# Configuration Design and Optimization of Circular Automated Storage and Retrieval System (C-AS/RS)

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# ABSTRACT

Automated Storage and Retrieval Systems (AS/RS) are used as warehouses, specifically designed for material handling in advanced manufacturing systems and are broadly utilized in distribution centers as subsystem for production area. Previous research efforts on have focused on the design and optimization of rectangular AS/RS configurations, however, there is still a gap of research on the design and optimization of Circular AS/RS Configurations. The aim of the research is to analyze, optimize and propose a Circular AS/RS Configuration for automotive car parking. Recently AS/RS are implemented to the automotive factories due to inventory control, landscape utilization, cost and efficiency. The proposed configuration is based on a single aisle; single S/R (Storage/Retreival) machine. Randomly storage assignment policy is applied for the proposed system. The Cost and Travel time models are adapted from the previous research on AS/RS. A mixed integer multi-objective optimization problem is formulated to be optimized using Genetic Algorithm (GA), which is a non-gradient, direct search metaheuristic optimization method, well suited for this class of problems. The design objectives are to minimize travel time, minimize carbon footprint, and minimize the total cost under the constraints for system height, diameter and storage capacity. The number of rows and columns, vertical, rotational and radial velocities of the S/R machine are taken as the decision variables. The results show that travel time, total cost, and the carbon footprint has been minimized up to 1.05%, 16.31% and 67% respectively.

**Keywords:** Configuration, Design, Automated Storage and Retrieval Systems, Optimization, Travel Time, Total Cost, Carbon Footprint.

# ÖZ

Otomatik Depolama Sistemleri depo olarak kullanima uygun olup ozellikler ileri derece üretim sistemlerinde malzemelerin taşınmasında ve depoanmasında kullanılmak için dizayn edilmişlerdir. Ayrıca dağıtım merkezlerinde ana eleman olarak kullanılmaktadırlar. Geçmiş araştırmalar dikdörtgen şeklinde otomatik depolama sistemlerinin konfigurasyon dizaynı ve optimizasyonu üzerine yapılmış olup, yuvarlak otomatık depolama sistemlerinin konfigurasyon dizaynı ve optimizasyonu hakkında yeterli bilgiye ve araştırmaya rastlanmamıştır. Bu tezin amacı, otomotiv endüstrisinde araç otoparkı olarak kullanılmak üzere otomatik depolama sistemi önermek ve önerilen sistemin analizi ve optimizasyonunu yapmaktır. Güncel olarak otomatik depolama sistemleri güvenliği arttırmak, daha iyi kontrol sağlamak, yeryüzünde daha az alan kaplaması, az kurulum maliyeti ve daha verimli bir sistem (hızlı depolama ve yüksek sayıda saatlik yapabileceği depolama) elde edilmesi için otomotiv alanlarına uyarlanmaktadır. Araç parkları için çeşitli otomatik depolama sistem konfigürasyonları analiz edilmiştir. Önerilen konfigurasyon dizaynı yalnızca bir koridordan, yalnızca bir taşıyıcı makineden oluşmaktadır. Ayrıca rastgele depolama politikası uygulanmıştır. Yani herhangi bir depolama hücresi rastgele eşit olarak seçilip depolama işlemi gerçekleştirilmektedir. Maliyet ve yolculuk süresi hesaplamaları daha önce yapılmış olan araştırmalardan yararlanılarak bulunmuş olup, karışık tamsayı birden fazla amaç için yapılan optimizasyon problemi formule edilip Genetik Algoritma tekniği kullanılarak önerilen sistem optimize edilmiştir. Gradyan olmayan doğrudan arama tekniğinin kullanıldığı Genetik Algoritma optimizasyonu otomatik depolama sistemi optimizasyonu için uygundur. Tezin amacı, toplam sistem maliyetini düşürmek, yolculuk süresini kısaltarak saatlik yapılan taşıma sayısını arttırmak ve sistemin yıllık açığa çıkarmış olduğu karbon dioksit miktarını düşürmektir. Bu amaçlar bazı kısıtlamalar altında gerçekleştirilmiş olup, sistem yüksekliği, sistem çapı ve depolama kapasitesi bu kısıtlamaları oluşturmaktadır. Toplam yatayda ve düşeyde bulunan hücre sayıları, taşıyıcı makinenin yatayda, düşeyde ve radyal hızları sistem dizayn değişkenleri olarak atanmıştır. Çalışma sonuçları yolculuk süresinde %1.05 kısalma olduğunu, toplam kurulum maliyetinde % 16.31 iyileşme olduğunu ve karbon dioksit emisyonunda %67'lik bir iyileştirme olduğunu göstermiştir.

**Anahtar Kelimeler:** Configrasyon, dizayn, otomatik depolama sistemleri, optimizasyon, seyahat süresi, maliyet, $CO_2$ tüketimi.

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| | |
|---|---|
| S/R | Storage and Retrieval |
| AS/RS | Automated Storage and Retrieval Systems |
| C-AS/RS | Circular Automated Storage and Retrieval Systems |
| R-AS/RS | Rectangular Automated Storage and Retrieval system |
| SC | Single Command |
| DC | Dual Command |
| $N_{columns}$ | Number of columns in the system. |
| $N_{rows}$ | Number of rows in the system. |
| $S$ | Number of S/R machines. |
| $R$ | Number of picking aisles in the system. |
| Y | No of required S/R machine |
| SC | Single command. |
| DC | Dual command. |
| PP | Per pallet. |
| GA | Genetics algorithm. |
| $V_{horizontal}\ (m/s)$ | Horizontal S/R machine velocity. |
| $V_{vertical}\ (m/s)$ | Vertical S/R machine velocity. |
| $V_{radial}\ (m/s)$ | Radial S/R machine velocity. |
| $V_{rotational}\ (degree/s)$ | Rotational S/R machine velocity. |
| E(SC) (s) | Single command. |
| E(DC) (s) | Dual command. |
| TC (EURO) | Total cost. |
| Q(amount) | Storage capacity |

| | |
|---|---|
| Pf (operation/h) | Throughput capacity. |
| $D_z$ $(l)$ | Share for the system. |
| $COST_1$ $\left(\frac{EURO}{m^2}\right)$ | Cost of the land. |
| $COST_2$ $\left(\frac{EURO}{m^2}\right)$ | Cost of foundation of the system per square meter |
| $COST_3$ $\left(\frac{EURO}{m^2}\right)$ | Cost of the construction walls of the system per square meter. |
| $COST_4$ $\left(\frac{EURO}{m^2}\right)$ | Cost of construction roof of system per square meter of roof. |
| $COST_5$ $\left(\frac{EURO}{m}\right)$ | Cost of upright frames per meter. |
| $COST_6$ $\left(\frac{EURO}{m}\right)$ | Cost of rack beams per meter. |
| $COST_7$ $\left(\frac{EURO}{piece}\right)$ | Cost of buffers per piece. |
| $COST_8$ $\left(\frac{EURO}{PP}\right)$ | Cost of assembly per pallet position. |
| $COST_9$ $\left(\frac{EURO}{PP}\right)$ | Cost of fire safety per pallet position. |
| $COST_{10}$ $\left(\frac{EURO}{m^2}\right)$ | Cost of air conditioning per cubic meter. |
| $COST_{11}$ $\left(\frac{EURO}{piece}\right)$ | Cost of S/R machine. |
| $COST_{12}$ $\left(\frac{EURO}{m}\right)$ | Cost of the picking aisle per meter. |
| $COST_{13}$ $\left(\frac{EURO}{m}\right)$ | Cost of the cross aisle per meter. |
| $H_{total}(m)$ | Height of the system |
| $L_{total}$ (m) | Length of the system |
| $W_{total}$ (m) | Width of the system |
| $D_{total}$ (m) | Diameter of the system |
| $CIR_{total}$ (m) | Circumference of the AS/RS |
| $CIR\_inner$ (m) | Circumference of the turntable. |

| | |
|---|---|
| $R_{total}$ (m) | Radius of the system |
| $R_{inner}$ (m) | Radius of the turntable |
| $CELL_{width}$ (m) | Storage rack width. |
| $CELL_{length}$ (m) | Storage rack length. |
| $CELL_{height}$ (m) | Storage rack height. |
| $CL_{roof}$ (m) | Clearance for the roof. |
| $CL_{base}$ (m) | Clearance for the base. |
| $CL_{rails}$ (m) | Clearance for the rails. |
| $CL_{crane}$ (m) | Clearance for the crane. |
| $CL_{ext}$ (m) | Clearance for the extension. |
| $CL_{side}$ (m) | Clearance for side. |
| $L_v$ (m) | Rack beam length. |
| $V_{horizontal}$ (m/s) | Maximum velocity the S/R machine in the horizontal axis. |
| $V_{vertical}$ (m/s) | Maximum velocity of S/R machine in the vertical axis. |
| $V_{rotational}$ (degree/s) | Maximum velocity in the radial direction. |
| $E_{SC}$ (s) | Expected single command travel time |
| $E_{DC}$ (s) | Expected dual command travel time |
| $n_{SC}$ (/) | Number of single command cycles |
| $n_{DC}$(l) | Number of dual command cycles |
| $T_{Shift}$ (s) | Time of one shift |
| g (%) | Efficiency of the S/R machine |
| $T_{dwellvertical}$ (s) | Vertical dwell time |
| $T_{dwellrotational}$ (s) | Rotational dwell time |
| $T_{dwellhorizontal}$ (s) | Horizontal dwell time |
| $T_{dwellradial}$ (s) | Radial dwell time |

# Chapter 1

# INTRODUCTION

## 1.1 Background

Automated storage and retrieval systems (AS/RS) have been broadly utilized within the production, pharmacy and distribution centers since their presentation in 1950s. Interaction between the subsystems of ASRS makes the overall system complicated. This complex system requires some design decisions which is given by optimizers in order to provide appropriate objectives. There are different essential classes of automated storage and retrieval systems that can be classified according to the bins arrangement, I/O capacity and number of S/R machines utilized in the system.

