Stewart-Gough-Platform (SGP):

Measurement	Flexibility-art Value	Layout Flexibility	Throughput, flexibility	Transport Material Flexibility
Mode of Transport	Increase of the number (0)	2	3	3
	Speed Increase (2)	3	3	3
Transport Process	Alteration of infrastructure (3)	2	1	1
	Adding new passing places (3)	2	2	2
Transport Unit	Varying the number and type of transport units (3)	0	2	2
	Replacing the load-carrying (0)	1	1	1
Changeable Potential		18	21	21

Table 7.3: Matrix for assessing the potential commercialization of a (SGP)

When considering one change-ability, the following Figure 7.1 can be derived. The SGP appears to demonstrate the conventional stacker cranes, in the point supports good flexibility and significantly superior throughput flexibility. Such graphics can be used to compare the performance of a material flow system. In this case, SGP has been compared with a conventional stacker crane.

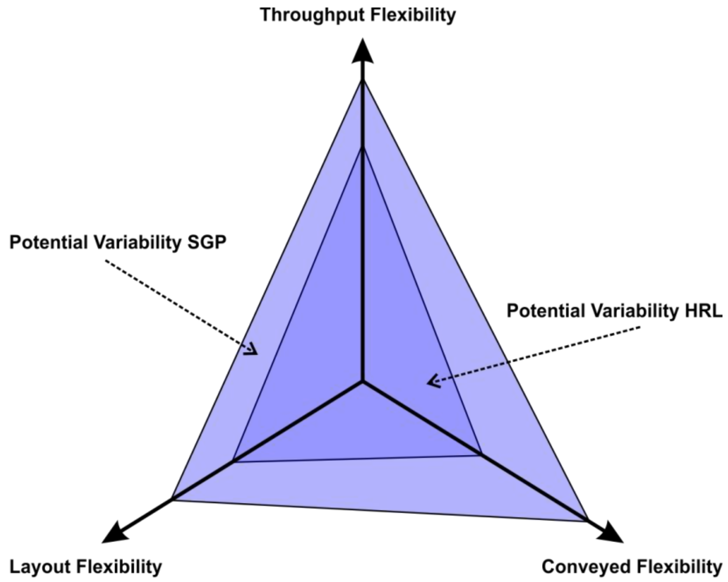


Figure 7.1: AS/RS and SGP Potential variability in comparison

7.5 Integration of (SGP-AS/RS)

In the area of Intra-logistics, optimization of material flow is aimed consecutively. Conventional stacker crane machines are considered their design of construction, and functionality methods are optimized and extended. Moreover, research of new technologies is called upon to counter the increasing levels of automation. This innovative concept becomes more important in order to meet market standards and competitive standards. Another aspect is energy efficiency, which is necessary as a result of climate change, because the energy costs might rise and therefore, it causes long-term results in the supply chain and in internal flow of materials. In this connection this elaboration describes an innovative and new device, which can be used in the internal flow of materials to fulfill the above mentioned aspects. Besides the conventional shelf operating device, its inflexible platform is substituted with a state-of-the-art draft, which was built on the basis of (SGP), a platform, which is driven with the help of eight pretense cables. In contrast to the customary (HSR) Machine, the SGP-AS/RS disposes on light cable. In addition, the platform distinguishes itself by a dynamic movement in the working space. Not only are the loads thereby reduced, but also the flexibility is raised. The areas of application for the (SGP) shelf operating device limit themselves in this consideration to automatic small parts storages. The purpose of this work is to indicate the optimum integration of the shelf operating device (SGP) in the material flow system (see Figure 7.2).

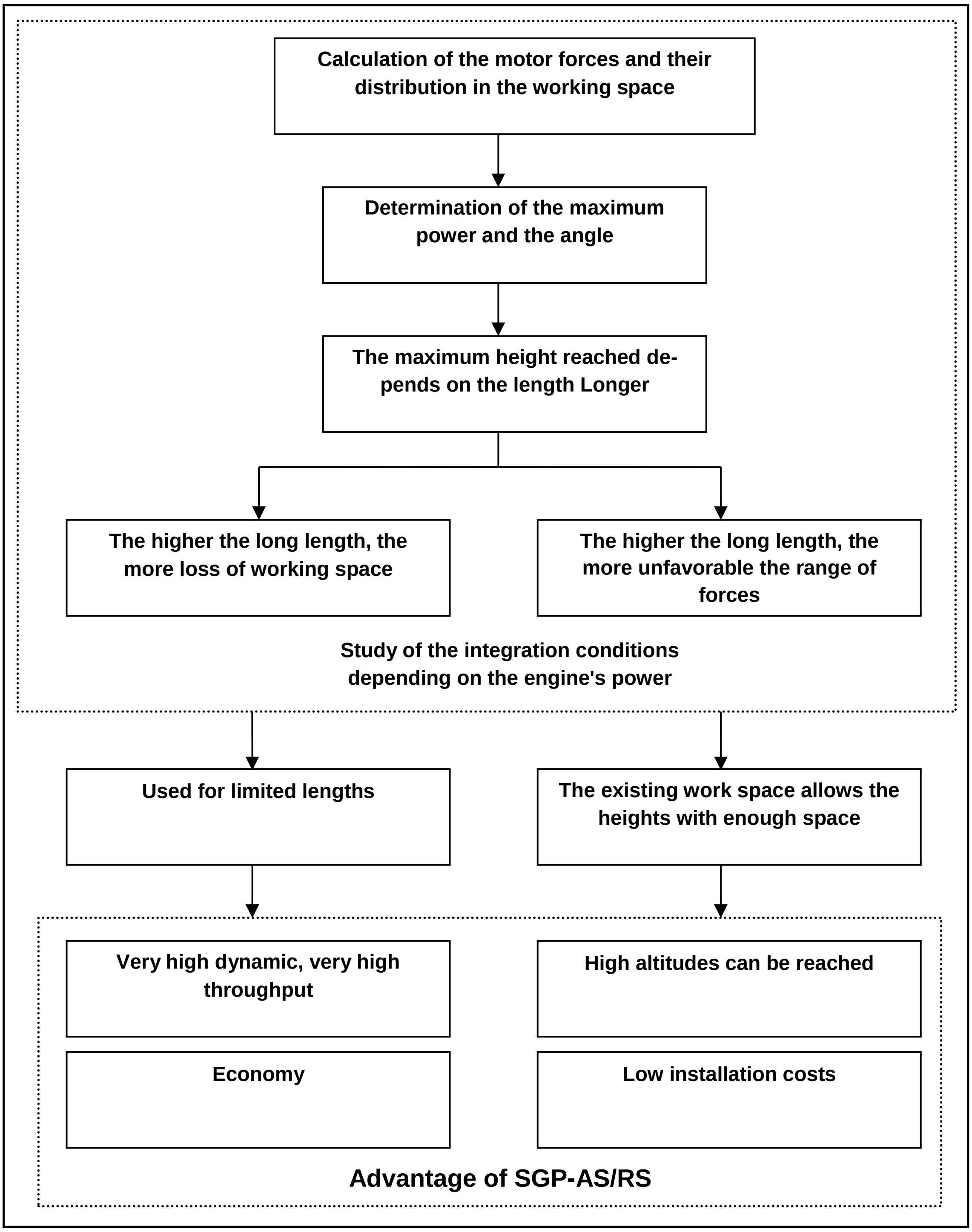


Figure 7.2: Concept for use of the SGP-AS/RS's

7.6 Market Analysis

Market analysis provides unique selling of figures carried out via (miniloads devices), with respect to the Pay-load category and mini-load height. Thus the functionalities of the SGP-AS/RS as well as the economic efficiency will be also be checked [63].

7.6.1 (VDMA) Statistics on the Number of AS/RS Sold for (AKL)

Calculations of the VDMA [54] statistics present sales figures of the delivered AS/RS on the national and international markets. In the following diagrams, the AS/RS statistics are described in Germany and in the international market. Figure 7.3 is a graphical representation of AS/RS statistics in the German market, presenting an increased demand in the year 2008 from 166 AS/RS having a payload of 50-100 kg. However, in the year 2009, this demand dropped to around 52 AS/RS. With a pay-load of up to 50 kg, the demand in 2008 and 2009 kept constant and amounted to a number of 109 AS/RSs.

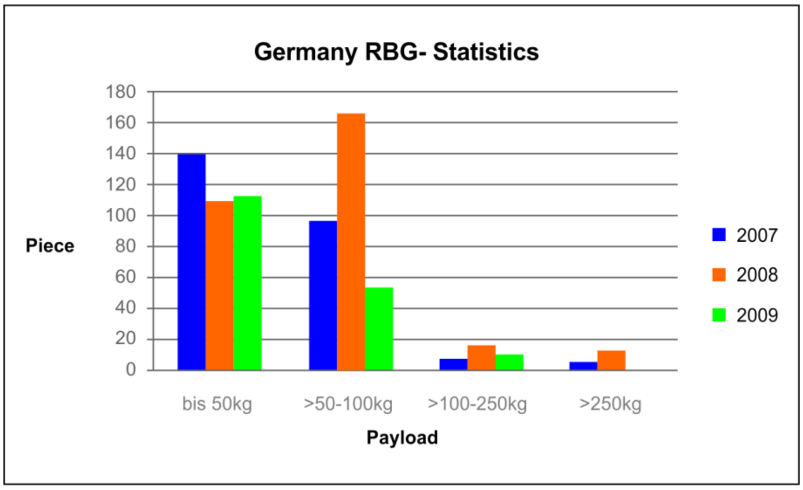


Figure 7.3: (miniload-AS/RS) sold according to [54]

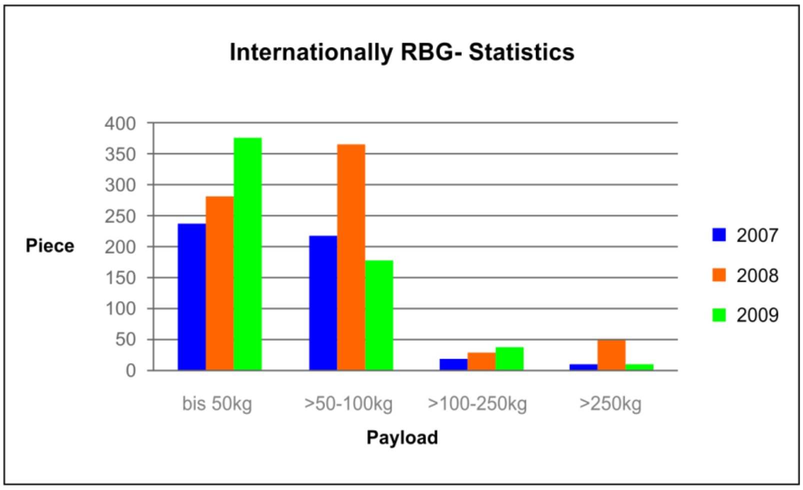


Figure 7.4: Internationally sold (miniload-AS/RS) according to [54]

It can be seen from Figure 7.4 that a growing payload worldwide and a payload increase of up to 50 generally exhibit a rather decreasing performance in the category of payload 50-100 kg.

The changed structure indicates that a sale of AS/RS with a payload of 50 kg is profitable. Based on these results, the SGP-AS/RS is suitable for a payload of 50 kg, in order to exploit the market potential, since the demand lies in this sector.

If the total height is considered, it can be said that it is profitable, both in Germany as well as in the international market, with a total height of six to twelve meters. Figure 7.5 claims that in 2008, in Germany, the statistical figure for AS/RSs sold with a height greater than twelve meters reached 132, whereas in 2009 it was only 65.

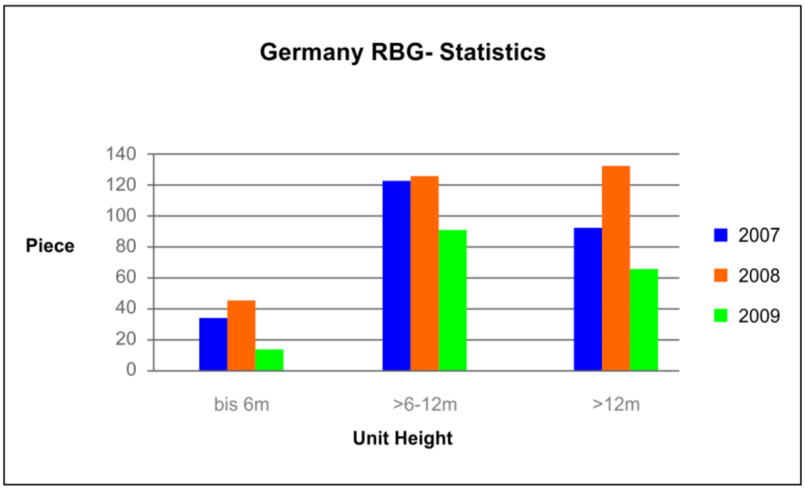


Figure 7.5: (**ASRS) Sold for small parts containers overall height according to [54]**

7.7 Inernal Transport and State of the Art

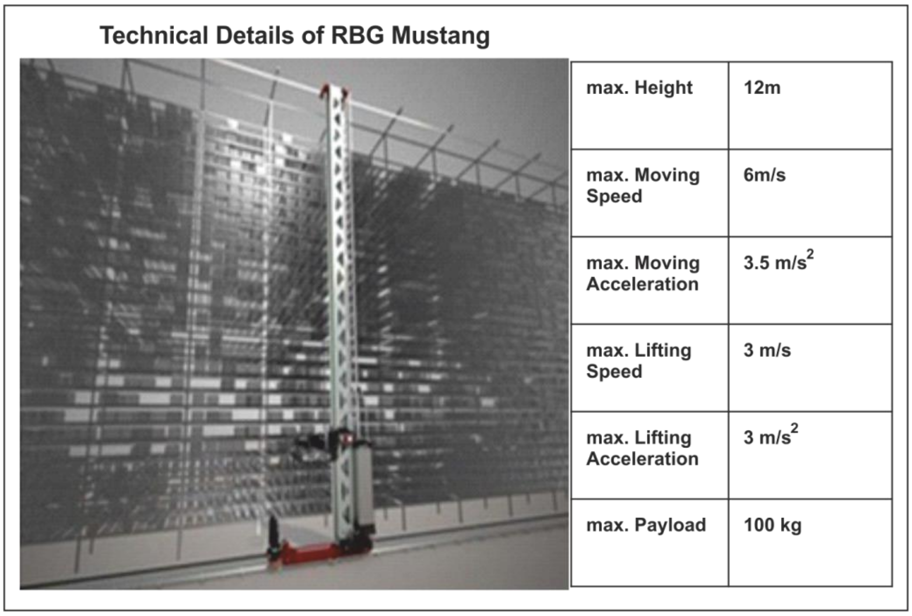
7.7.1 Conventional High Storage Rack Machines

While preceding further, three customary AS/RS’s are introduced to indicate the topical state of the technology and to produce a relation with the SGP-AS/RS.