Awareness of bottlenecks and overcapacity issues is one of the key point that towards to effective solution for the customer demanding requirements to be handled while designing an AS/RS. AS/RS's physical design and its equipment has inflexible system. Therefore, it is indispensable to design it in a best way in one time. Otherwise inflexible system will not be appropriate or efficient for the demanding job. It is crucial to recognize that AS/RS is just one of the many systems that can be found in industries used as warehouses. Thence, AS/RS performance is mostly studied by performance evaluation of AS/RS between similar AS/RS models utilized in industry.

Mostly operations done by I/O-points are prior for performance evaluation. Products are loaded and unloaded at an I/O station by the S/R machine. It is needed to provide a subsystem that provide an access between I/O station and other stations located in warehouse such as conveyor belt systems. If delay occurs in any subsystem of AS/RS, causes delays transmission to other subsystem and this delay causes delays in the relative systems. Naturally whole system delays that is absolutely undesirable for industrial companies. Thus, the number of I/O points, their locations and also their buffer capacity requires detailed evaluation to be designed. While designing subsystems, other systems' characteristics also be involved in evaluation.

### 1.1.1 Supply Chain

A supply chain is a center point where inventory control, distribution, management and manufacturing processes are done while satisfying customer demanding requirements.

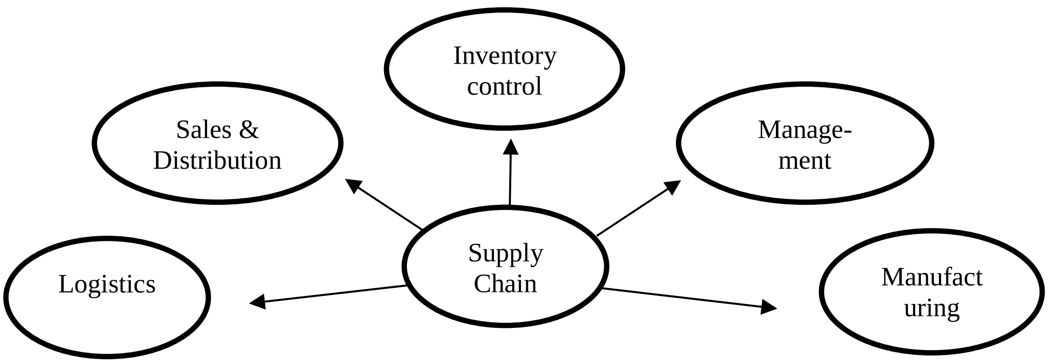


Figure 1.1: Supply chain management.

### 1.1.2 Distribution Centers

Industrial companies' supply chain success is supported by distribution centers. Distribution centers play an essential role for the supply chain by providing product shipment in the demanded configuration to the downriver member in the supply chain. Essential work is to manage the load flow between a point located for product entry and the point located as end-users.


Figure 1.2: Distribution Center in Constellation Europe, UK [64].

### 1.1.3 Facility Logistics

Logistics partially concentrates on facility operations and its management. Facility logistics consist of design of the facility, product loading and loading as well as product transportation while providing solution for inventory control and management within manufacturing and distribution centers.

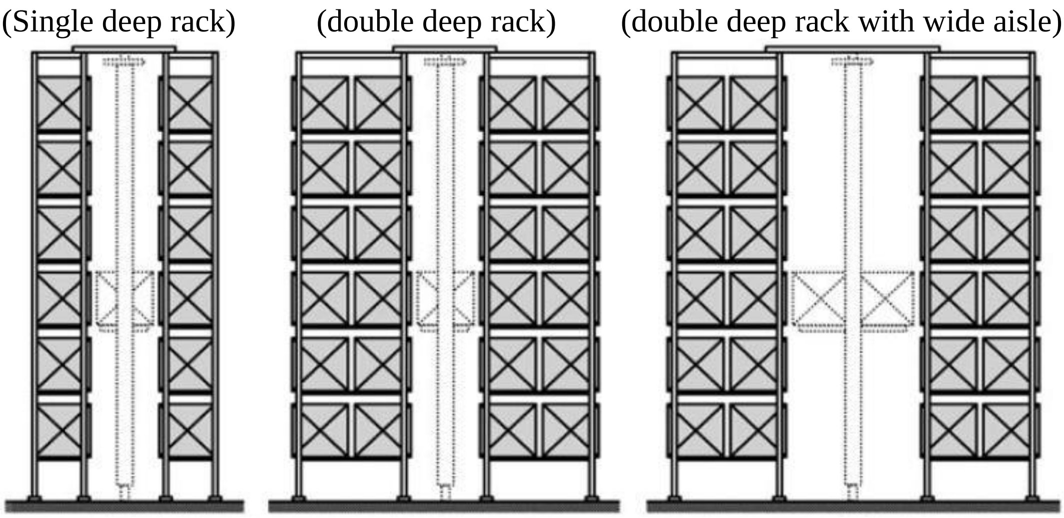

Figure 1.3: Common type of AS/RSs [52].

### 1.1.4 Material Handling and Order picking

Material handling is the process of storing, retrieving, moving, loading and unloading of product, bin or basket. Material handling systems has got many types and they are categorized as manual, semi-automated and fully automated. For production and distribution centers, most labor-intensive process is material handling. Whereas, order picking is a process termed for loading and unloading the product while the S/R machine is retrieving it.

Figure 1.4: Circular Type ASRS of Volkswagen Company [65, 66]

Moreover, environment of the system where AS/RS is implemented has got specific requirements for product transportation. In manufacturing environments, it is a must that material handling and order picking processes are done in a specific sequence and in any delay or confusion of product sequence, it costs the manufacturer huge amount of money or other negative effects such as delay in production that towards unsatisfactory for customer demands. In distribution environments, Mostly AS/RSs in this environment has larger volume capacity to handle larger and bigger products and commonly used for supporting to the order retrieval processes. Design of the AS/RS is crucial and should be designed carefully with respect to the environment to be utilized. Therefore, First, we have the choice of the AS/RS type (system choice). Second, the chosen system must be configured regarding to system choice.

## 1.2 Objectives of AS/RS

Specifically focused objectives in the thesis shown at the below:

a. To increase storage capacity,

b. To increase throughput,

c. To increase travel time,

d. To decrease total cost.

Commonly demanded objectives that other researchers focused are:

a. To increase storage density,

b. To reduce carbon footprint,

c. To reduce labor cost while increasing labor productivity,

d. To improve safety of products,

e. To improve inventory control,

Also commonly demand requirements regarding to demanded objectives is presented as follows [59].

1) Number of orders received per unit time
2) Number of items are stored or retrieved. Larger products take larger time than the smaller products.
3) The arrival pattern of the order to the P/D station.
4) Size and weight of the products to be stored that is affecting the acceleration and speed of the S/R machine.
5) Storage and retrieval operating policies are limited by constraints such as early due dates of the stored product. Therefore, the performance of the AS/RS is also limited to constraints.

## 1.3 Aim of the Study

There are problems related to design and optimization for automated storage and retrieval systems that are divided into three groups. First, reduction in inventory levels of AS/RS while satisfying the customer requirements in a way that is forced to adopt various and continuously developing technologies by manufacturing enterprises. Second, space consumption problem that bring out minimization on investment cost, discounted operation cost and maintenance costs under volumetric, space and environmental constraints and the last problem is minimization in travel time and carbon footprint consumption in order to provide sustainable system.

The aim of the research is to analyze, optimize and propose a Circular AS/RS Configuration for automotive car parking. Recently AS/RS are implemented to the automotive factories due to improved safety, inventory control, landscape utilization, cost and efficiency i.e. decrease the travel time and increase the throughput capacity. Various AS/RS configurations for car parking have been analyzed. The proposed configuration is based on a single aisle; single S/R machine. Randomly storage assignment policy is applied for the proposed system. The cost and travel time models are adapted from the previous research on R-AS/RS. The design objectives are to minimize travel time, maximize throughput capacity, and minimize the total cost, under the constraints for system height, system diameter and storage capacity. The number of rows, number of columns, vertical, rotational and radial velocities of the S/R machine are taken as the decision variables.

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Finally, a mixed integer multi-objective optimization problem is formulated to be optimized using Genetic Algorithm (GA), which is a non-gradient, direct search. a metaheuristic optimization method, well suited for this class of problems. Obtained optimization result is then presented in the results and discussion section.

## 1.4 Scopes and Limitations

Automated storage and retrieval systems are specifically designed for material handling process and they are broadly utilized in distribution centers as subsystem for production area. AS/RS are developed warehouses and they are utilized for subsystem of a system i.e. advanced manufacturing system. AS/RS can also be implemented to the automotive factories due to improve safety, inventory control, utilized landscape and increase the travel time with capacity. In the proposed configuration, a single aisle and a single S/R machine is serving for the AS/RS. Storage assignment is based on randomized storage rather than class based storage system and travel time is representing cycle time of the S/R machine for storage and retrieval proposes. Therefore, both proposed R-AS/RS and C-AS/RS are limited with number of aisles and cranes while having randomized storage assignment.