7.7.2 High Storage Rack Machine "Mustang Evolution" of (TGW)

The international Intra-logistics System integrator (TGW) with more than 1100 employees offers solutions for handling equipment storage systems in the areas of warehousing, production, order picking and distribution [55].

The Mustang AS/RS Evolution, as shown in Figure 7.6, is comparable with SGP-AS/RS and was developed according to the latest standard of technology.



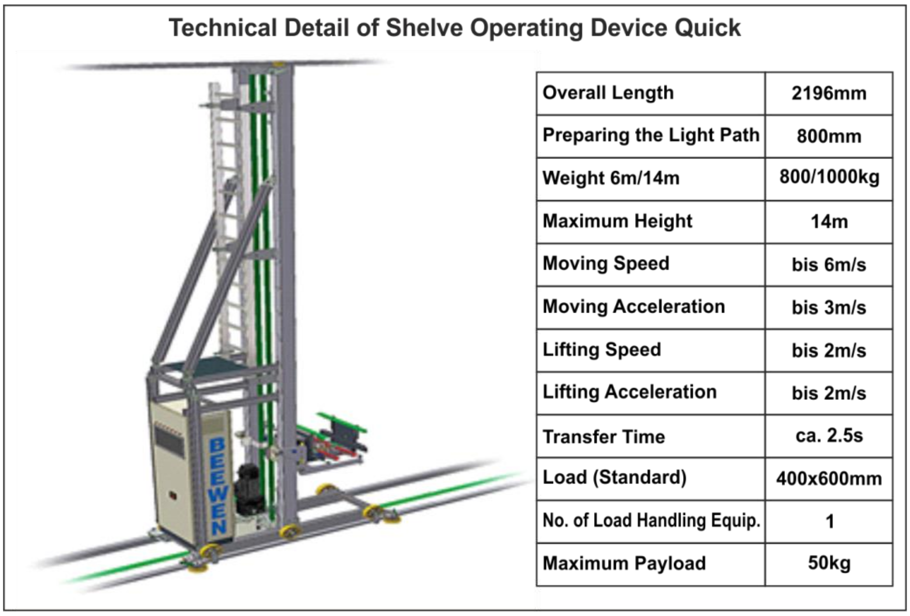
Technical Details of RBG Mustang

max. Height	12m
max. Moving Speed	6m/s
max. Moving Acceleration	3.5 m/s^2
max. Lifting Speed	3 m/s
max. Lifting Acceleration	3 m/s^2
max. Payload	100 kg

Figure 7.6: Mustang Evolution [55].

7.7.3 High Storage Rack "Quick store 2.1"

Beewen Company has specialized in the production of storage and material flow systems of automatic small parts storage. The range of products includes AS/RS, batch devices, resting place management systems, the control of AS/RS and the material handling technology. (HSR) Machines which go on a double rail are called "Quick store" because these are built of aluminum. They have been built with low weight and can accelerate low masses very fast. In addition, the energy consumption can be reduced effectively. In order to carry out a comparison with the AS/RS, in this case (HSR) Machine "Quick store 2.1" is used and a standard container of 50kg is chosen. Figure 7.7 elaborates the technical data of this device [56]



Technical Detail of Shelve Operating Device Quick

Overall Length	2196mm
Preparing the Light Path	800mm
Weight 6m/14m	800/1000kg
Maximum Height	14m
Moving Speed	bis 6m/s
Moving Acceleration	bis 3m/s
Lifting Speed	bis 2m/s
Lifting Acceleration	bis 2m/s
Transfer Time	ca. 2.5s
Load (Standard)	400x600mm
No. of Load Handling Equip.	1
Maximum Payload	50kg

Figure 7.7: Quick Store 2.1 [56]

7.7.4 High Storage Rack Viaspeed from Viastore System

The third comparative company produces Viaspeed Intra-logistic arrangements and conceives AS/RS in different dimensions and speeds. Due to the high throughput, the cost can be minimized, increasing the flexibility and optimizing the energy efficiency. The high speed control units can reach a high acceleration and hence high speed. The AS/RS Viaspeed, as shown in Figure 7.8 is characterized by its light-weight design and creates a necessary flexibility and enhanced performance in the (Mini-load) with an innovative performance and control technology.

max. Height	bis 20 m
max. Moving Speed	5 m/s
max. Moving Acceleration	3 m/s^2
max. Lifting Speed	2 m/s
max. Lifting Acceleration	1.5 m/s^2
Capacity	300 kg

Figure 7.8: Viaspeed of Viastore system [57]

7.8 Innovative High Storage Racks

7.8.1 Dematic Multi-Shuttle Captive

The multi-shuttle, which delivers an innovative storage solution for the storage of containers, consists of four essential elements: shelf, shuttle, driving rails and control. In every shelf, a shuttle is used, moving either vertically or horizontally, so that the inputs and outputs run parallel. A shuttle has a weight of 80 kg and can transport up to 40 kg of loads. Therefore, the basic advantage is the energy efficiency of the device [58].

7.8.2 TransFaster

Another alternative to the conventional AS/RS is the so called TransFaster. This is preferred above all for storage and the narrow way stacker, which works freely. The TransFaster consists of a moving unit, which is connected by a heavy platform with four ropes. This moving unit runs on two driving rails which are placed in the lanes of the uppermost shelf [59].

7.9 Workroom Synthesis of the (SGP- AS/RS)

The central question to be raised is that of the ideal draft regarding the role of optimum integration of (HSR) Machine in the material flow. The integration depends on certain criteria, which are examined in the following passages.

7.9.1 Constructions of the (SGP- AS/RS)

The cable-driven parallel kinematic structure consists of eight motors that control the platform. The work area is served by the platform, which can be positioned by the pre-stressed cables. This model requires stretched ropes always maintaining a linear shape, so that a force can be transmitted. The motor forces are dependent on the platform and storage dimensions (see Figure 7.9).

- High-level shelf
- Ropes
- Electric motor
- Transport platform
- (I/O) point
- Loading aid / container
- Roller
- Control environment as an external influence

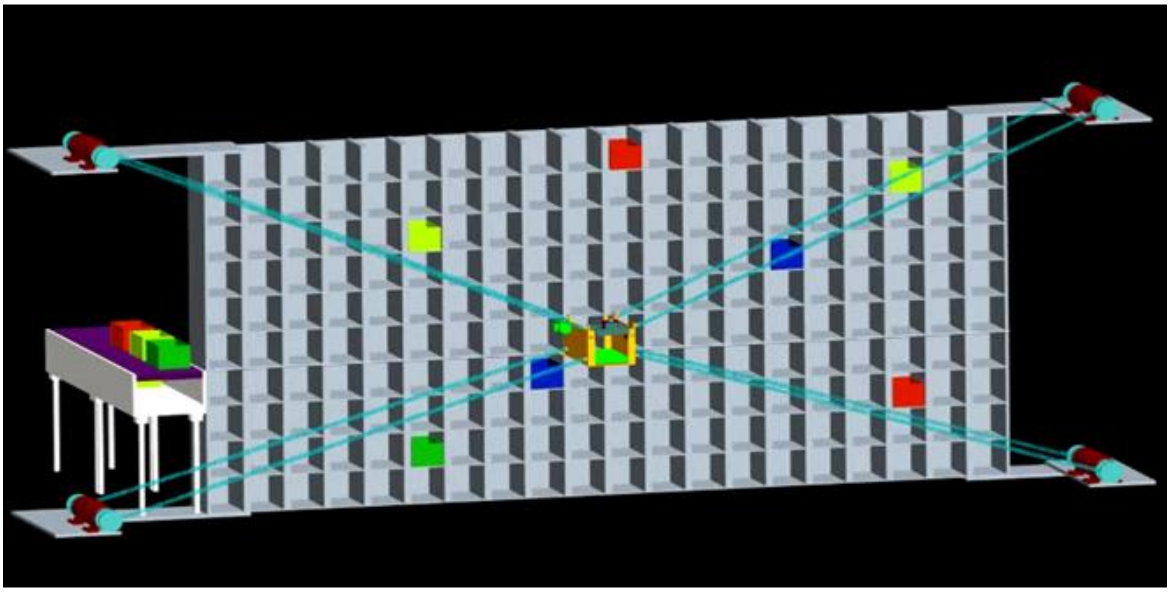


Figure 7.9: The first version of SGP- AS/RS

7.9.2 Calculations of the Maximum Motor Forces

The motor forces of all the eight motors that move the platform are concentrated in the corner; the following values are gathered to calculate the maximum motor strength:

1. The movement acceleration amounts to 10 (m/s^2) with a mass of 10g. (1 g=9.81 m/s^2).
2. The mass (m) of the platform with the container and the pay load makes a total of 100 kg.

3. The pay load amounts to 25 kg.
4. The platform is accepted as a point mass.
5. The platform is steered by eight motors, which all have the same performance.
6. If the platform is pulled vertically upwards, the maximum motor power is reached.

Therefore, the force of a single motor is F=250 N. In the next subsection, the angular dependence is described in connection with the motor power.

7.9.3 Relations of the Angular Dependence of the Motor Forces

Figure 7.10 depicts the angular dependence of the motor forces. The angle α is between the cable and the Y axis. Furthermore, the rack dimension presents the warehouse. Besides, the angle α amounts between 0 and 90 degrees and increases with rising height and length [63]

.

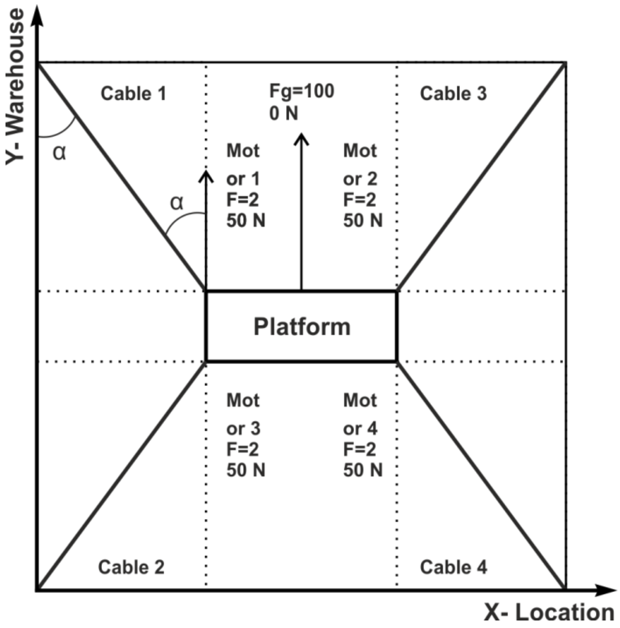


Figure 7.10: Angle dependence of the motor forces

The calculation of the angle α can be carried out with the following formula:

$$\alpha = tan^{-1}\left(\frac{X_{Platform}}{(Warehouse\ Height - Y_{Platform})}\right) \qquad (6-1)$$

$X_{Platform}$: Position of the platform in horizontal direction.

$Y_{Platform}$: Position of the platform in vertical direction.

The calculation for the motor forces can be determined as follows:

$$F_g = m * g = 100kg \times {}^{10m}/_{S^2} = 1000N \qquad (6-2)$$

Because the platform is raised by four ropes, hence the above formula is employed to calculate F_g for the individual cables:

$$F_e = \frac{F_g}{4} = \frac{1000N}{4} = 250\ N \qquad (6-3)$$

The value of the single motor power can be calculated as follows:

$$F_{Motor} = \frac{F}{\cos\alpha} = \frac{250\ N}{cos\alpha} \qquad (6-4)$$

The overall performance can be calculated by:

$$P_{Motor} \ = F_{Motor \times V_{max}}\ (V_{max}\ = 6\,m/s) \qquad (6-5)$$

To explain the formula, a sample calculation is made to determine how the forces are distributed in the work space. It is calculated for each platform position: the engine power, the engine performance and overall engine performance.

The table contains the following sizes:

- Rack Dimensions: LxH (rack length x height) [meters].
- Platform Position: X_plattform, Y_ (platform.)
- Angle: α [degrees].
- Motor power: F_{motor} [N].
- Power:P_{motor}
- Total engine power: P_{total} [kW].