## 1.5 Organization of the Thesis

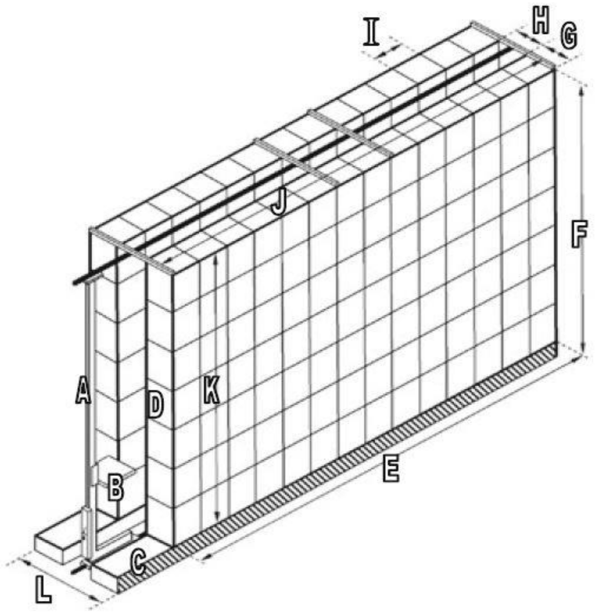
According to the proposed topic, the structure of paper is divided into chapters in order to highlight the research. Paper layout is structured as follows; Firstly, a general description of AS/RSs and a classification based on AS/RS subsystems are presented and explained. The next, Chapter 2 shortly revises the storage assignment strategies, design decisions, time and energy evaluations and their effects to performance of AS/RS are presented. Chapter 3 introduces the models to evaluate the travel time, performance evaluation to S/R a product from a generic storage location and total cost model for R-AS/RS. Chapter 4, In addition to the objective function, parameters and the constraint definition, this chapter proposes a practical rule-of-thumb to determine an effective configuration design and describes a full application of the proposed models for both R-AS/RS and C-AS/RS. Chapter 5 presents the GA optimization of proposed SUV car parking C-AS/RS and optimization details. Finally, Chapter 6 finalize this paper with essential remarks and valuable suggestions for further research.

# Chapter 2

# LITERATURE REVIEW

## 2.1 History of AS/RSs

Automated storage and retrieval systems (AS/RS) have been broadly utilized within the production, pharmacy and distribution centers since their presentation in 1950s. AS/RS are developed warehouses and designed for specifically material handling and order picking processes. They are utilized for subsystem of a system i.e. advanced manufacturing system. AS/RS can also be implemented to the automotive factories due to improve safety, inventory control, utilized landscape and increase the travel time with capacity. Inventory control, storage time, labor cost and space occupation problems can be overcome by use of AS/RS. AS/RS has a complex system in which equipment and control system combined together. This complex system offers automatically handle, storage and retrieval of loads with ideal speed and high accuracy without a labor assistance.




A) Stacker crane (S/R machine)
B) Stacker crane’s carriage
C) I/O station
D) Storage rack
E) Rack length
F) Rack height
G) Rack width
H) Aisle
I) Storage location (cell)
J) Row (tier)
K) Bay (column)
L) AS/RS Width

Figure 2.1: AS/RS structure and principal constituents [55].

Mostly AS/RS racks are made by steel or aluminum structures where storage cells are located. Product accommodation is provided inside the storage cells. Unconventionally product transportation, loading and unloading processes are provided by AS/RS crane. The space occupied for S/R crane to mode vertically termed as aisle. The place for incoming loads to be stored, outgoing loads to be retrieved are specified as I/O stations. There may be pick positions in AS/RS, specific locations where human labor needed to move single items from a retrieved load before the load sent back into the system termed as pick position.

A typical AS/RS works as follows: first of all, items to be stored are sequenced and allocated to the special bins, containers or boxes. The containers with the items inside are taken to the weighting location for confirming the load weights are within limit requirements. In some cases, different parameters of loads such as dimensions, danger level, fragile status should also be checked and tested in a specific station. Those successfully passed all tests are transported to Input / Output station. while transportation, testing and evaluation processes are being processed, status of loads are regularly and currently received by the central computer. The central computer assigns decision of the next step of loads and then status of loads are saved in its memory. The loads are then moved to corresponding places by the help of S/R machine. Upon receipt of a request for an item, the central computer gives decision about loads whether where to store or from which storage cell to retrieve and then sends command to the crane to do the task. The loads are then taken from I/O station by the supporting transportation system to be transported to its final destination.

## 2.2 Classification of AS/RS

AS/RSs can be classified as follows.

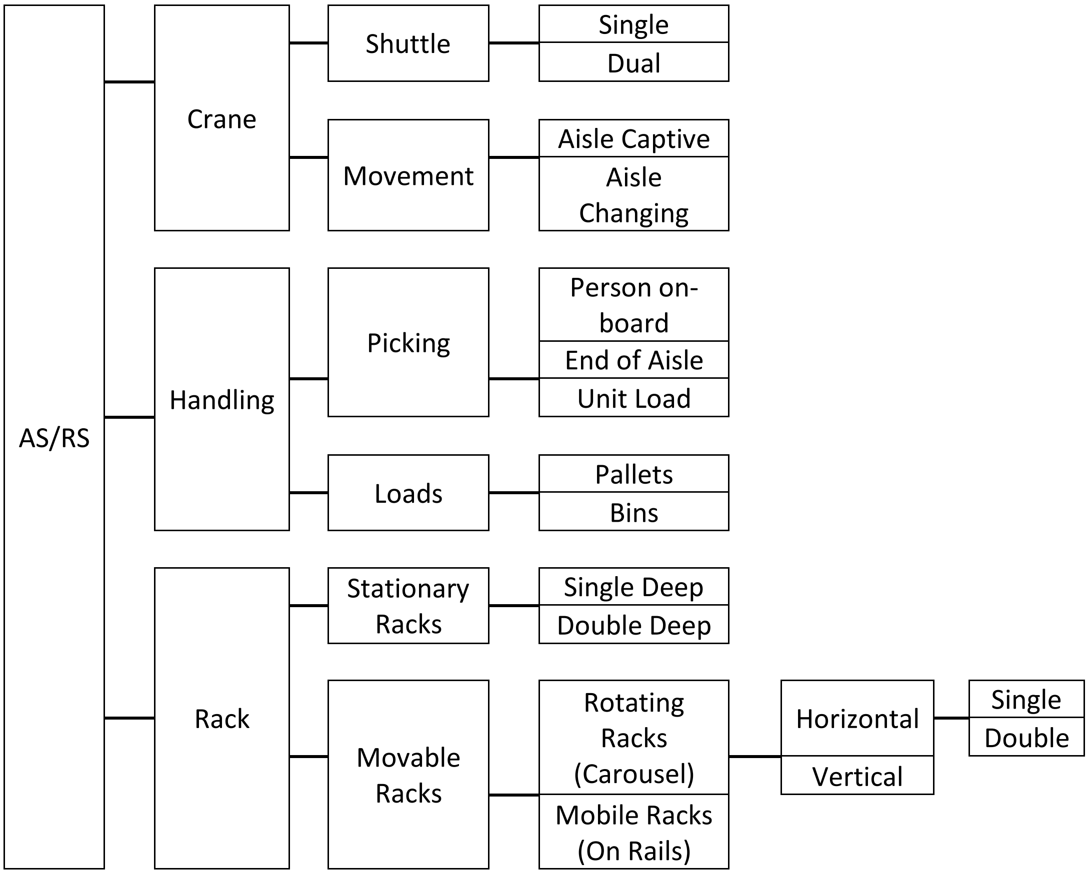



Figure 2.2: Classification of AS/RS [38].

**Unit load AS/RS**

Typical unit load AS/RS consist of large size racks, crane, aisle and they are designed for handling loads with pallets or containers. Computer integrated and controlled system is act as the brain of the system and crane movements adjustable for the type of containers, type of work and requirements.

**Deep-Line AS/RS**

This type of AS/RS is known as unit load systems that can carry high density products and they are used to store and retrieve large quantity of items. However, system has got small number of distinct items. The loads are able to be stored with higher depths in storage rack the storage depth is greater than two loads deep on one or both sides of the aisle.

**Mini-load AS/RS**

Mini-load AS/RS is mostly smaller than a unit load AS/RS. This system is used to store and retrieve small size loads contained in small size containers, bins or boxes. Mini-load AS/RSs' working principle is similar to the unit load AS/RS but their S/R machine is differed from the unit load AS/RS. They are mostly designed to handle bins, boxes and containers that contains the small size items inside.

**Man-on-board AS/RS**

A man-on-board AS/RS is one of the alternative AS/RS for individual product storage and retrieval problem. Man-on-board AS/RS is distinguished from other type with the labor requirement. Carriage of the S/R machine requires a labor to be ridden.

**Automated Item-Retrieval Systems**

S/R systems are designed to store and retrieve whether individual items or system product cartons. The system is distinguished from other AS/RS's by the item storage. Items are stored directly to the storage cells rather than using containers or bins.

**Vertical lift storage modules (VLSM)**

Vertical lift storage systems (VL-AS/RS) is an another type of AS/RS system designed around a vertical aisle rather than other type of AS/RSs which are considered round a horizontal aisle. In this system, there is a single central aisle located in the middle to access loads in an easier way. Vertical lift storage modules are well designed with a high height dimension such as 10 meter or more and system is capable of holding large number size of items while saving satisfactory floor space. Example of VL-AS/RS is shown in Figure 2.3.