The calculations are summarized in Table 7.4:

LxH	**Platform Position**	**α**	**F_{Motor} [N]**	**Motor Performance [kW]**	**Total Motor Performance [kW]**
10m x 2m	10m, 0m	78.7	1276	7.66	61.28
	10m, 1m	84.29	2513	15.08	120.64
10m x 5m	10m, 0m	63.43	559	3.35	26.8
	10m, 3m	78.7	1276	7.66	61.28
	10m, 4m	84.29	2513	15.08	120.64
10m x 10m	10m, 0m	45	345	2.12	16.96
	10m, 2m	51.34	400	2.4	19.2
	10m, 5m	63.43	559	3.35	26.8
	10m, 8m	78.7	1276	7.66	61.28
	10m, 9m	84.29	2513	15.08	120.64
20mx 2m	20m, 0m	84.29	2513	15.08	120.64

	20m, 1m	87.14	5010	30.06	240.48
20m x 10m	20m, 0m	63.43	559	3.35	26.8
	20m, 2m	68.2	673	4.04	32.32
	20m, 5m	75.96	1031	6.19	49.52
	20m, 8m	84.29	2513	15.08	120.64
	20m, 9m	87.14	5010	30.06	240.48
20m x 20m	20m, 0m	45	354	212	16.96
	20m, 5m	53.13	417	2.5	20
	20m, 10m	63.43	559	3.35	26.8
	20m, 12m	68.2	673	4.04	32.32
	20m, 15m	75.96	1031	6.19	49.52
	20m, 18m	84.29	2513	15.08	120.64
	20m, 19m	87.14	5010	30.06	240.48
30m x 2m	30m, 0m	86.19	3762	22.57	180.56
	30m, 1m	88.1	7540	45.24	361.92
30m x 5m	30m, 0m	80.54	1521	9.13	73.04
	30m, 3m	86.19	3762	22.57	180.56
	30m, 4m	88.1	7540	45.24	361.92
30m x 10m	30m, 0m	71.57	791	4.75	38
	30m, 2m	75.07	970	5.82	46.56
	30m, 5m	80.54	1521	9.13	73.04
	30m, 8m	86.19	3762	22.57	180.56
	30m, 9m	88.1	7540	45.24	361.92
30m x 20m	30m, 0m	56.3	451	2.71	21.68
	30m, 5m	63.34	559	3.35	26.8
	30m, 10m	71.57	791	4.75	38
	30m, 12m	75.07	970	5.82	46.56
	30m, 15m	80.54	1521	9.13	73.04
	30m, 18m	86.19	3762	22.57	180.56
	30m, 19m	88.1	7540	45.24	361.92
30m x 30m	30m, 0m	45	354	2.12	16.96
	30m, 5m	50.19	390	2.34	18.72
	30m, 10m	56.3	451	2.71	21.68
	30m, 15m	63.34	559	3.35	26.8

	30m, 20m	71.57	791	4.75	38
	30m, 22m	75.07	970	5.82	46.56
	30m, 25m	80.54	1521	9.13	73.04
	30m, 28m	86.19	3762	22.57	180.56
	30m, 29m	88.1	7540	45.24	361.92
50m x 10 m	30m, 0m	78.69	1275	7.65	61.2
	30m, 5m	84.29	2513	15.078	120.62

Table 7.4: Distribution of forces as well as Motor performance as a function of rack dimensions.

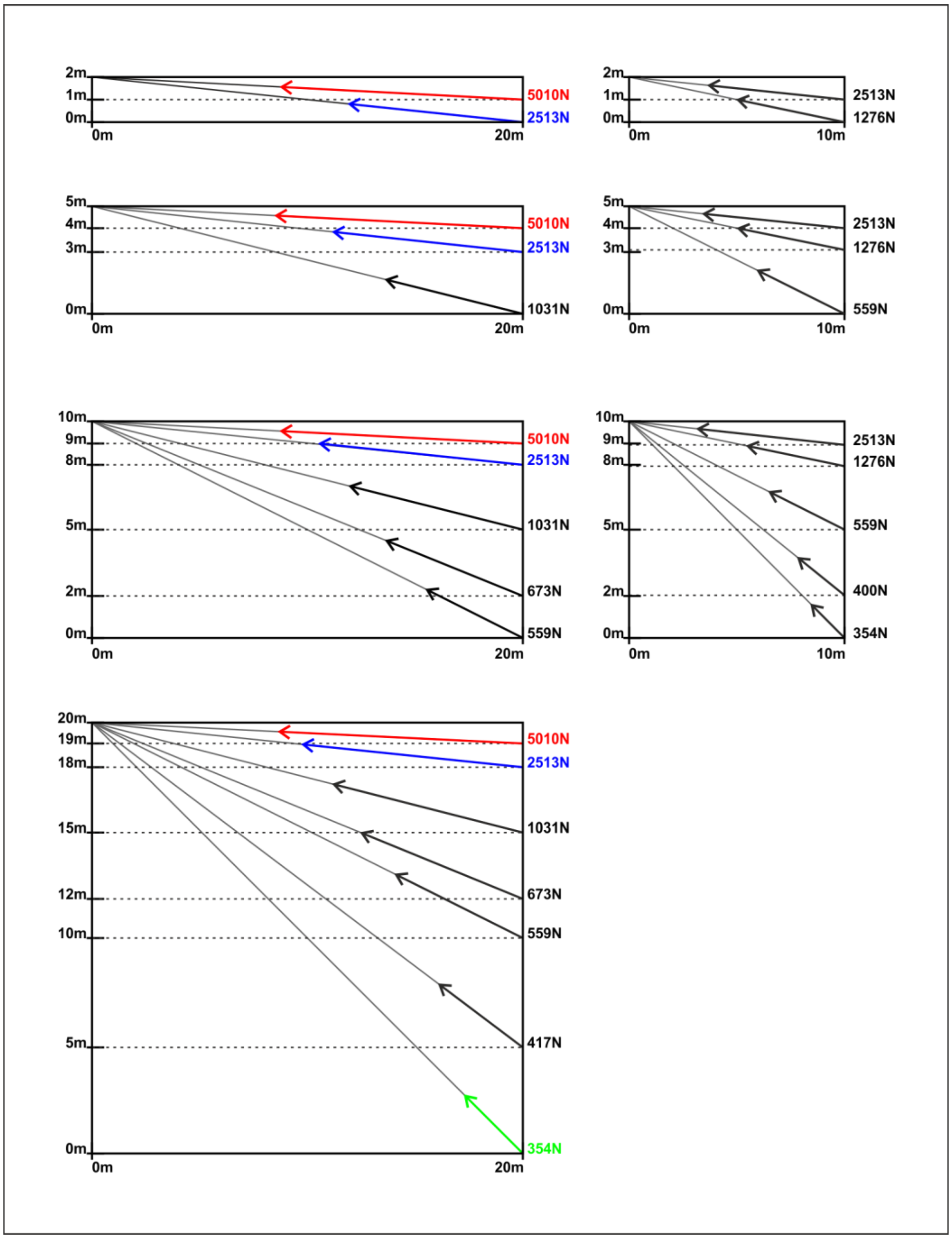


Figure 7.11: Distribution of forces as a function of warehouse dimensions

As shown in Figure 7.11, the calculation results are illustrated. Using this figure, it can be seen that the forces increase with the same rack length with increasing height.

Calculations show that the motor forces increase with constant storage length and with rising storage height. Similarly, with identical storage height the motor forces rise when the storage length is increased. Besides, SGP-AS/RS with increasing angle α is not very efficient concerning economic efficiency and the technical conversion. Because of this, it is relevant to determine the maximum motor power. The maximum value of the angle α should be limited to 85 degrees. These results from the following calculations are shown in Table 7.5.

LxH	Platform Position	α	Motor Power	Motor Performance	Total Motor Power
	20m,0m	45	354	2.12	16.96
	20m, 5m	53.13	417	2.5	20
	20m, 10m	63.43	559	3.35	26.8
	20m, 12m	68.2	673	4.04	32.32
20m x 20m	20m, 15m	75.96	1031	6.19	49.52
	20m, 18m	84.29	2513	15.08	120.64
	20m, 19m	87.14	5010	30.06	240.48
	20m, 19,5m	88.57	10018	60.11	480.85
	20m, 19,8m	89.43	25130	150.78	1206.25

Table 7.5: Calculation of the corner α for different storage heights with a steady storage length

On account of the fact that the angle α should be limited, it is proved that the total work space cannot be used. Hence, the total height could not be fully utilized. The loss of the amount due to the angle dependency is called (LH). This loss rises with increasing storage length. This connection is illustrated in the calculations shown in Table 7.6:

$$\tan\alpha = \frac{Rack\ Length}{Losses_{Hight}} \qquad (6-6)$$

$$Losses_{Hight} = \frac{Rack\ Length}{\tan\alpha} \qquad (6-7)$$

Rack length	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m
Loss of height in m	0.875	1.75	2.62	3.5	4.375	5.25	6.12	7	7.87	8.75

Table 7.6: Value of the height loss

8 Evaluation of SGP-AS/RS and Conventional AS/RS

8.1 Introduction

This chapter deals with the design of an algorithm to control the SGP-AS/RS machine in an automatic small-parts warehouse. The algorithm, which is presented as a flowchart and pseudo-code [60], has been implemented in Matlab.

The algorithm will allow a fast and efficient order processing by an intelligent combination of storage and retrieval requests. This includes mechanisms which regulate all combinations of orders to be executed. It is designed on the concept of ABC zone storage and global strategies such as FIFO or LIFO. The core principle of the algorithm is the control module, which depends on the state presented in Figure 8.1. The modular design provides the benefits that can be gained by the flexible changes, as well as the adaptations and optimizations in the sequence.

The algorithm is then implemented in Matlab and applied to the warehouse model which has previously undergone some modifications. The results obtained by the subsequent simulations of the SGP-AS/RS and throughput of the warehouse are analyzed and evaluated.

8.2 Warehouse Organization

Warehouse management was considered to be very easy to handle in the past when everything was performed manually. The biggest problems then were the bar codes and space utilization in the warehouse. There have been drastic changes in today’s Internet world. After the introduction of Internet technology, everything seemed simpler than in the past, with more efficiency, and less consumption of time. Moreover, a competitive advantage was gained with potential economical savings. The evolving technology changed the warehousing methods considerably, with logistics being carried out at a quicker pace and with very little chance of error. Although there are many technologies evolving every day, many problems have also emerged, making warehouse management more complex. This, in turn, is affecting the whole supply chain management.

The following are some of the problems being faced by today’s warehouses:

1. The automation of all the mechanized or manual operations.

2. Meeting the requirements of the customer with as little customization as possible.
3. Integration of warehouse data with supply chain applications.
4. Compatibility with the cost-effective global supply chain.

In designing an AS/RS, a number of issues must be considered, including the physical configuration of the storage system, the location of the I/O station and the storage method to be used. Several methods exist for assigning products to storage locations in the racks. Two storage assignment methods for AS/RSs which are often used are described here in more detail [41], [42] and [43]. These methods are:

1. Dedicated Storage Assignment
2. Random Storage Assignment

8.2.1 Dedicated Storage Assignment

With this method, each product type is assigned to a fixed location. Replenishments of that product always occur at the same location. The main disadvantages of dedicated storage are its high space requirements and consequent low space utilization. This is due to the fact that locations are reserved even for products that are out of stock. Furthermore, for each product type, sufficient space must be reserved to accommodate the maximum inventory level that may occur. Advantages of dedicated storage, such as locating heavy products at the bottom or matching the layout of stores, are related to non-automated order-picking areas and are not interesting for AS/RSs.

8.2.2 Random Storage Assignment

With this method, any pallet is equally likely to be stored in any of the vacant "n" rack locations. A location is randomly picked and assigned to the pallet on which it is to be stored if it is empty. Otherwise, another location will be picked. This is an approximation to the closest open location rule in which the storage location for a given pallet is selected from a list of open rack locations. Among them, the one closest in time to the I/O station is selected. The pallet is stored in this location, regardless of its turnover.

8.3 Algorithm Core

8.3.1 Control Module

The heart of the algorithm is the control module, which (depending on the state), calls for other modules. It evaluates the upcoming orders from the entry storage and entry retrieval modules. The above orders, which are assigned on the storage bays for storing and/or retrieving, are determined and then added to the commands list. If possible, dual command cycles should always be generated because these cause a positive impact on the throughput. A fast processing of all orders is ensured by selecting shortest routes for single and dual command cycle time.

8.4 The Flowchart

The operating principle of the control module is described by the flowchart in the following Figure 8.1.