Figure 2.3: Vertical lift storage at Hanel Storage Systems [67].

**Multi Aisles AS/RS**

Multi aisles AS/RS is consisted of several aisles which are connected and served by a single S/R device. This system is appropriate to store and retrieve big number of products.

**Carousel Systems**

Carousel systems are distinguished from other AS/RS by the rack type and rack movement. The system has got a rack that rotates on a circular track and storage and retrieval processes are carried out by the picking machine at a certain position. A carousel system is comprised a sequence of baskets suspended from an overhead chain conveyor that rotates around an extended oval rail system.

### 2.2.9 Mobil Rack AS/RS

Mobil rack AS/RS is similar to multi aisle AS/RS and known as a picker to rack retrieval system. This system consists of a movable rack that are moving on rails as the rails are moving on rails, new aisles are created between two nearby racks. Principle terms of the rack can be seen in Figure 2.4.

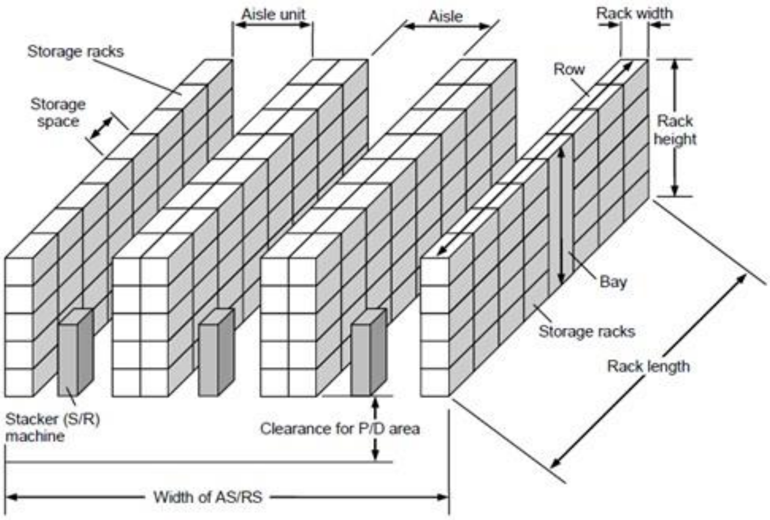



Figure 2.4: Principle of Mobil racks [68].

The AS/RS are mostly used in the applications where high volume of loads is required to transport, stored and retrieved in the specific cells. Some parameters are significant to evaluate before design of an AS/RS such as number of storage locations, storage density, turnover cost. While design decisions are being given, accuracy should be high enough for the AS/RS due to safety of the products stored in racks.

## 2.3 Advantages of AS/RS

For manufacturing system, AS/RS play an essential role in warehouses due to transportation of loads. Also, AS/RS systems are implemented in some facilities such as hospital and libraries. Therefore, there are significant benefits of AS/RS in various areas and major benefits are as follows:

a. Improvement in efficiency of operators and storage capacity
b. reduction of WIP inventory
c. improvement in the quality and the performance of system
d. control the inventory in real-time manner and prompt reporting functionality
e. higher inventory security
f. less product damage

## 2.4 Disadvantages of AS/RS

Although there are many advantages of AS/RS, there are some inaccuracies of AS/RS that are as follows:

a. inflexibility of the layout
b. high capital cost
c. fixed storage capacity
d. lack of visibility

## 2.3 Subsystems and Operating Requirements of AS/RS

Commonly all AS/RS are included following subsystems [69]:

1. Storage structure
2. S/R machine
3. Storage modules
4. I/O stations
5. Control systems
6. Radio-frequency identification system

**Storage Structure**

Storage structure is made by metal or aluminum and called as rack structure, which supports stored loads inside the storage cells and mostly storage structure is made of fabricated steel. In order to carry high weighted loads in storage rack without significant deflection, structure must have sufficient strength and rigidity. Alternatively, storage structure supports the crane system, roof and sliding system of the ASRS. Another function is to support aisle hardware by the guide rails that are located at the top and at the bottom for the rack structure. End stops are connected to guide rails to provide safe operations.

**Storage and Retrieval Machine**

Storage transactions, load delivery from Input locations to the storage cells and load retrieval from storage cells to the output locations are essential motions that assigned on AS/RS and those processes are accomplished by S/R machine. To do those motions, the S/R machine is required to travel vertically and horizontally to line up the corresponding carriage in the rack structure. The carriage is supported by a shuttle system that also permit load transfer from S/R machine to I/O station thus loads are transferred to other departments.

In order to provide a way for S/R machine motion, AS/RS must capable to provide horizontal movement of the mask, vertical movement of the carriage and shuttle transportation between the carriage and a storage cell. In middle size and large enterprises have non-traditional S/R machines. Non-traditional S/R machines has got up to 200m/min horizontal, 50m/min vertical speed. Speed of vertical and horizontal travels are prior for time evaluation of the S/R machine to accomplish desired motions. However, acceleration and deceleration of S/R machine have immediate effect on travel time over short distances.

**Storage Modules**

Storage modules used to carry bins including stored products inside. Pallets, baskets, bins, containers, drawers are commonly used in AS/RS as storage modules and they are standardized in a certain dimension to be handled automatically by S/R machine.

**I/O Stations**

The station where the loads are taken in or sent out of the AS/RS termed as pick and deposit stations. They are mostly accessed by external handling system that brings the loads into the AS/RS or takes the loads out of AS/RS. Therefore, location of P&D stations is at the end of the aisles for easy access. Pick up and deposit stations are located at the opposite ends of the aisle thus avoids confusion between incoming loads or outgoing loads. Manually loading and unloading, forklifts, AGVs and conveyor belt systems are generally used as external material handling system that has direct access to the P&D stations.

**Control System**

A control system of AS/RS manages, commands and regulates the behavior of AS/RS subsystems. For instant, controlling the position of S/R machine within an acceptable tolerance at a storage cell in the AS/RS rack for product storage and retrieval. Layout design with dimensions are well determined and clearance areas between rack and carriage are well defined in the control system in order to provide accurate control process. AS/RS each compartment in the rack structure is identified within a given aisle by its right, left, horizontal and vertical sides. Location identification is carried out by a scheme based on alphanumeric code. Each cell in the storage rack is referenced to an individual location in the aisle and saved in the item location file. Item location file contains the information of performed transactions by S/R machine.

Positioning of S/R machine can be controlled with several methods. One method utilizes a counting technique in which the number of loading highs and bays are counted in direction of travel to identify the position. Other method for positioning the S/R machine is numerical identification technique in which each cell is identified with an identical tag with binary coded location identification. Optical scanners read identical tags and then control system sends command to the S/R machine to store or retrieve a load. Programmable logic controllers then determine required locations and S/R machine is guided to its final position.

Computer controlled control system allows physical operation of AS/RS to be integrated with supporting information and recording system. Therefore, real time work in process can be performed as the controller receives the storage transaction. Real time work in process pave the way for accurate maintenance, better system performance and better communication and monitoring of the AS/RS by a computer controlled system. This automated control can be replaced by manual controls in case of emergency conditions.

### Radio-Frequency Identification System

Identification systems are used to identify storage cells or loads in AS/RS and load identification is essential factor for load transaction and cell detection. The scanners are mostly located at easily accessed points such as I/O locations. Scanners read the identification code placed on tag. Upon reading id code, the data written in id code is received and it is sent to computer controlled AS/RS, which manages by sending the load to the storage cell. Scanners also play an essential role on integration of AS/RS to industrial companies by supplying separate loads in a faster way and product information and status to the related computers as the load transaction is completed.

Alternative method for positioning the S/R machine is numerical identification. This technique works by identification of each cell. Identification number transferred to an identical tag with binary coded location identification. Optical scanners read identical tags and then control system sends command to the S/R machine for product storage and retrieval.

## 2.4 Design Decisions

General overview of warehouse control and design haven been studied in the past years. Fraction of the AS/RS with a comprehensive literature are studied by Van den Berg (1999), Rouwenhorst et al. (2000), De Koster et al. (2007), Gu et al. (2007) and Baker and Canessa (2009). The clarification of the current developments of the AS/RS design and design issues are presented by Roodbergen and Vis (2009). This paper appears as a first review paper on AS/RS over last 10 years with a comprehensive study of the AS/RS design.

Moreover, AS/RS designs consist of several subsystems that makes the system complex and inflexible. Due to the inflexibility of the physical outline and the subsystems, design decisions should be given at once. Beside system can be inefficient and less productive. Physical design and related decisions are shown in Table 2.1. listed system choice and system configuration of an AS/RS should be selected before the appropriate decision is given.

Table 2.1: Configuration design and related decisions.

| System Choice | System Configuration |
|---|---|
| Unit Load AS/RS | No of aisles |
| Deep-line AS/RS | Rack height |
| Mini load AS/RS | aisle length |
| Man-on-board AS/RS | Equally / unequally sized cells |
| Automated item-retrieval system | No of the I/O stations with their location |
| Vertical lift storage modules (VLSM) | density capacity of the I/O station |
| | No of S/R machines |

Sarker, B.R. et al. (1995) studied design aspects of an AS/RS and travel time model of the rectangular type AS/RS. In his research, Throughput capacity is explained as the inverse of the mean transaction time that is the expected travel time required for storage or retrieval process and P/D time. Therefore, Travel time of an AS/RS usually related to the S/R machine features as well as AS/RS rack configuration. Moreover, Sarker, B.R. et al. (1995) made a list of top interested design problems and it is presented as shown:

1) Assignment of the products to the storage locations in the storage structure.
2) Configurations of the storage structure (Ratio of length to height, $N_{rows}$ to $N_{columns}$.
3) Operating policies for order storage and retrieval.