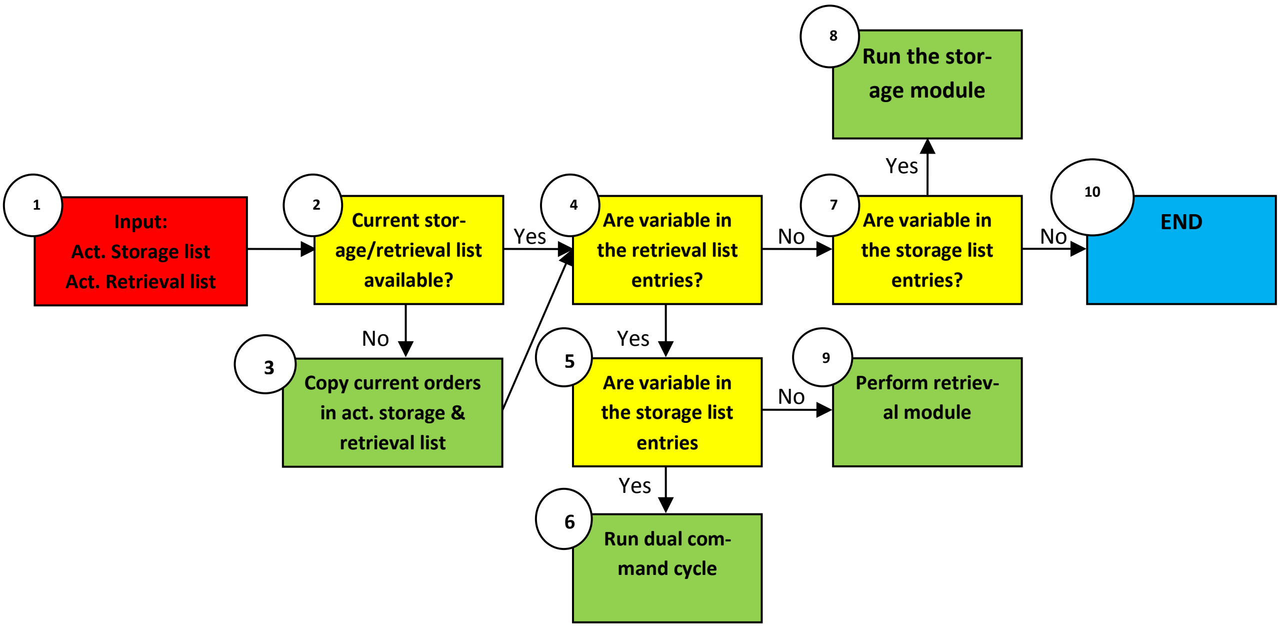


Figure 8.1: Flowchart of the control module

The entry storage and entry retrieval lists are available: (1) for the following decisions which have passed the control module, first check whether there are entries in “storage input and retrieval orders”. (2) If both lists are empty, then the data of the pending and the current time orders are copied in the current list. (3) Then verify whether current delivery list entries are available (4) If not available, the current warehouse entry list queries is queried for existing entries. (7) If so, the warehouse model is running. (8) Exist to outsource orders. (4) and (5) ask again for warehouse entry orders in the list to generate combined cycles through (DCCM) in (6). Otherwise, delivery module (9) is used accordingly.

8.4.1 Entry Storage Module

The ideal storage position for an object in the warehouse is determined by the storage module. The free-place list is determined by the place from which the suitable field is selected. The field which lies closest to the (I/O) point is always taken.

8.4.2 Retrieval Module

The retrieval module determines the position of the shelf for the shortest delivery route. The determination is based on the level list of the warehouse, which includes all the occupied places including the article number of the stored objects in the respective zones of the shelves.

8.5 Comparison Performance

This section presents the performance calculations of SGP-AS/RS with comparable storage and retrieval systems under the same specified constraints. These calculations are based on the projected performance of the SGP-AS/RS. In contrast, the performance of comparable storage and retrieval systems are specified by the manufacturer.

As part of this comparison, single and dual command cycles of SGP-AS/RS are compared with conventional AS/RS. The calculations are performed for 5000 storage dimensions (length, height). Then the difference is calculated for each storage dimension. The difference between single and dual command cycles of SGP-AS/RS and those conventional storage and retrieval systems are referred to as the performance difference, whose value is calculated as a percentage. Finally, 2D and 3D images are created, which illustrates the difference in performance for different 5000 storage dimensions.

The applied formulas for the calculation of single and dual command cycles of SGP-AS/RS are normally suitable for conventional AS/RS. It is assumed that SGP-AS/RS will move the same way as conventional AS/RS. Under this assumption, the worst case for SGP-AS/RS is that it may use the same formulas which are applied to conventional AS/RS [61]. In the best case, formulas for single and dual command cycles can be determined, which describe the precise movement of SGP-AS/RS as described in Chapter 4.

8.5.1 Calculations with Applied Formulas

Estimation travel time for a single command cycle will be calculated using the following formula:

$$E(t_s) = t_0 + 2t_y + 2E(t_l)\ [61] \qquad (8-1)$$

t_0: Dead time of travel cycle (e.g. $t_0 = 3\,sec$ used in calculations)

t_y: Time for the work cycle (e.g. $t_y = 3\,sec$ used in calculations)

$E(t_l)$: The estimation value of path-dependent time shares

t_l: The maximum value of path-dependent times t_x and t_z.

The estimation value of path-dependent time shares $E(t_l)$ for single command cycle will be calculated, depending on the shelf parameter w.

$$E(t_1) = \left(1 - \frac{w}{2}\right)\frac{v_x}{a_x} + \frac{w}{2}\frac{v_z}{a_z} + \frac{L}{v_x}\left(\frac{1}{2} + \frac{1}{6}w^2\right); when\, w \leq 1 \qquad (8-2)$$

$$E(t_1) = \frac{1}{2w}\frac{v_x}{a_x} + \left(1 - \frac{1}{2w}\right)\frac{v_z}{a_z} + \frac{L}{v_x}\left(\frac{w}{2} + \frac{1}{6w}\right); when\, w \geq 1 \qquad (8-3)$$

w: Shelf parameter

$$w = \frac{v_x}{v_z} . \frac{H}{L}$$

The estimation value of travel time for dual command cycle can be calculated using the following formula:

$$E(t_s) = t_0 + 4t_y + 3\frac{1}{2}\left(\frac{v_x}{a_x} + \frac{v_z}{a_z}\right) + 2\frac{2}{3}\frac{L}{v_x} + \frac{14}{30}\frac{L}{v_x} \qquad (8-4)$$

t_0: Dead time of travel cycle (e.g. $t_0 = 3\, sec$ used in calculations)

t_y: Time for the work cycle (e.g. $t_y = 3\, sec$ used in calculations)

$E(t_l)$: The estimation value of path-dependent time shares for dual command cycle

$$E(t_1) = 3\frac{1}{2} + \left(\frac{v_x}{a_x} + \frac{v_z}{a_z}\right) + 2\frac{2}{3}\frac{L}{v_x} + \frac{14}{30}\frac{L}{v_x} \qquad (8-5)$$

8.5.2 Calculations with Matlab

For each storage dimension, the estimation travel times for single and dual command cycles are calculated. The storage dimension is (length x height) [63].

The storage height will be under those calculations between 0m and 50m. The calculations are carried out only for values in intervals of one meter. This means that the storage height will take 50 values.

$$Value\ of\ storage\ height = \{1, 2, 3, 4, 5, 6, 7 \ldots\ 50\}$$

The storage length will be under those calculations between 0m and 100m. The calculations are carried out for the values in steps of one meter. This means that the storage length will accept 100 values.

$$Value\ of\ storage\ length = \{1, 2, 3, 4, 5, 6, 7 \ldots\ 100\}$$

The estimation of travel time for single and dual command cycles in a matrix that has dimension

(m x n) is calculated. The dimension of the matrix is derived from the number of values in the storage height and storage length.

m: number of rows of the matrix.

n: number of columns of the matrix.

In our case:

$m = 50$ (The values of the storage height form the number of rows of matrix, which contains the estimation values for single or dual cycles).

n=100 (The values of the storage length form the number of columns of matrix, which contains the estimation values for single or dual cycles).

The matrix, which contains the estimation values for single or dual cycles, has a dimension of (m x n = 50 x 100). It follows that this matrix contains 5000 estimation values for single or dual cycles for the corresponding storage dimensions. Estimation values calculated for single and dual cycle of SGP-AS/RS compared with those of other conventional (AS/RS). The difference of these values is calculated as a percentage in a matrix and illustrated as a 3D image.

8.5.3 Calculation and Evaluation of SGP-Machine and the first Conventional AS/RS

Relevant technical data in the calculations:

	SGP-AS/RS	First Conventional AS/RS
Max. Speed	6 m/s	6 m/s
Max. Acceleration	5 m/s²	3,5 m/s²
Max. Lifting speed	6 m/s	3 m/s
Max. Lifting acceleration	5 m/s²	3 m/s²

Table 8.1: Acceleration and Speed of SGP-AS/RS and first Conventional AS/RS

- Matlab used in formulas to calculate the difference of the path-dependent time shares for single command cycle in percent.

The difference of the single command cycle will be calculated using the following formula:

$$Single\ cycle\ difference\ in\ percent = [(E_{SGP}(t_1) - E_{FIR}(t_1))/E_{FIR}(t_1)] \times 100 \qquad (8-6)$$

$Single\ cycle\ difference\ in\ percent$: is a matrix which contains values of the position-dependent 5000 time units for the difference of the single command cycle in percent.

$E_{SGP}(t_1)$: is a matrix which contains the 5000 estimation values for single command cycle of SGP-AS/RS.

$E_{FIR}(t_1)$: is a matrix which contains the 5000 estimation values for single command cycle of a conventional AS/RS.

- Matlab is used in formulas to calculate the difference of the path-dependent time shares for dual command cycle in percent.

The difference of the single command cycle will be calculated using the following formula:

$$Dual\ cycle\ difference\ in\ percent = \left[(E_{SGP\_Dual}(t_1) - E_{FIR\_Dual}(t_1))/E_{FIR\_Dual}(t_1)\right] \times 100 \qquad (8-7)$$

$dual\ cycle\ difference\ in\ percent$: is a matrix which contains values of the position-dependent 5000 time units for the difference of the dual command cycle in percent.

$E_{SGP\_Dual}(t_1)$: is a matrix which contains the 5000 estimation values for dual command cycle of (SGP-AS/RS).

$E_{FIR\_Dual}(t_1)$: is a matrix which contains the 5000 estimation values for dual command cycle of first Conventional AS/RS.

- **Calculation Results of Single Command Cycle:**

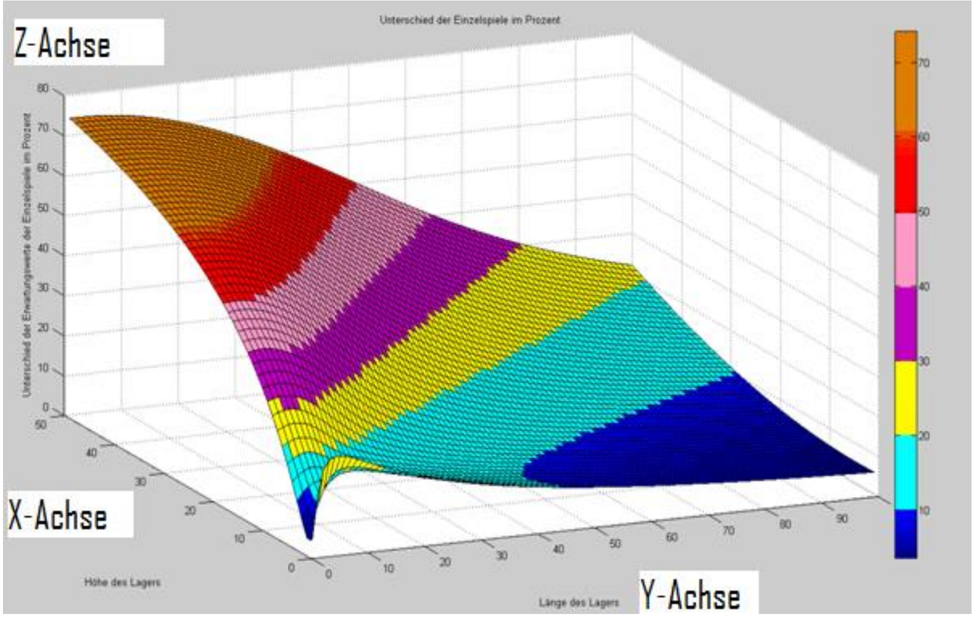


Figure 8.2: Difference of the travel-dependent time for single command cycle in percent

In Figure 8.2, the difference of the estimation values of the path-dependent time shares for single command cycle in percentage is shown for 5000 storage dimensions. The X-axis shows the height of the storage rack, which is between 0m and 50m. The Y-axis represents the length of the storage rack, which is between 0m and 100m. The Z-axis includes the differences in percentage between 0% and 75%. In this illustration, seven different areas of the power difference can be seen as a percentage. The brown area is the difference in performance over 60%. In the red zone the values are between 50% and 60%. Pink represents a difference in performance of 40% to 50%. Purple represents the values between 30% and 40%. The light blue area represents a difference in performance between 10% and 20%. In the blue region, the values are between 0% and 10%.

As a result using this image, we arrive at the following conclusion: The lower the values of the storage length and the higher the values of the storage height, the higher are the performance differences in percent.

- **Calculation Results of Dual Command Cycle:**

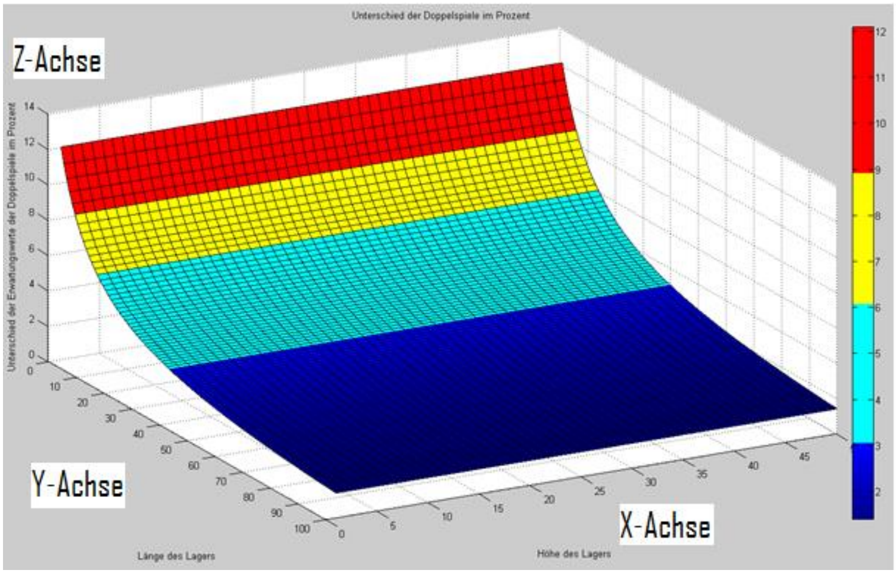


Figure 8.3: Difference of the travel-dependent time for dual command cycle in percent

In Figure 8.3, the difference of the estimation values of the path-dependent time shares is represented for the dual command cycle in percent for 5000 storage dimensions. The X-axis shows the height of the storage, which is between 0m and 50m. The Y-axis represents the length of the storage, which lies between 0m and 100m. The Z-axis includes the difference between 0% and 12%. In this image, four areas can be recognized. In the red zone, the values are between 9% and 12%. Yellow corresponds to a difference of 6% to 9%, light blue, the values between 3% and 6%, and the blue region represents the values between 0% and 3%.

Using this figure, we arrive at the following conclusion: For a particular storage length the performance differences for all the storage heights are still the same. However, the performance difference will depend on the length of storage rack.

8.6 Representation of Results

8.6.1 Comparison of the SGP-AS/RS with second Conventional AS/RS

As was mentioned before (Chapter 7, Section 7) conventional high storage rack machines are introduced to estimate the expected difference in travel time of SGP-AS/RS, and in order to analyze and calculate the expected travel cycle time for both single and dual command cases.

- **Single Command Cycle**

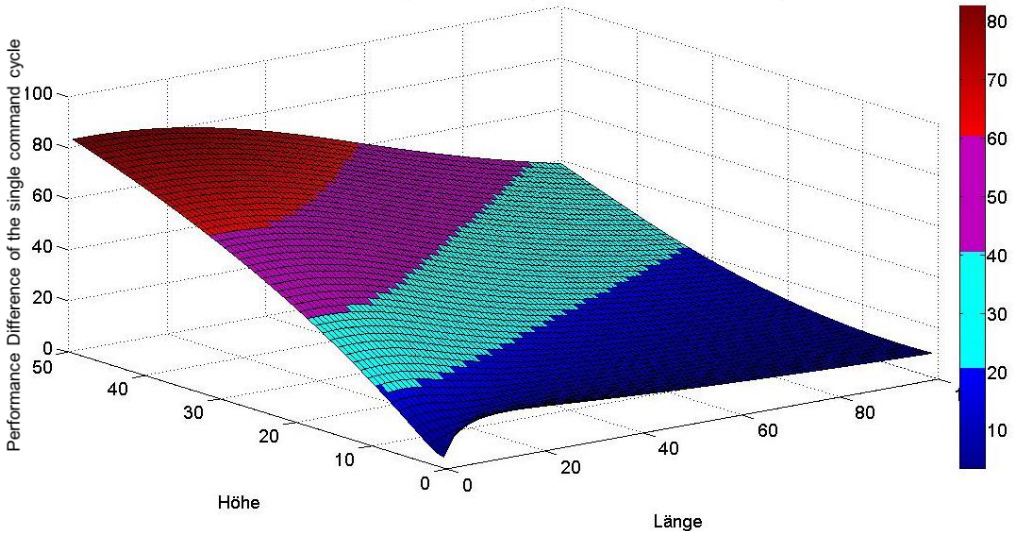


Figure 8.4: Difference between the single command cycle in SGP-AS/RS and second Conventional AS/RS

Figure 8.4 shows the difference in performance of the single command cycle of 5000 storage dimensions that illustrate: four areas with four different colors can be seen. In the blue area the difference of the single command cycles is below 20%. Light blue represents a difference of 20% to 40%, violet values between 40% and 60%, and in the red area the difference is between 60% and 82%.

	Length in m	10	20	30	40	50	60	70	80	90	100
height in m	Difference in %										
10		22	18	16	14	13	12	11	10	10	9
20		42	38	32	26	22	19	16	15	13	12

30		58	55	50	43	37	31	27	23	21	18
40		71	69	65	59	52	46	40	35	31	27
50		82	80	77	72	66	60	54	48	43	38

Table 8.2: Difference between the single command cycle in SGP-AS/RS and second Conventional AS/RS

These values were calculated using the formula (8-7).

As can be seen in Table 8.2, all the values of the difference of the single command cycle in percent are positive. This means that the number of cycles of the SGP-AS/RS which is greater for all storage dimensions is available for the second Conventional AS/RS. The mean of differences of single command cycle is 34%. The maximum value of differences of single command cycle is 82%. The minimum value of differences single command cycle is 9%.

The smaller the values of storage length and the greater the values of storage height, the higher is the power difference and the difference in percentage of throughput between SGP-AS/RS and the second Conventional AS/RS.

- **Dual Command Cycle**

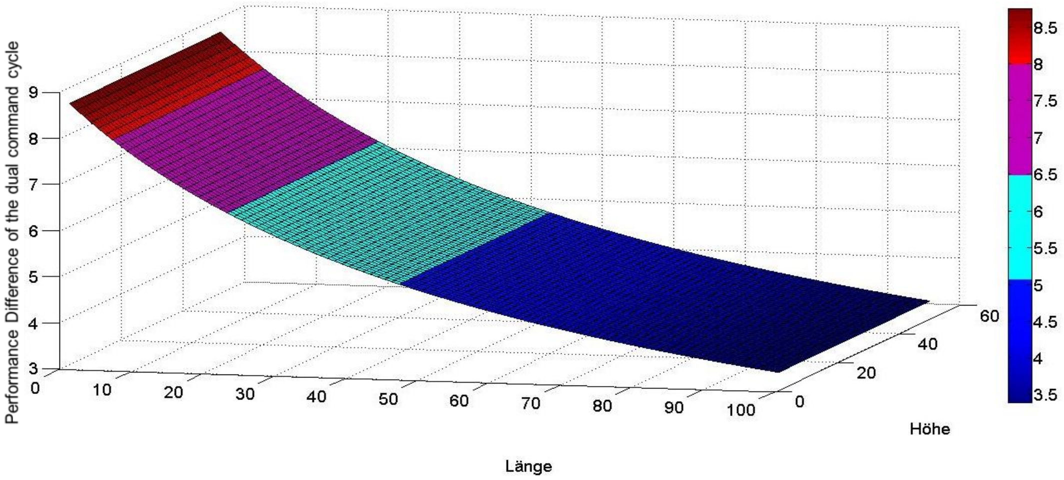


Figure 8.5: Difference between the dual command cycle in SGP-AS/RS and second Conventional AS/RS

Figure 8.5 shows the difference in performance of the dual command cycle of 5000 storage dimensions that illustrate: four areas with four different colors can be seen. The difference in the blue region of the dual command cycle is below 5%. Light blue, a difference of 5% to 6.5%. Purple represents the values between 6.5% and 8%, and the red area represents the difference between 8% and 8.7%.

	length in m	10	20	30	40	50	60	70	80	90	100
Height in m	Difference in %										

10 to 50		8	7	6	5	5	5	4	4	4	3

Table 8.3: Difference between the dual command cycle in SGP-AS/RS and second Conventional AS/RS

The values of the differences of the dual command cycle in percent, which are summarized in the table, were calculated with the formula (8-7).

As can be seen in Table 8.3, all values are the differences between the dual command cycles in positive percent. This means that the number of dual command cycles of SGP-AS/RS is greater for all storage dimensions than that of the second Conventional AS/RS. The mean of the differences of the dual command cycles is 5%. The maximum value of differences of dual command cycles is 8%. The minimum value of the differences dual command cycles is 3%. Therefore, the advantage of the SGP-AS/RS for the dual command cycles is low (less than 8%).

8.6.2 Comparison of the SGP-AS/RS with the third Conventional AS/RS

- **Single Command Cycle**

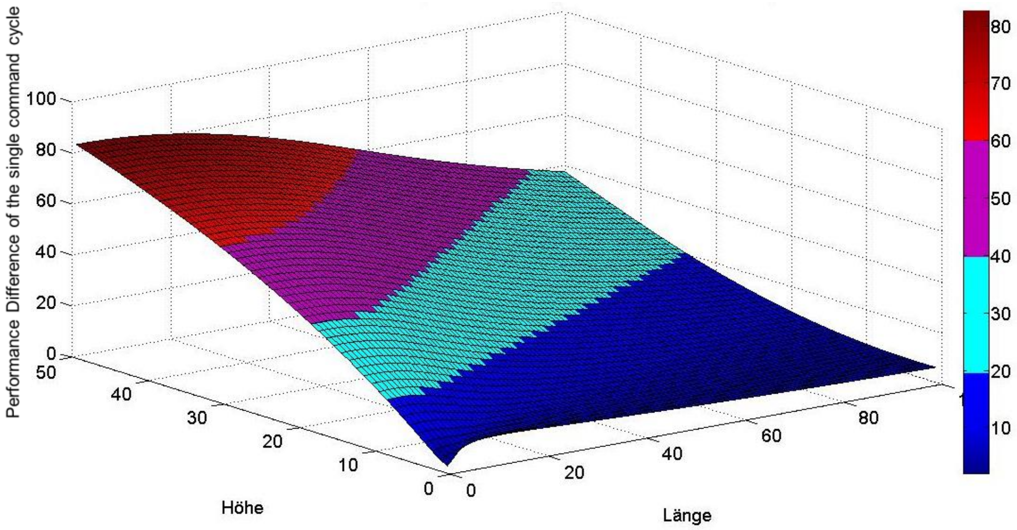


Figure 8.6: Performance difference between the single command cycle in SGP-AS/RS and third Conventional AS/RS

Figure 8.6, shows the difference in performance of the single command cycles of 5000 storage dimensions that illustrate: four areas with four different colors can be seen. In the blue area the difference of the single command is below 20%, light blue, a difference of 20% to 40%, violet, the values between 40% and 60%, the red area represents the difference between 60% and 80%.

	Length in m	10	20	30	40	50	60	70	80	90	100
Height in m	Difference in %										
10		21	16	13	11	10	9	8	7	7	6
20		42	37	30	24	20	16	14	12	11	10
30		58	54	49	42	36	30	25	22	19	16
40		71	68	64	58	51	45	39	34	30	26
50		82	80	76	71	66	59	53	47	42	37

Table 8.4: Difference between the single command cycle in SGP-AS/RS and third Conventional AS/RS

These values were calculated using the formula (8-7).

As can be seen in Table 8.4, all values are the differences between the single command cycles in positive percent. This means that the number of cycles of the SGP-AS/RS for all storage dimensions is greater than that of the storage dimensions of third Conventional AS/RS. The mean of the differences of the single command cycles is 32%. The maximum value of differences of the single command cycles is 82%. The minimum value of the differences single command cycles is 6%.

The smaller the values of storage length and the greater the values of storage height, the higher is the power difference and the difference in percentage of throughput between SGP-AS/RS and third Conventional AS/RS

- **Dual Command Cycle**

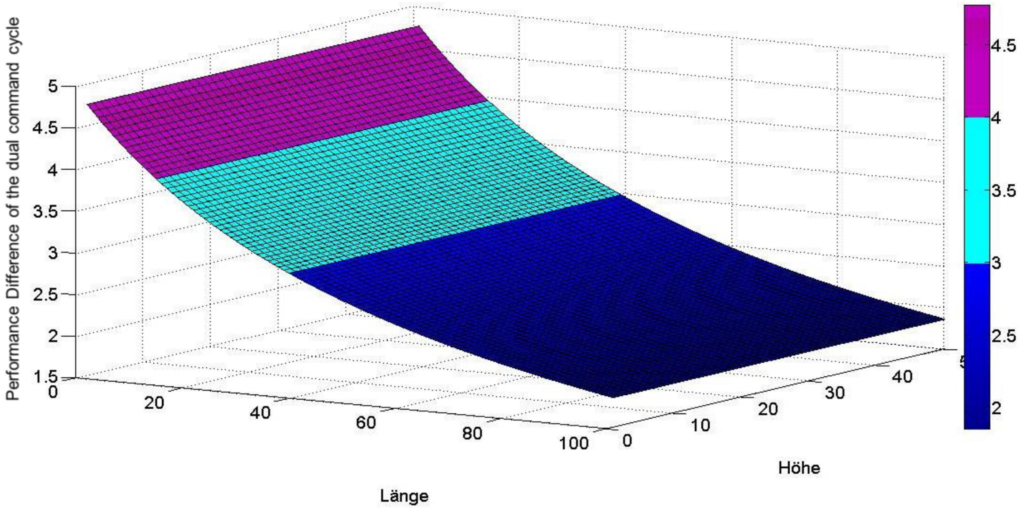


Figure 8.7: Difference between the dual command cycle in SGP-AS/RS and third Conventional AS/RS

Figure 8.7shows the difference in performance of the Dual command of 5000 storage dimensions that illustrate: three areas with three different colors can be seen. In the blue area the difference of the single command cycle is below 3%, light blue a difference of 3% to 4%, violet constitutes between 4% and 4.7%. Therefore, with increasing storage length, the difference in percentage of dual command cycle is low.

	Length in m	10	20	30	40	50	60	70	80	90	100
Height in m	Difference in %										
10 to 50		4	4	3	3	3	2	2	2	2	2

Table 8.5: Difference between the dual command cycle in SGP-AS/RS and third conventional AS/RS

The values of the differences of the dual command cycle in percent, which are summarized in the table, were calculated with the formula (8-7).

As can be seen in Table 8.5, all values are positive. This means that the number of dual command cycles of SGP-AS/RS is greater for all storage dimensions than that of the third conventional AS/RS. The mean of the differences of the dual command cycles is 3%. The maximum value of differences in dual command cycles is 4%. The minimum value of the differences dual command cycles is 2%. Therefore, the advantage of the SGP-AS/RS for the dual command cycle is low (below 4%).