## 2.5 Efficiency of AS/RS

According to Roodbergen and Vis, Lerher, T. et al. (2012) and Rajkovic, M. et al. (2017) the following five lists are the most recurrent assignment strategies for AS/RS warehouses [38].

- Dedicated storage suggests assigning items to a fixed set of storage locations. For each product, it is necessary to guarantee, anytime, the storage capacity defined in the design phase. This strategy enables to consider the product features, such as weight and shape (De KosterandNeuteboom,2001);
- Random storage enables every incoming product to be stored in any random empty storage location (Choe and Sharp,2015);
- Closest open location strategy proposes to store the products to the empty locations closest to the pick-up & delivery (P&D) point. Thus, the warehouse configuration is distinguished by full zones near the P&D point and empty ones far from it (Rosenblatt andRoll,1988);
- Full-turnover based strategy requires storing the products considering their turnover frequencies. Fast moving's are near the P&D point, whereas slow-movings are located far from the P&D point. The literature evaluates the

turnover frequency through the cube per order index(COI) proposed by Heskett (1963, 1964);

- Class-based storage is proposed by Hausman (1976) to over- come the disadvantages and maintain the advantages of the dedicated storage and the full turnover based strategies. This strategy divides the warehouse into classes and assigns products considering their turnover frequencies. Within each class, products are assigned randomly.

The adopted assignment strategy highly affects the AS/RS handling performances. The standard literature focuses on the average travel distance and time to S/R products from the warehouse (Chiang et al., 2011; Ming-Huang Chiang et al., 2014; Chuang et al., 2012; Fumi et al., 2013; Kasemset and Rinkham, 2011; Kofler et al., 2011; Bortolini et al., 2015). From such a perspective, AS/RSs differ from traditional handling tools such as forklift. Those tools follow disjoint horizontal and vertical movements, while AS/RSs allow simultaneous movements in the two directions (Atmaca and Ozturk, 2013). Given the generic storage location, the required time to S/R a load is the maximum between the vertical and horizontal time intervals. Such a difference between AS/RSs and traditional handling systems leads to consider the travel time as a relevant KPI in automatic warehouses (Moon and Kim, 2001). Several authors propose storage assignment strategies to minimize the AS/RS travel time. Bozer and White (Bozer and White, 1984) first develop a model to evaluate the AS/RS travel time whereas Hwang and Ko (Hwang and Ko, 1988) suggest a storage assignment strategy to minimize it. The authors assume infinite crane acceleration to simplify the models. This assumption is overcome by several contributions that develop models considering the crane acceleration profile (Hwang and Lee, 1990; Hwang et al., 2004;

Chang and Wen, 1997; Wen et al., 2011). In addition, addition, Van den Berg (2002) studies the optimal dwell point of the S/R machine to minimize the load/unload cycle time.

Extending the study to multiple goals beyond the crane travel distance and time, Fontana (2014) recently propose a multi-criteria method to simultaneously minimize the travelled distance, the total operation cost and the space requirement. This method heavily depends on the weights assigned by the decision makers to the different objective functions. To overcome this weakness, Wu et al. (2010) and Li et al. (2008) propose a multi-objective optimization model to assign the products to the storage locations for AS/RS warehouses. The authors define two objective functions: the former minimizes the S/R travel time, the latter maximizes the stability of the racks. As far as the author knowledge, no contribution simultaneously minimizes the energy consumption and the travel time within the AS/RS assignment problem.

## 2.6 Configuration Design

Most of the published papers are about manufacturing environments and a few papers are highlighted the AS/RS configuration designs. Petri Nets and Taguchi methods are applied to scheduling of AS/RS used in manufacturing systems by Chincholkar and Krishnaiah Chetty (1996). AS/RSs used in automotive systems are also discussed by Inman (2003). The sequence issues of AS/RS are evaluated at the several processes in the facilities based on a proposed model in order to determine the capacity of the AS/RS. As a result, the AS/RS design is wholly subordinated to the assembly processes in the industries. Beside, mini load AS/RS combined with automatically guided vehicles are designed and non-linear model and heuristics are applied by

Hwang et al. (2002). Due to the determination of optimal number of loads to be transported by AVG.

Park and Webster (1989), proposed an approach that synchronously picks the storage size and shape of storage of AS/RS. Summerly, almost all simulation models are addressed to physical design features and only a few AS/RSs and their configurations are evaluated in combination with constant input values.

Sarker, B.R. et. al. (1995) is studied specific parameters of the physical design of an AS/RS. In the research, it is well defined that size of the storage bins, baskets or boxes is important to determine storage cell dimensions as well as expected travel time to a specific location. Shape factor is another parameter that deals with the AS/RS length and height. It is also used to determine AS/RS structure as square in time or rectangle in time. Shape factor known as the time spent to reach an extreme location in the storage structure. Depth of the rack is another parameter for physical design and can be single or double deep rack. Last parameter is the capacity and the no of S/R machines utilized in the system. As known S/R machines are having direct impact on travel time and throughput. As the number of S/R machine increases, faster product storage and retrieval process can be done. However, for the system performance, the no of S/R machines utilized in the system should be selected based on demand requirements.

Lerher, T. et al. (2012) focused on energy efficiency model for the mini-load automated storage and retrieval systems. Crane velocities, accelerations, number of rows and number of columns with required number of crane are set as design variables. In the paper, $CO_2$ consumption of the system is evaluated.

## 2.7 Performance of AS/RS

For the design evaluation, several parameters related to performance of AS/RS can be analyzed. Following performance variables are considered for performance [70]:

a. Storage time and travel time estimations,

b. throughput capacity

c. loading times of S/R machine

d. number of upcoming requests,

e. waiting times of S/R machine,

f. $CO_2$ estimations

g. Utilization of rack and stacker crane

Throughout performance of AS/RS are evaluated by Lee (1997), Malmborg and Altassan (1997) and Bozer and Cho (2005). Time efficient models which can used for random and class based storage system's space approximation by Eldemir et al. (2004). Categorization of all literature are presented in Figure 2.5.

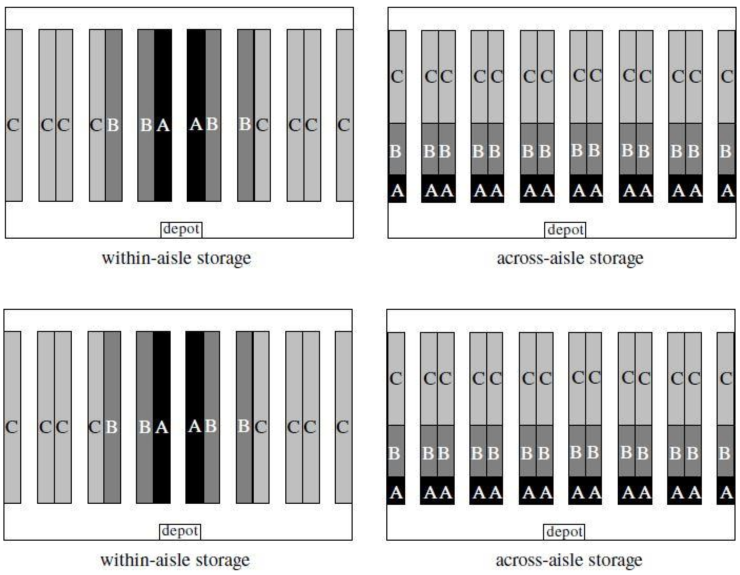



Figure 2.5: Class-based storage systems [44].

In this way, time consumption of activity can be compared to the percentage of order picking time. Both analytical and simulation studies are confirmed that turnover based and class based storage systems outperform random storage. load with the accommodation time is shortest in the storage cell, are allocated to storage cells closest to I/O locations, if duration of stay technique applied. Besides, three class based technique is outperformed to the duration of stay technique if only if there are small products to be stored. Such a Petri Nets methods are able to update the system to avoid rapidly environmental changes. COI method is applicable to independent demand of products in static environments. Usage of predicted product mix, correlated demand of products and demand forecasts are integrated to systems in order to minimize total processing time, which includes order-picking time and relocation time. Therefore, dynamic policy prior to the static COI rule. As a result, several storage techniques are developed in the previous studies and compared through simulation and analytical models.

## 2.9 Recent Developments in Design of AS/RS

Nowadays, AS/RS are becoming most important subsystems for distribution centers in order to offer better inventory control and faster product distribution as well as car parking systems where numerous number of cars required to be stored with less land occupation and higher storage capacity. There are many varieties of AS/RS available and they are studied by the researchers as presented in the literature review. There are several objectives for AS/RS, presented by researchers.

It can be concluded from the literature that most common objectives for the AS/RS:

1. To stabilize the total cost of distribution by eliminating labor cost, reducing land cost.
2. To increase throughput that enhances customer service by faster product delivery with precise inventory control.
3. To increase accuracy and accidental issues by eliminating labor assistance.