8.6.3 Comparison of the SGP-AS/RS with the forth Conventional AS/RS

- **Single Command Cycle**

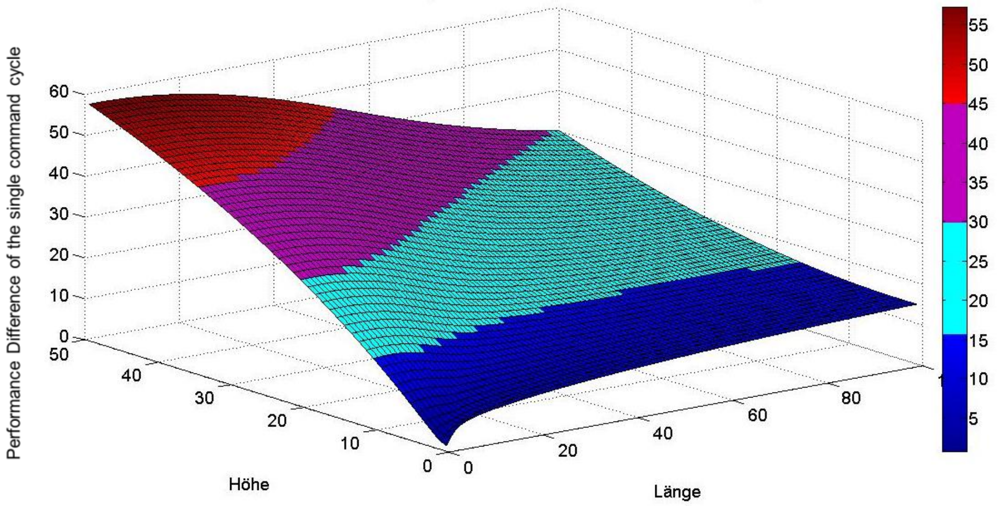


Figure 8.8: Difference between the single command cycle in SGP-AS/RS and forth conventional AS/RS

Figure 8.8 shows the difference in performance of the single command cycle of 5000 storage dimensions that illustrate that four areas with four different colors can be seen. The difference in the blue region of the single command cycle is below 15%. Light blue, a difference of 15% to 30%. Purple represents the values between 30% and 45%, and the red area represents the difference between 45% and 57%.

	Length in m	10	20	30	40	50	60	70	80	90	100
Height in m	Difference in %										
10		15	13	12	13	13	13	14	14	14	5
20		29	26	22	19	18	17	17	17	17	17
30		40	38	34	30	27	24	22	21	20	20
40		49	48	45	41	37	33	30	27	25	24
50		57	56	53	50	46	42	38	35	32	30

Table 8.6: Difference between the single command cycle in SGP-AS/RS and forth conventional AS/RS

These values were calculated using the formula (8-7).

As can be seen in Table 8.6, all values are positive. This means that the number of cycles of the SGP-AS/RS is greater for all storage dimensions than that of the forth conventional AS/RS. The mean of the differences of the single command cycles is 26%. The maximum value of differences of the single command cycles is 57%. The minimum value of the differences single command cycles is 5%.

The smaller the values of storage length and the greater the values of storage height, the higher is the power difference and the difference in percentage of throughput between SGP-AS/RS and forth conventional AS/RS.

- **Dual Command Cycle**

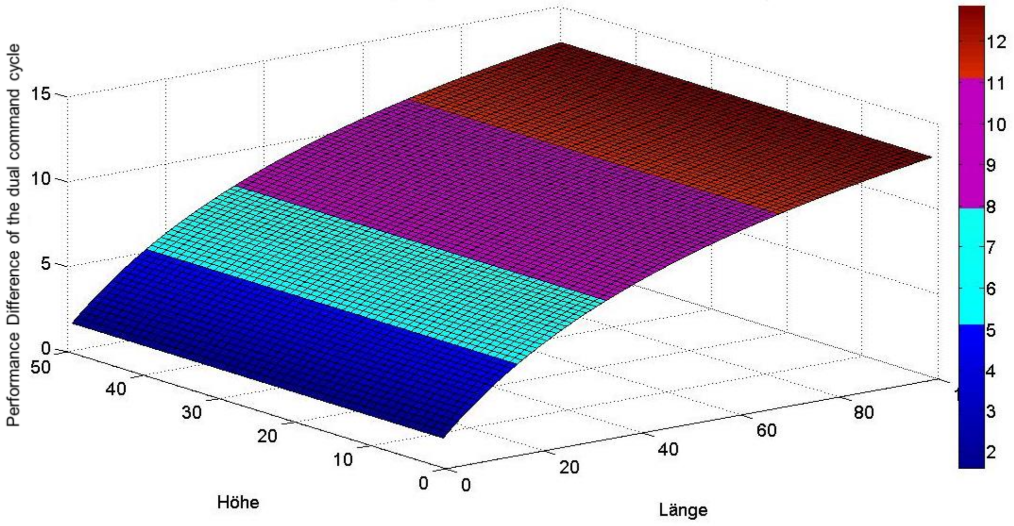


Figure 8.9: Difference between the dual command cycle in SGP-AS/RS and forth Conventional AS/RS

Figure 8.9 shows the difference in performance of the dual command cycle of 5000 storage dimensions that illustrate: four areas with four different colors can be seen. The difference in the blue region of the single command cycles is below 5%. Light blue, a difference of 5% to 8%. Purple represents the values between 8% and 11%, the red area represents the values between 11% and 13%. Therefore, with increasing storage length the difference in percentage of dual command cycle increases.

	Length in m	10	20	30	40	50	60	70	80	90	100
Height in m	Difference in %										
10 to 50		4	6	7	9	10	11	11	12	12	13

Table 8.7: Difference between the dual command cycle in SGP-AS/RS and forth conventional AS/RS

The values of the differences of the double cycles in percent, which are summarized in the table, were calculated with the formula (8-7).

As can be seen in Table 8.7, all values are positive. This means that the number of dual cycles of SGP-AS/RS is greater for all storage dimensions than that of the forth conventional AS/RS. The mean of the differences of the dual command cycle is 9%. The maximum value of the differences of the dual command cycle is 13%. The minimum value of the differences of the dual command cycle is 4%. Therefore, the advantage of the SGP-AS/RS with the dual command cycle is not low (to 13%).

8.6.4 Comparison of the SGP-AS/RS with fifth conventional AS/RS

Relevant technical data in the calculations:

	SGP-AS/RS	Fifth conventional AS/RS
Max. speed	6 m/s	6 m/s
Max. acceleration	5 m/s²	2,4 m/s²
Max. lifting speed	6 m/s	2 m/s
Max. lifting acceleration	5 m/s²	2 m/s²

Table 8.7: Acceleration and speed of SGP-AS/RS and fifth conventional AS/RS

- **Single Command Cycle**

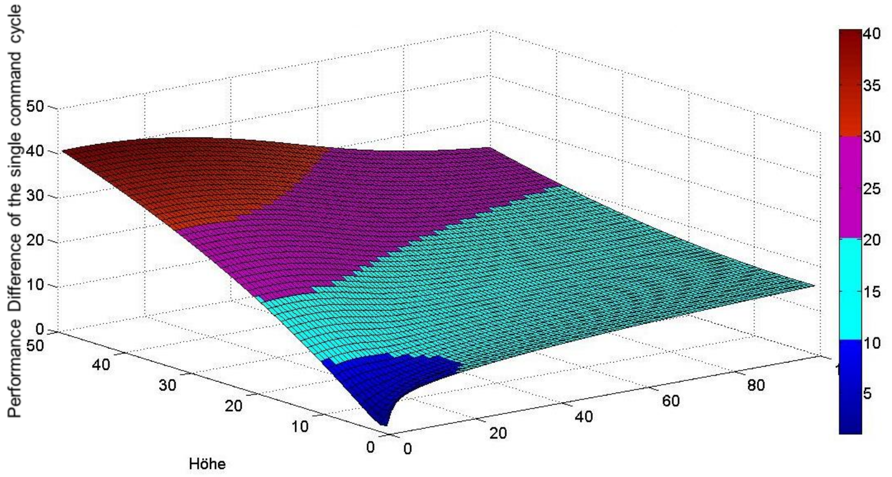


Figure 8.10: Difference between the single command cycle in SGP-AS/RS and fifth conventional AS/RS

Figure 8.10 shows the difference in performance of the single command cycle of 5000 storage dimensions that illustrate: four areas with four different colors can be seen. The difference in the blue region of the single command cycles is below 10%, light blue, a difference of 10% to 20%, violet, the values between 20% and 30%, and the red area represents the difference between 30% and 40%.

	Length in m	10	20	30	40	50	60	70	80	90	100
Height in m	Difference in %										
10		11	11	12	13	13	14	14	15	15	15
20		20	19	17	16	16	16	16	16	16	16
30		28	27	25	23	21	19	19	18	18	18
40		35	34	32	30	27	25	23	22	21	20

50		40	39	38	36	34	31	28	26	25	24

Table 8.8: Difference between the single command cycle in SGP-AS/RS and fifth conventional AS/RS

These values were calculated using the formula (8-7).

As can be seen in Table 8.8, all values are positive. This means that the number of cycles of the SGP-AS/RS for all storage dimensions is greater than that of the storage dimensions of fifth conventional AS/RS. The mean of the differences of the single command cycles is 21%. The maximum value of differences of the single command cycles is 40%. The minimum value of the differences single command cycle will be 15%.

The smaller the values of storage length and the greater the values of storage height, the higher is the power difference and the difference in percentage of throughput between SGP-AS/RS and fifth conventional AS/RS.

- **Dual Command Cycle**

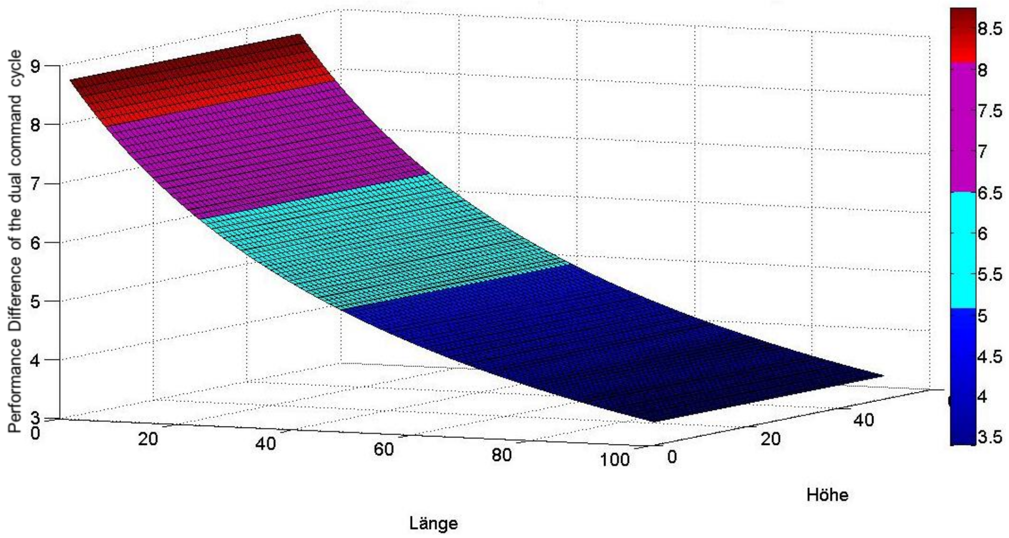


Figure 8.11: Difference between the dual command cycle in SGP-AS/RS and fifth conventional AS/RS

Figure 8.11shows the difference in performance of the dual command cycles of 5000 storage dimensions that illustrate: four areas with four different colors can be seen. The difference in the blue region of the single command cycles is below 5%, light blue, a difference of 5% to 6.5%. Purple represents the values between 6.5% and 8%, and the red area represents the values between 8% and 8.7%. Therefore, with increasing storage length increases the difference in percentage of dual command cycle

	Length in m	10	20	30	40	50	60	70	80	90	100
Height in m	Difference in %										
10 to 50		8	7	6	5	5	5	4	4	4	3

Table 8.9: Difference between the dual command cycle in SGP-AS/RS and fifth conventional AS/RS

These values were calculated using the formula (8-7).

As can be seen in Table 8.9, all values are positive. This means that the number of dual cycles of SGP-AS/RS is greater for all storage dimensions than that of the fifth conventional AS/RS. The mean of the differences of the dual command cycles is 5%. The maximum value of differences of dual command cycles is 8%. The minimum value of the differences of dual command cycles is 3%. Therefore, the advantage of the SGP-AS/RS for the dual command cycle is low (less than 8%).