For the total cost of an AS/RS, there are many studies are done such as Bozer, A.Y. et al. (1978) presented a minimum cost design for an automated warehouse. Ashayeri, J. et al. (1985) created mathematical cost model and then conducted a microprocessor based optimization to find optimal cost for the proposed system. Bartley, W. et al. (1990) studied cost analysis of warehouse facility establishment at Fort ord. California. Lerher, T. et al. (2013) studied total cost of an AS/RS and conducted Pareto optimization design to find optimal investment cost with respect to optimal travel time and reliability. Zrnić, N. et al. (2017) studied a multi-objective optimization model for minimizing cost, travel time and energy consumption in an AS/RS.

Throughput is defined as capacity of the storage and retrieval processes (load activity) in a certain time period. Therefore, throughput is function of crane travel time, loading

/ unloading time, storage rack and warehouse dimensions. There are several studies base on travel time, throughput. Hausman et al. (1976) and Graves et al. (1977) studied travel time model of an AS/RS based on square in time (shape factor =1), which can be expressed as system has got same travel time for the farthest cell in horizontal axis as well as farthest cell in the vertical axis. Bozer, Y.A. et al. (1984) analytical travel time model for an automated storage and retrieval system, which was applied whether turnover based storage assignment rules or class based storage assignment rules. Hwang, H. et al. (1990) considered operating characteristics of S/R machine to create a travel time model for the proposed design. Koh, S.G et al. (2002) stated a travel time model based on a tower crane S/R machine utilized for AS/RS and expected travel time of the proposed system is evaluated. Geaps-Nelson, G.T. (2005) analyzed and improved throughput of an AS/RS at master level. Lerher, T. et al. (2005) provided analytical travel time for multi aisle AS/RS and expected travel time is computed based on provided model. Sari, Z. et al. (2005) proposed travel time model based on flow-rack AS/RS. Vasili, M.R. et al. (2008) provided a statistical travel time model for mini-load automated storage and retrieval system and then evaluated expected travel time of proposed design. Azzi, A. et al. (2011) proposed an innovative travel time model for dual-shuttle automated storage system. Lerher, T. et al. (2013) researched shuttle based AS/RS in terms of cost minimization, quality maximization and travel time minimization. In addition, Genetic algorithm optimization technique utilized to find optimal system. Bortolini, M. et al. (2016) proposed time and energy factors for a unit-load AS/RS in order to find optimal load assignment. Lerher, T. et al (2013), Lerher, T. et al. (2012) and Rajkovic, M. et al. (2017) considered energy efficiency and throughput capacity of AS/RS and designed an environment-friendly automated warehouse. Eder, M. et al. (2016) presented throughput analysis of shuttle type S/R system as well as digging optimal geometrical configuration for better performance. There can be found several review papers base on AS/RS such as Sarker, B.R. (1995), Koster, R.D et al. (2006), Roodbergen, K.J. et al. (2008), Gagliardi, J.P. et al. (2010).

Design process of an AS/RS is complicated and contains a large number of interconnected decisions among the warehouse processes, resources and alignments. AS/RS design problem is classified into three level of decisions by Rouwenhorst et al. (2000). Strategic level, tactical level and operational level. There are numerous decisions that required to be made such as determination of number of warehouses, dimensional properties, location, selection of material handling system related to desired throughput rate. This level is also including determination of functional locations in the warehouse, process flow determination based on the layout design and selection of management system to be used in AS/RS. At the tactical level of design process, determination of labor for system operation, distribution of loads to the functional spots, development of order picking and retrieval strategies and determination of capacity are mostly focused decisions that need to be made. However, operational level consists of several concerns such that selection of routing strategies, determination of batch size, dock assignments, short term work force assignments and task assignments. Please find a tabular literature review below, adapted from Roodbergen, K. J. et al. (2008):

Table 2.2: Literature review of recent development in the Design and Optimization of AS/RS.

| Author | Objectives | | | | | | | | Configurations | | | | | | | | | | | | Crane | | | | Products | | | Storage | | | | Analytical based | | | | | | | Simulation based | | | | | Application areas | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Modelling assumptions | | | | | | | | | | | | | | | | | | | | | | | Optimization and Methodology | | | | | | | | | | | | | | |
| | Review Paper | Travel time | Cost minimization | Comparison between models | System Configuration | Requests sequencing | Storage Capacity / Assingment | CO2 | Flow-rack AS/RS | Mobil racks | Unit-Load AS/RS | Order picking system | All locations have the same dimentions | Multi-load AS/RS | Single crane, Single Aisle | Symetrical Distances | Each I/O can perform S/R | Square in time rack | Rectangular in time rack | Circular rack | Tchebychev time | Robotic load carrying carts | Constant crane acceleration | Constant pickup and deposit times | Constant item turnover | Various types | Items ordered following EOQ model | Very narrow storage (VNA) | Random storage assignment | Constant number of pallets | %100 Rack utilization | Mathematical modelling | Statistical-Based | Genetic algorithm | Dynamic sequencing | Eye ball technique | Dwell-Point location | Informed search algorithm | Pareto curve and UL mass distribution | AMPL/CPLEX | AutoMod | AMCLOS | ARENA | Baggage handling | Automated parking | Industrial warehousing system |
| Hausman et al. (1976) | | | | | | | X | | | | X | | X | | X | X | X | X | | | | | X | X | X | | X | | | X | X | X | | | | | | | | | | | | | | X |
| Graves et al. (1977) | | | | | | X | X | | | | X | | X | | X | X | X | X | | | | | X | X | X | | | | | X | X | X | | | | | | | | | | | | | | X |
| Bozer and White (1984) | | | | | | | X | | | | X | | X | | X | X | X | | X | | | | X | X | X | | X | | X | X | X | X | | | | | | | | | | | | | | X |
| Ashayeri, J. et all. (1985) | | | X | | X | | | | | | X | | X | X | | X | X | | X | | | | X | X | | | X | | X | X | X | X | | | | | | | | | | | | | | X |
| Sarker, B.R. (1995) | X | X | | X | | | | | | | X | | X | X | X | X | | X | X | | | | | | | X | | | X | X | | | | | | | | | | | | | | | | |
| Van den Bergh, J. C. (2000) | | X | | | X | | X | | | | | | | X | | | | | | | | | X | X | X | | | | X | X | | | | | X | | | | | | | | | | | X |
| Malmborg, C.J (2003) | | | X | | X | | | X | | | X | | | | X | X | | | X | | X | | X | X | | | X | | | | X | X | | | | | | | | | | | | | | X |
| HACHEMI K. et al. (2005) | | | | | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | | | | | | X |
| Koster, R.D. et al. (2006) | X | X | X | | | X | X | | | | X | X | | | X | | X | | X | | | | | | X | X | X | | X | X | | | | | | | | | | | | | | | | X |
| De Koster, R et all. (2007) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X |
| Roodbergen, K. J. et al. (2008) | X | X | | | X | X | | | | | X | | X | X | | | X | | X | | | | X | X | X | | | | X | | X | | | | | | X | | | | | | | | | X |
| Vasili, M.R. et al. (2008) | | X | | X | X | | X | | | | X | | | | X | X | | | X | | | | | | X | | | | | | | | | | | | | | | | | | | | | X |
| Roodbergen, K. J. et al. (2009) | | X | | X | X | X | X | | | | X | | X | X | | | X | | X | | | | X | X | X | | | | X | | X | | | | | | X | | | | | | | | | X |
| Felix T.S. et all.(2010) | | X | X | | X | | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | | | X |
| Gagliardi, J.P. et al. (2010) | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X |
| Klaus Moellera et all. (2011) | | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | | | X |
| Vasili, M. R. et all. (2012) | | | X | | X | | X | | | | X | | | | X | X | X | | X | | | | | | X | | X | | X | X | | | | | | | | | | | | | | | | X |
| Khalid H. et all.(2012) | | X | | | | X | | | | | X | | X | | X | | X | | | | | | | X | X | | | | X | | X | X | | | | | | | | X | | | | | | X |
| Haneyah, S. W. A. et al.(2012) | | | | X | | | X | | | | | X | | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | X | | |
| Dou, C. (2012) | | | X | | X | | X | | | | | | X | X | | | | | X | | | X | | | X | X | X | | | X | | | | | | | | X | | | | | | | X | |
| Lerher, T. et all. (2012) | | X | | X | | | X | X | | | | | | | | | | | X | | | | X | X | | | | | | | X | | | | | | | | | | | | | | | |
| Lerher, T. et all. (2013) | | X | X | X | | | X | | | | X | X | X | | | | | | X | | | | X | X | X | | X | | | | X | | | X | | | | | | | X | | | | | X |
| Guezzen, A. H. (2013) | | X | | | | | X | | | X | | | | | | | | | X | | | | | | X | | | | X | X | X | X | | | | | | | | | | | X | | | X |
| Lisa M.Thomas et all. (2013) | | | | | X | | X | X | | | | | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | | | | X |
| Zollinger, H. (2014) | | | | X | X | X | | | | | X | X | X | | | X | | | X | | | X | X | | X | | | X | | | | | | | | | | | | | | | | | | X |
| Hisham Said et all. (2014) | | | X | | | X | | | | | X | | X | | | | X | | X | | | | X | X | X | | X | | | | X | | | X | | | | | | | | X | | | | X |
| Lerher, T. et al. (2014) | | X | X | | | | X | | | | | | X | | | | X | | X | | X | | | X | | | | | X | | X | | | X | | | | | | | | | | | | X |
| Lerher, T. et al (2015) | | X | | | | | X | X | | | | | X | | | | X | | X | | X | | | X | | | | | X | | X | | | | | | | | | | | | | | | X |
| B.Y.Ekren rf.(2015) | | X | | | | | | X | | | X | X | X | | | | X | | X | | | | | X | X | | | | X | X | X | | | | | X | | | | | | | X | | | X |
| Ghomri, L. et all. (2015) | | X | | | X | | | | X | | | | X | | X | | X | | X | | | | | X | X | | X | | X | | X | X | | | | | | | | | | | X | | | X |
| Naji Bricha et all. (2015) | | | | | | | X | | | | X | | X | | X | | X | | X | | | | X | X | X | | | | X | X | X | | | | | | | | | X | | | | | | X |
| Lerher, T (2016) | | X | | | | | X | | | | X | | X | | X | | | | X | | | X | | | X | | | | X | X | | | X | | | | | | | | | | | | | X |
| Bortolini, M. at all. (2016) | | X | X | | | | X | X | | | X | X | X | | X | X | | | X | | X | | X | X | X | | X | | | | | X | | | | | | | X | | | | | | | X |
| Cinar, D. et all. (2016) | | X | | | | | X | | | | | | X | | | | X | | X | | | | | X | | | | | X | X | | | | X | | | | | | | | | | | | X |
| Zrnić, N. et al. (2017) | | X | X | | | | | X | | | | | | | | | | | X | | X | | | | | | | | X | | | | | X | | | | | | | | | | | | X |
| Proposed Study | X | X | X | X | X | | X | | | | X | | X | | X | X | | | | X | X | | X | X | | | | | X | | | X | | X | | | X | | | | | | | | X | |

For the the literature review chapter, we can conclude that most of the researchers are focused on rectangular AS/RS and square AS/RS as it is seen from the tabular literature in theTable 2.2. There is no article have been found base on circular type AS/RS or circular type car parking system in the literature. As it is seen from the tabular literature, common objectives can be listed as; travel time minimization, storage assignment, configuration design, storage configurations and cost minimization, energy optimization. Again regarding to the tabular literature, crane, storage configuration, product types and crane features are the critical parameters for the design of AS/RS. Researchers are performed both simulation based analysis and analytical based analysis. It is also concluded that most of the simulation method is

ARENA and analytical method is dwell point location based modelling. Apparent disadvantages and advantages of the AS/RS are mentioned previously. Although there are a few disadvantages, apparent advantages are significantly higher than the number of disadvantages of the AS/RS. In this regard, Travel time model and cost model from the literature is utilized for the R-AS/RS, in order to find expected travel time, throughput and total cost of the system. Then models are utilized to propose travel time model and total cost model for C-AS/RS configuration. Results are presented in tabular form explicitly for travel time as well as total cost.

# Chapter 3

# PROPOSED CONFIGURATION FOR CAR PARKING AS/RS

## 3.1 Rectangular Type of R-AS/RS

### 3.1.1 Cost Model of R-AS/RS

The total cost of an AS/RS depend on several factors such as land cost, building cost, rack cost and S/R machine cost. Therefore, they are also called as initial cost of the system. There are many more factors than mentioned above such as hardware, software, maintenance, labor cost for man on board AS/RS etc. In order to design and optimization of AS/RS, cost affecting parameters are crucial for cost minimization.

Cost model of an AS/RS is created in this section similar with the Zrnić, N. et al. (2017). However, the model proposed in the thesis distinguished from the article in terms of load and AS/RS type. Cost parameters are taken from Zrnić, N. et al. (2017). The model is then used for cost analysis of R-AS/RS and cost analysis of C-AS/RS. As a result, both proposed AS/RS models are compared in terms of cost, travel time, throughput and some other physical parameters.

Zrnić, N. et al. (2017) studied cost analysis of AS/RS based on land cost, S/R machine cost, building cost etc. After evaluation of calculations, total cost of the R-AS/RS and C-AS/RS will be found and then compared.

**Assumptions**

a. $N_{cranes}$ is equal to the ($N_{aisles}$).

b. S/R machine can travel within specific aisle and located at the left lowest floor.

c. The storage and retrieval operation is performed in the same picking aisle.

d. The S/R machine can travel in the vertical, radial and horızontal directions.

e. System height and system length are having enough distance for the S/R machine to reach its maximum speed.

f. When performing the operation of the DC, two different cases have been used: (i) the storage and retrieval operation is performed in the same picking aisle i and (ii) the storage and retrieval operation is performed in two randomly chosen picking aisles i and j.

g. The S/R machine travels in the picking aisle simultaneously in the radial, horizontal and vertical directions.

h. The length and height of the SR are large enough for the S/R machine to reach its maximum velocity v in the horizontal and vertical directions.

i. The length of the cross aisle is large enough for the transferring vehicle with the S/R machine to reach its maximum velocity v in the cross direction.

j. Randomly storage assignment policy is applied for the proposed system.

k. Rectangular racks are assumed to be single deep rack.

l. For the travel time calculation, acceleration of the crane is neglected.

m. Randomly assigned storage policy is utilized for the proposed system.

$N_{rows}$, $N_{columns}$, $V_{vertical}$, $V_{rotational}$, $V_{radial}$ are taken as design variables for minimization of travel time as well as minimization of total cost.

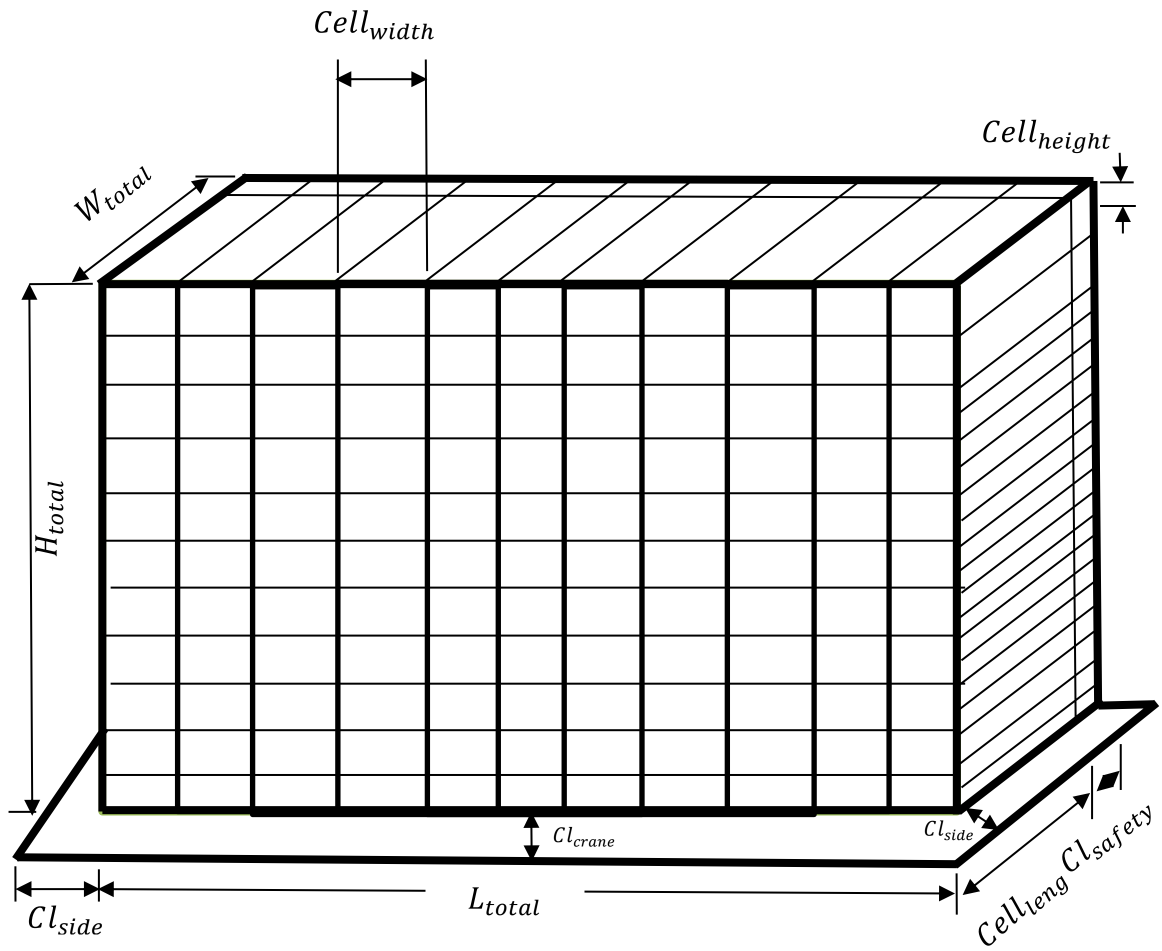



Figure 3.1: The view of the R-AS/RS.

The proposed AS/RS configuration design is aimed to accommodate SUV cars in the storage racks with the help of fully automated storage S/R machine. Proposed configuration is car parking storage system based. Therefore, design decisions for the storage cells are given with respect to specific SUV cars. Specification of the SUV cars based upon the information gathered from [73], which can be accommodated in the proposed system, is listed in Figure 3.1.