8.6.5 Comparison of the SGP-AS/RS with sixth conventional AS/RS

- **Single Command Cycle**

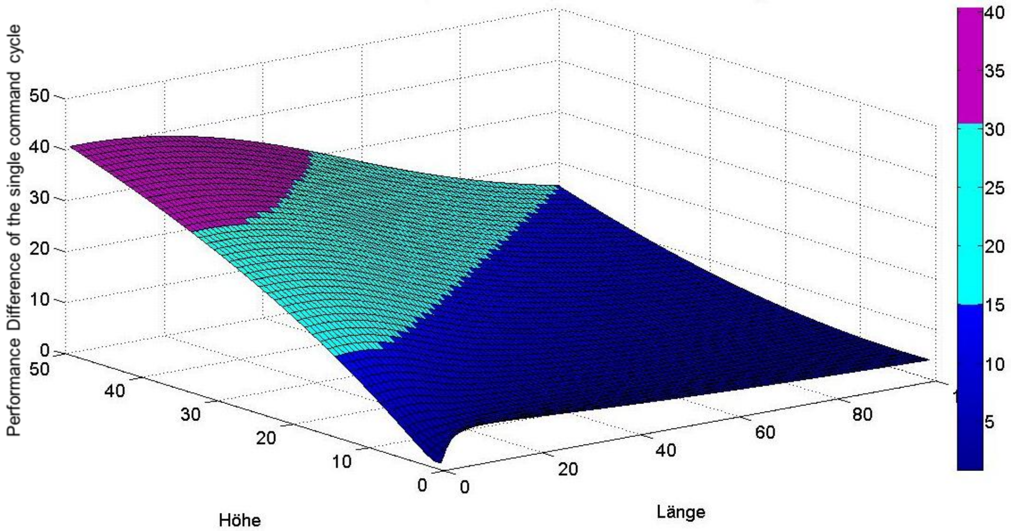


Figure 8.12: Difference between the single command cycle in SGP-AS/RS and sixth conventional AS/RS

Figure 8.12 shows the difference in performance of the single command of 5000 storage dimensions that illustrate; three sections with three different colors can be seen. The difference in the blue region of the single command cycles is below 15%, light blue, a difference of 15% to 30%, purple represents the values between 30% and 40%.

	Length in m	10	20	30	40	50	60	70	80	90	100
Height in m	Difference in %										
10		10	8	7	6	5	5	5	4	4	4
20		20	17	13	11	9	8	7	6	5	5
30		28	26	23	19	15	13	11	9	8	7
40		35	33	31	27	23	20	17	14	12	11
50		40	39	37	34	31	27	23	20	17	15

Table 8.10: Difference between the single command cycle in SGP-AS/RS and sixth conventional AS/RS

These values were calculated using the formula (8-7).

As can be seen in Table 8.10, all values are positive. This means that the number of cycles of the SGP-AS/RS is grater for all storage dimensions than the storage of sixth conventional AS/RS. The mean of the differences of the single command cycles is 15%. The maximum value of differences of the single command cycles is 40%. The minimum value of the differences single command cycles is 4%.

The smaller the values of storage length and the greater the values of storage height, the higher is the power difference and the difference in percentage of throughput between SGP-AS/RS and sixth conventional AS/RS.

- **Dual Command Cycle**

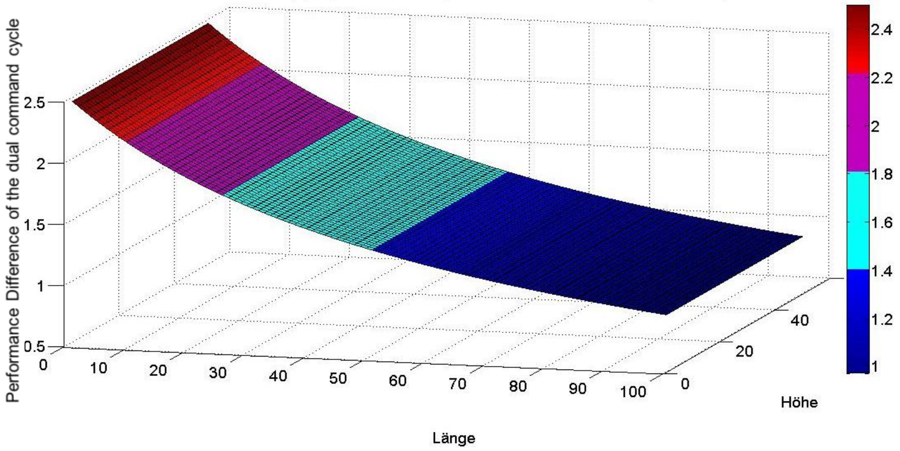


Figure 8.13: Difference between the dual command cycle in SGP-AS/RS and sixth conventional AS/RS

Figure 8.13 shows the difference in performance of the dual command cycle of 5000 storage dimensions that illustrate: four areas with four different colors can be seen. In the blue region of the difference of single command cycles below 1.4%, light blue corresponds to a difference of 1.4% to 1.8%, purple represents the values between 1.8% and 2.2%, and the red area represents the values between 2.2% and 2.5%. Therefore, with increasing storage length the difference in percentage of dual command cycle increases.

	Length in m	10	20	30	40	50	60	70	80	90	100
Height in m	Difference in %										
10 to 50		2	2	2	2	1	1	1	1	1	1

Table 8.11: Difference between the dual command cycle in SGP-AS/RS and sixth conventional AS/RS

These values were calculated using the formula (8-7).

As can be seen in Table 8.11, all values are positive. This means that the number of dual cycles of SGP-AS/RS is greater for all dimensions than the storage of sixth conventional AS/RS. The mean of the differences of the dual command cycles is 1.4%. The maximum value of the differences of the dual command cycles is 2%. The minimum value of the differences of the dual command cycles is 1%. Therefore, the advantage of the SGP-AS/RS for the dual command cycles is very low (below 2%).

8.6.6 Summary of Comparison

8.6.6.1 Differences of the Single Command Cycles in percent

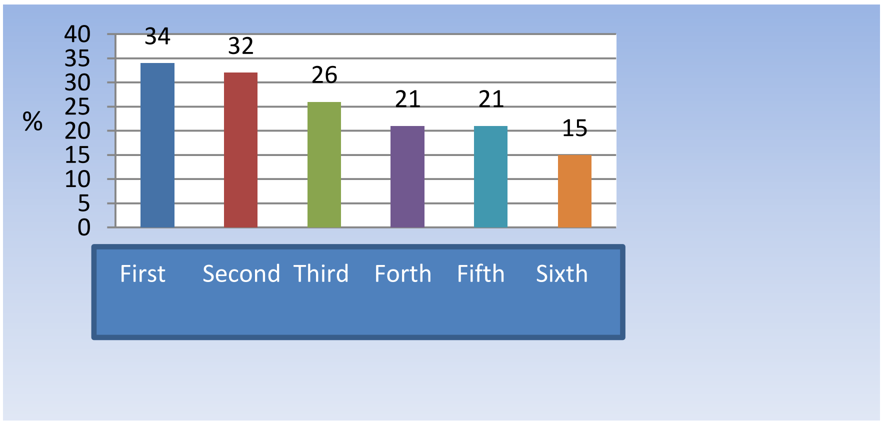


Figure 8.14: Difference in percentage (%) of singles command cycles between the SGP-AS/RS and 6 other storage and retrieval systems

In Figure 8.14 it can be seen that the SGP-AS/RS at worst reaches 15% more singles cycles than the most advanced storage and retrieval device on the market. This can be seen on the bar with the orange color. In the best case the SGP-AS/RS achieves 34% more than the single cycle's first AS/RS. This can be recognized by the dark blue bar. The SGP-AS/RS, due to their high speed and acceleration, achieves more singles cycles than any other storage and retrieval systems.

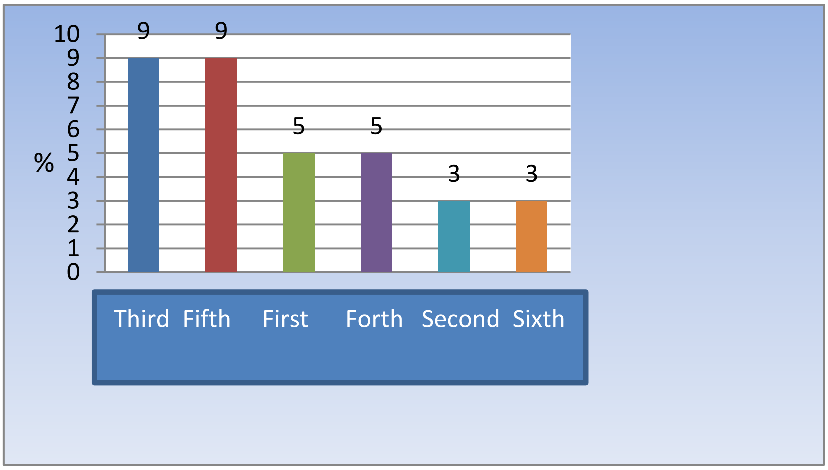


Figure 8.15: Difference in percentage (%) of dual command cycles between the SGP-AS/RS and 6 other storage and retrieval systems

From Figure 8.15 it can be seen that the SGP-AS/RS at worst reached 3% more singles matches as the most advanced storage and retrieval device on the market AS/RS. This can be seen on the bar with the orange color. In the best case SGP-AS/RS reaches 9% more than the single command cycles of third conventional AS/RS and the fifth conventional AS/RS. This can be recognized by the dark blue and bright red bars.

8.6.6.2 Differences of the Single Command Cycles per Hour

	SGP	Fifth conv.	First conv.	Second conv.	Forth con.	Sixth conv.	Third conv.
Average of Dual Command Cycle/hour	115	106	109	111	109	113	106
Average of Dual Command Cycle/hour	177	148	135	137	148	155	143

Table 8.12: Mean values of the single and dual cycles of the seven AS/RS.

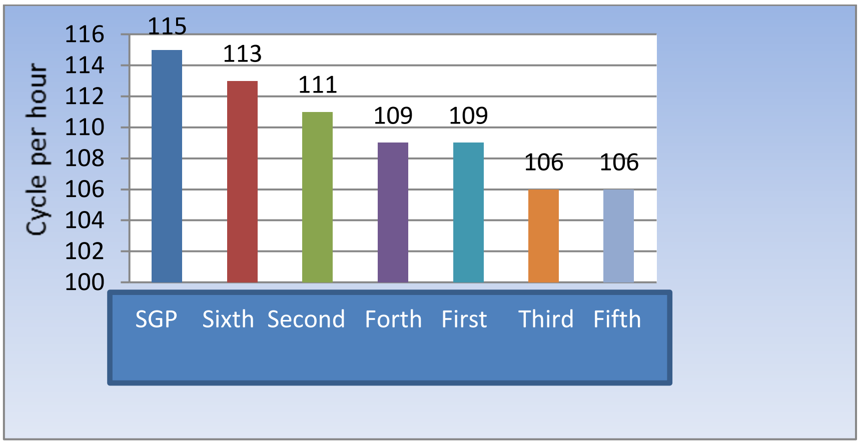


Figure 8.16: Comparison of the average values of the single command cycles of the SGP-AS/RS with the 6 other AS/RS

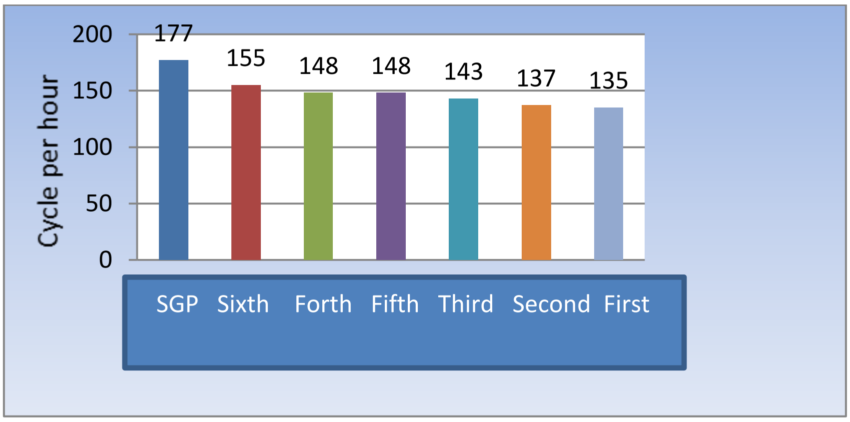


Figure 8.17: Comparison of the average values of the dual command cycles of the SGP-AS/RS with the six other AS/RS

In this comparison, it can be seen that in the worst case, better numbers of dual and single command cycles can be achieved than those of most advanced conventional storage and retrieval devices on the market, whereby the values which can be seen in the figures are average values. These are averages of 5000 storage dimensions. As was mentioned earlier in this chapter, these dimensions include the length (from 0m to 100m) and the height (0m to 50 m).

9 Conclusion and Future Work

As a part of the market analysis, seven conventional stacker cranes were microscopically examined and compared with (SGP-AS/RS). It was found that all conventional storage and retrieval devices have a certain height restriction. The typical height achieved by these storage and retrieval devices is 12m. However, in exceptional cases, a stacker crane with a height of 24m is also available. In contrast, (SGP- AS/RS) is not burdened with this restriction. Another advantage of the (SGP- AS/RS) cranes is their high dynamic range (high speed and acceleration), which is hardly achieved by other stacker cranes. Conventional storage and retrieval devices are constructed to be as light as possible, in order to reduce the moving mass. However, upon high acceleration and velocity distribution, this sleek design tends to transfer the vibrations to the resulting suspension. It also causes negative effects, especially, during braking and acceleration processes as the inertia of post adversely affects the stability of the stacker crane, making essential use of an auxiliary propulsion system. In (SGP- AS/RS), these problems are overcome by the replacement of the platform.

According to (VDMA), the number of stacker cranes delivered in 2007, 2008 and 2009 internationally and in Germany as well, show an increased demand for storage and retrieval systems with a height of 6m and a payload of less than 100kg. In this work, the singles and duel command cycle of (SGP- AS/RS) cranes and the other six presented stacker cranes for 5000 rack dimensions were calculated. The (SGP- AS/RS) works with all stock dimensions more efficiently than the conventional AS/RS with respect to single and dual command. According to the performed calculations, lower values of rack length and higher values of storage height, lead to a greater difference in the handling capacity of the (SGP- AS/RS) cranes in comparison to the other storage and retrieval devices.

According to the calculations of forces and simulations from the Mechatronics Department, it has been determined that the forces are very high at the edge of the workspace. Using a rope crossing in two planes, the movement of platform can improve the distribution of forces and thus increase the workroom and further increase the system stability.

An important part of this work is to plan the experimental setup. To accomplish this, firstly a specification was created in which the requirements for the experimental setup are listed. The next step is to create a specification, describing a way in which the experimental setup can be realized. On the basis of specifications, components are procured and installed as scheduled. All provisions and conditions that are defined in the specification are observed.

The theoretical maximum performance of eight engines of (SGP)-cranes in the test setup is calculated and compared to a conventional stacker crane. Here, the overall performance of engines of (SGP- AS/RS) cranes is much higher than that of conventional cranes.

From the economic point of view the proposed S/R unit with Stewart-Gough-Platform costs similar or equal to the available S/R unit in the market, but the big advantage is its lets its investment within three years in return, due to its high output potential. Furthermore if the maintenance costs are reduced along with high quality equipments the S/R with Stewart-Gough-Platform makes it a good solution for small load warehouses.

9.1 Future Work

Form a design point of view, the general design has to be analyzed element by element, and a tool has to be developed to supply the platform machine with power, because this is one of the difficulties facing the new design, taking into consideration the cost of this tool. Besides that, the idea of utilization of the height of the storage rack instead of its length is very important to minimize the utilized area. However, the question remains open: Is this idea feasible from a mechanical point of view? Therefore, comprehensive studies from a mechanical side have to be carried out.

Although this thesis has provided a significant study of the SGP-AS/RS systems for the automated material handling environment, there are still other equally important areas that require attention. They include the analysis of multi-shuttle SGP-AS/RS, which have been proven to be efficient in terms of throughput. The storage assignment policies for multi-shuttle SGP-AS/RS, storage assignment policies for SGP-AS/RS having multiple I/O stations, batching and dwell point rules for SGP-AS/RS can also be analyzed and results can be compared with the technologies discussed in a preceding chapter (Chapter 5). Storage assignment policies for such types of configuration (e.g. multi-shuttle or multiple I/O stations) have been hardly formulated.

With respect to the requirement of the customer for speedy recovery of the system after breakdown a good service concept has to be designed giving not only good service, support but also being flexible with the changes of the working environment.

Lastly, no attention has been paid so far to the relationship between SGP-AS/RS and another material handling system in production or distribution facilities. Especially in situations where the SGP-AS/RS is just one of many systems, overall warehouse management systems' performance cannot be assessed by simply adding up the performance of all individual performances. An integrated approach would be desirable. Therefore, a first step would be to develop approaches which simultaneously optimize the design of an SGP-AS/RS and another material handling system.

References

[1] Hans-Georg Harnisch: AutoCAD-Zeichenkurs 2. Auflage: Vieweg Verlag, (2002).

[2] Creo Elements/Pro-en.wikipedia.org/wiki/Creo_Elements/Pro (10.February 2013). .

[3] MathWorks. Matlab Documentation. MathWorks Inc, (2004).

[4] Asef-Vaziri, A. G. Laporte, and C. Sriskandarajah “The Block Layout Single Loop Design Problem” To appear in IIE Transactions.

[5] Mikell P. Groover: "Automation, Production Systems and Computer Integrated Manufacturing," Second Edition, Pearson Education (2008).

[6] S. Hsieh and K. C. Tsai: "A BOM oriented class-based storage assignment in an automated storage/retrieval system, "International Journal of Advanced Manufacturing Technology (2001) 17, 683-691.

[7] M. Aslam, Farrukh, A. R. Gardezi and N. Hayat: "Design, Development and Analysis of Automated Storage and Retrieval System with Single and Dual Command Dispatching using MATLAB, "World Academy of Science, Engineering and Technology (2009).

[8] Y. A. Bozer, and J. A. White: "Travel-time models for automated storage/retrieval systemes," IIE Transactions (1984) 16(4), 329-338.

[9] H. Hwang and Lee, B. Seong: "Considerations for planning and installing an Automated Storage/Retrieval System,"Material Handling Instiute, Inc., AS/RS Document-100 7M (1977).

[10] H. Hwang and Lee, B. Seong: "Travel-time models considering the operating characteristics of the storage and retrieval machine," International Journal of Production Research (1984) 28(10), 1779-1789.

[11] D. T. Chang and U. P. Wen: "The impact on rack configuration on the speed profile of the storage and retrieval machine," IEE Transactions (1997) 29, 525-531.

[12] P. J. Egbelu and C. T. Wu: "A comparison of dwell point rules in an automated storage/retrieval system,"International Journal of Production Research (1993) 31(11), 2515-2530.

[13] A. Eynan and M. J. Rosenblatt: "Establishing zones in single-command class-based rectangular AS/RS,"IEE Transactions (1994) 26(1), 38-46.

[14] S. C. Graves, W. H. Hausman and L. B. Schwarz: "Storage-retrieval interleaving in automatic warehousing systems,"Management Science (1977) 23(9), 935-945.

[15] W. H. Hausman, L. B. Schwarz and S. C. Graves: "Optimal storage assignment in automated warehousing systems, "Management Science (1976) 22(6), pp. 629-638.

[16] Automated Storage and Retrieval System. [Online] Available: http://www.ignou.ac.in/upload/Unit4-55.pdf.

[17] B. C. Park, R. D. Foley, J. A. White and E. H. Frazelle: "Dual command travel times and miniload system throughput with turnover-based storage," IIE Transactions (2003) 35, 343-355.

[18] N. Jawahar, Aravindan and Ponnambalam, (1998), “Optimal Random Storage Allocation for an AS/RS in an FMS” Springer, pp. 14:116-132.

[19] Automated Storage/Retrieval Systems Product Section of Material Handling Industry of America, (2009).

[20] University of Chicago Library, “the Joe and Rika Mansueto Library”, http://mansueto.lib.uchicago.edu/shelving.html.(30.March 2010).

[21] L. B. Schwarz, S. C. Graves and W. H. Hausman: "Scheduling policies for automatic warehousing systems: Simulation results," AIIE Transactions (1978) 10(3), 260-270.

[22] The Knowledge-Based Economy, organisation for economic cooperation and development (1996).

[23] VDI-Richtlinie 3561, Testspiele zum Leistungsvergleich und zur Abnahme von Regalförderzeugen. Düsseldorf: Verein Deutsche Ingenieure (1973).

[24] BOZER, Y.A., and WHITE, J.A., (1984), “Travel-Time Models for Automated Storage/Retrieval Systems” IIE Transactions, 329-338.

[25] PAN, C.H. and WANG, C. H, (1996), “A framework for the dual command cycle travel time model in automated warehousing systems” International Journal of Production Research, 34, 2099-2117.

[26] Gudehus, T. (1973) Grundlagen der Kommissioniertechnik Dynamik der Wareverteilung Lagersysteme. (Principals of Order Picking Operations in Distribution and Warehousing System), W. Girardet, Essen, West Germany.

[27] HWANG H, LEE SB (1990) Travel time models considering the operating characteristics of the storage and retrieval machine. Int J Prod Res 28(10):1779–1789.

[28] MELLER, R.D. and MUNGWATTANA, A., (1997), “Multi-shuttle automated Storage/retrieval systems”, IIE Transactions, 29, 925-938.

[29] H. A. Zollinger: " AS/RS application, benefits and justification in comparison to other storage methods: A white paper," Automated Storage Retrieval Systems Production Section of the Material Handling Industry of America (1999).

[30] Handbook of Simulation, Edited by Jerry Banks. ISBN 0-471-13403-, 1998 John Wiley & Sons, Inc.

[31] http://www.mathworks.de/company/newsletters/articles/creating-a-stewart-platform-model-using-simmechanics.html (04.February 2012).

[32] University of Duisburg-Essen, Chair of Mechatronics, “Seilgetriebene Stewart -Plattformen in Theorie und Anwendung”, http://www.uni-due.de/segesta/ (15.April, 2011).

[33] Yavuz A. Bozer and John A. White Design and Performance Models for End-of-Aisle Order Picking Systems Management Science 1990 36:852-866; doi:10.1287/mnsc.36.7.852.

[34] Han, MH, McGinnis, LF, Shieh, JS, and White, JA, “On sequencing retrievals in an automated storage–retrieval system”, IIE Transactions 19 (1): 56–66, 1987.

[35] FEM 9.851, European Federation of Material Handling, (2003), “Leistungsnachweis für Regalbediengeräte Spielzeiten” FEM Section IX, 1-22.

[36] Hu, YH, Huang, SY, Chen, CY, Hsu, WJ, Toh, AC, Loh, CK, and Song, TC, “Travel time analysis of a new automated storage and retrieval system”, Computers & Operations Research 32 (6): 1515–1544, (2005).

[37] Bengtson and Gomez (1988) “Why a single aisle miniload system is not simple to model” Proceedings of the (1988) Winter Simulation Conference.

[38] D. J. Medeiros, E. E. Enscore, and A. Smith “performancaen anlysis of mini-load systems” Proceedings of the (1986) Winter Simulation Conference.

[39] Robert D. Foley, Back-of-the-Envelope Mini-load Throughput Bounds and Approximations, School of Industrial and Systems Engineering, 2002.

[40] HAUSMAN, W. H., SCHWARZ, L. B. and GRAVES, S. C., “Optimal storage Assignment in automated warehousing systems” Management Science, Vol. 22,No.6 (February 1976), pp. 629- 638.

[41] GRAVES, S. C., HAUSMAN, W. H. and SCHWARZ, L. B., “Storage-retrieval Interleaving in automatic warehousing systems” Management Science, (1977), pp. 23, 935-945.

[42] Roodbergen, K.J. and Vis, I.F.A. A “Survey of literature on automated storage and retrieval systems” European Journal of Operational Research 194(2), (2009), pp. 343-362.

[43] R. J. Linn and R. A. Wysk, August 1986, "An analysis of control strategies for an automated storage/retrieval system", INFOR, pp. 66-83.

[44] Dieter Arnold, “Materialfluß in Logistiksystemen”, third edition, Springer, (2002).

[45] Shin-Ming Guo and Tsai-Pei Liu: "Performance Analysis of Single Shuttle and Twin Shuttle AS/RS" 10.1109/IEEM.(2007).4419293.

[46] Bashir Salah, Muawia Ramadan, Bernd Noche, “Travel Time Analysis of Stewart-Gough-Platform in Automated Storage and Retrieval System” Automation and Logistics (ICAL), IEEE International Conference (2011).

[47] M. Guenov and R. Raeside: "Zone shapes in class based storage and multi-command order picking when storage/retrieval machines are used," European Journal of Operational Research (1992) 58, 37-47.

[48] IPE-Computer Aided Engineering, www.uni-due.de/cae, University Duisburg-Essen, (August 2012)

[49] VDI Richtlinie 2516 „Flurförderzeuge für die Regalbedienung. Spielzeitberechnung in Schmalgängen“, 2003.

[50] Department of transport system and logistics, University of Duisburg-Essen http://www.uni-due.de/tul/onlineberechnung_spielzeit01.shtml, (15.February 2011).

[51] MLOG Logistics GmbH (Project partner: „development of a cable robot based rack feeder for high racks “), http://www.mlog-logistics.com/, (12.February 2011).

[52] Liros Gesamtkatalog, Yachttauwerk,Industrietauwerk, Flightsporttechnique, Seite 6 http://www.liros.com/ 5mm, (August 2012)

[53] Markus Heinecker, Methodik zur Gestaltung und Bewertung wandelbarer Materialflusssysteme, Dissertation, München 2006.

[54] Verband Deutscher Maschinen- und Anlagen Bau (2011): VDMA-Statistik.

[55] TGW Mechanics GmbH, „Mustang Evolution”, http://www.tgw-mechanics.com/index.php?id=2915&L=1, (10.February 2011).

[56] Beewen, „Quickstor 2“, http://www.beewen.de/quickstore2.html#, Abruf am 04.Januar 2011

[57] Via Store Systems, „Regalbediengeräte mehr Leistung im Lager“, http://www.viastore.de/fileadmin/Mediendatenbank/Loesungen/Regalbediengeraete/Regalbediengeräte.pdf, Abruf am 10.Februar 2011.

[58] Dematic-Multishuttle, http://www.dematic.com/de/Produkte/Lagertechnik/Dematic Multishuttle Lagersystem/Dematic-Multishuttle-Captive/page31063.htm, (12.February 2011).

[59] Unruh, Volker, „Transfaster etabliert sich als Alternative für die flurfreie Regalbedienung“.10.01.2008,http://www.maschinenmarkt.vogel.de/themenkanaele/materialflusslogistik/foerdertechnik/articles/104735/, Abruf am 10.Januar 2011.

[60] Strehle, M.: „Entwicklung eines Konzepts zum Lagermanagement mit Optimierungsansätzen auf Ebene eines Regalbediengeräts“, Master Thesis, (2009).

[61] Arnold, Dieter et al. (2009): Handbuch Logistik, 3. Aufl., Berlin: Springer.

[62] Ramadan, M.: „Optimisation and Analysis of Stewart-Gough Platform based Automated Storage/Retrieval System“, Master Thesis, (2010).

[63] Amine, M.: „Untersuchung von Methoden und Technologien von der Entwicklung eines neuartigen seilbasierten Regalbediengeräts bis zu seiner Integration in den innerbetrieblichen Materialfluss “, Diplomarbeit, (2011).

[64] Sheikh, M.: „Designing Logistics Warehouse to improve the overall Performance for the existing Warehouse Management Systems (WMS) using SGP-AS/RS “,Master Thesis, (2010).