Table 3.1: SUV Specifications for the proposed AS/RS.

| MODEL | LENGTH (m) | HEIGHT (m) | WIDTH (m) | WEIGHT (kg) |
|---|---|---|---|---|
| Tesla Model X P85D | 5.004 | 2.362 | 2.584 | 2390 |
| Porsche Cayenne Turbo S | 4.855 | 1.705 | 1.938 | 2375 |
| Porsche Cayenne Turbo | 4.855 | 1.705 | 1.939 | 2184 |
| BMW X6 M | 4.876 | 1.684 | 2.195 | 2350 |
| Mercedes Benz ML63 AMG | 4.820 | 1.860 | 1.950 | 2880 |
| Jeep Grand Cherokee SRT8 | 4.871 | 1.807 | 1.966 | 2315 |
| BMW C5 xDrive50i | 4.908 | 1.762 | 1.938 | 2336 |
| Range Rover Sport Supercharged | 4.871 | 1.780 | 1.984 | 2335 |
| Audi SQ5 | 4.671 | 1.659 | 2.141 | 1994 |
| GMC Typhoon | 4.326 | 1.524 | 1.732 | 1734 |
| Mercedes Benz G63 AMG | 4.762 | 1.938 | 1.938 | 3201 |
| Porsche Cayenne GTS | 4.855 | 1.689 | 2.164 | 2105 |

$N_{rows}$, $N_{columns}$, $V_{vertical}$, $V_{rotational}$, $V_{radial}$ are taken as design variables for minimization of travel time as well as minimization of total cost. Design of the proposed R-AS/RS are determined by the specific parameters that are presented as following.

**Operational parameters of the warehouse:**

Table 3.2: Operational parameters for R-AS/RS.

| Parameters | Symbol | Unit | Value |
|---|---|---|---|
| Cell height | $CELL_{height}$ | m | 2.1 |
| Cell length | $CELL_{length}$ | m | 5.5 |
| Cell width | $CELL_{width}$ | m | 3 |
| Cell weight | $CELL_{weight}$ | kg | 3200 |
| Clearance for roof | $CL_{roof}$ | m | 2.1 |
| Clearance for base | $CL_{base}$ | m | 2.1 |
| Clearance for crane | $CL_{crane}$ | m | 1 |
| Clearance for safety | $CL_{safety}$ | m | 5.5 |
| Clearance for extension | $CL_{ext}$ | m | 0.5 |
| Clearance for side | $CL_{side}$ | m | 3 |
| Dwell time for vertical axis | $T_{dwellvertical}$ | s | 25 |
| Dwell time for horizontal axis | $T_{dwellhorizontal}$ | s | 25 |
| Dwell time for radial direction | $T_{dwellradial}$ | s | 15 |

**S/R Machine Specifications:**

S/R machine : $V_{radial}$ = 1 m/s, $V_{vertical}$ = 1 m/s, $V_{rotational} = 1m/s$.

**Costs are presented as following [63]:**

Table 3.3: Cost parameters.

| Parameters | Symbol | Unit | Value |
|---|---|---|---|
| Cost of the land | $COST_1$ | EURO/m$^2$ | 500 |
| Cost of foundation | $COST_2$ | EURO/m$^2$ | 168 |
| Cost of the construction walls | $COST_3$ | EURO/m$^2$ | 23 |
| Cost of construction roof | $COST_4$ | EURO/m$^2$ | 25 |
| Cost of upright frames | $COST_5$ | EURO/m$^2$ | 30 |
| Cost of rack beams | $COST_6$ | EURO/m$^2$ | 23 |
| Cost of buffers | $COST_7$ | EURO/piece | 200 |
| Cost of assembly | $COST_8$ | EURO/PP | 10 |
| Cost of fire safety | $COST_9$ | EURO/PP | 5 |
| Cost of air conditioning | $COST_{10}$ | EURO/m$^3$ | 10 |
| Cost of S/R machine | $COST_{11}$ | EURO/piece | 431 |
| Cost of the picking aisle | $COST_{12}$ | EURO/m | 50 |

### 3.1.1.1 Land Cost

Land cost can be differed in each city or in each country due to the land cost of place where the system to be set up. In the cost analysis of proposed system, Land cost is termed as $L_{Cost}$ and its value taken as 500 EURO/m$^2$. $D_z$ is representing the share for the warehouse building and its value is set to be 71 based on the Zrnić, N. et al. (2017).

$$\text{Cost of Land } (COST_{land})=L_{total}*W_{total}*\frac{100}{Dz}*COST_1 \qquad (3.1.1.1)$$

### 3.1.1.2 Warehouse Building Cost

1) **Cost of Floor**

$$\text{Cost of Floor } (COST_{floor})=L_{total}*W_{total}*COST_2 \qquad (3.1.1.2)$$

2) **Cost of Walls**

$$\text{Cost of walls } (COST_{walls})=(L_{total}*W_{total})*H_{total}*2*COST\_3 \qquad (3.1.1.3)$$

3) **Cost of Roof**

$$\text{Cost of the roof } (COST_{roof}) = L_{total} * W_{total} * COST_4 \quad (3.1.1.4)$$

### 3.1.1.3 Storage Construction Cost

**1) Cost of Up Frame**

$$\text{Cost of upright frames } (COST_{upframe}) = (N_{rows}+1) * N_{cranes} * (H_{total} - CL_{roof}) * COST_5 \quad (3.1.1.5)$$

**2) Cost of Supporting Beam**

$$\text{Cost for the load supporting beams } (COST_{beam}) = N_{columns} * N_{rows} * 2 * N_{cranes} * (R_{total} - R_{inner}) * COST_6 \quad (3.1.1.6)$$

**3) Cost of Buffer**

$$\text{Cost of Buffer } (COST_{buffer}) = 2 * N_{aisles} * COST_7 \quad (3.1.1.7)$$

**4) Cost of Assembly**

$$\text{Cost of assembly } (COST_{assembly}) = N_{columns} * N_{rows} * N_{cranes} * COST_8 \quad (3.1.1.8)$$

### 3.1.1.4 Fire Safety Cost

$$\text{Cost of fireprot } (COST_{fireprot}) = N_{columns} * N_{rows} * N_{cranes} * COST_9 \quad (3.1.1.9)$$

### 3.1.1.5 Air Ventilation Cost

$$\text{Cost of Airvent } (COST_{airvent}) = \pi * R_{total}^2 * H_{total} * COST_{10} \quad (3.1.1.10)$$

### 3.1.1.6 S/R Machine Cost

Products are both horizontally and vertically moved by the S/R machine to be stored or retrieved in R-AS/RS, whereas products are moved in theta axis and vertical axis by the S/R machine to be stored and retrieved. So that for the AS/RS, S/R machine is the most important mechanism and can be %50 more compared to other costs [63].

$$\text{Investment for S/R machine} (COST_{SR}) = S * C_{11} + CELL_{length} * C_{12} * N_{aisles} \quad (3.1.1.11)$$

#### 3.1.1.7 Total Cost

Total Cost

$$(TC)=COST_{land}+COST_{floor}+COST_{wall}+COST_{roof}+COST_{upframe}+COST_{beam}+COST_{buffer}+COST_{assembly}+COST_{fireprot}+COST_{airvent}+COST_{SR} \quad (3.1.1.12)$$

Detailed cost analysis of the proposed R-AS/RS design with two different configuration is listed in Table 3.4. Design variables, parameters and output are categorized in the table. Alternative 1 and alternative 2 represents different configuration based on ratio height to length. Alternative 1 consist of $N_{rows}$=10 and $N_{columns}$= 10 whereas, Alternative 2 consist of $N_{rows}$=20 and $N_{columns}$= 20. Although, crane velocity for vertical, horizontal and radial directions are kept as the same for alternative 1 and alternative 2.

Table 3.4: Proposed R-AS/RS design and cost analysis.

| | CONFIGURATION | SYMBOL | UNIT | R-AS/RS | |
|---|---|---|---|---|---|
| | | | | Alternative 1 | Alternative 2 |
| VARIABLES | NUMBER OF COLUMNS | $N_{columns}$ | amount | 10 | 20 |
| | NUMBER OF ROWS | $N_{rows}$ | amount | 10 | 20 |
| | VERTICAL CRANE VELOCITY | $V_{vertical}$ | m/s | 1.0000 | 1.0000 |
| | HORIZONTAL CRANE VELOCITY | $V_{horizontal}$ | m/s | 1.0000 | 1.0000 |
| | RADIAL CRANE VELOCITY | $V_{radial}$ | m/s | 1.0000 | 1.0000 |
| PARAMETERS | NUMBER OF PRODUCTS | $N_{products}$ | amount | 100 | 400 |
| | CELL LENGTH | $CELL_{length}$ | m | 5.5000 | 5.5000 |
| | CELL HEIGHT | $CELL_{height}$ | m | 2.1000 | 2.1000 |
| | CELL WIDTH | $CELL_{width}$ | m | 3.0000 | 3.0000 |
| | LOAD WEIGHT | $CELL_{weight}$ | m | 3200.0000 | 3200.0000 |
| | ROOF | $CL_{roof}$ | m | 2.1000 | 2.1000 |
| | BASE | $CL_{base}$ | m | 2.1000 | 2.1000 |
| | SAFETY | $CL_{safety}$ | m | 5.5000 | 5.5000 |
| | CRANE | $CL_{crane}$ | m | 1.0000 | 1.0000 |
| | EXTENSION | $CL_{ext}$ | m | 0.5000 | 0.5000 |
| | SIDES | $CL_{side}$ | m | 3.0000 | 3.0000 |
| | CONCRETE THICKNESS | $t_{concrete}$ | m | 0.1000 | 0.1000 |
| | BUYING LAND | $COST_1$ | EURO/$m^2$ | 500.00 | 500.00 |
| | LAYING FOUNDATION | $COST_2$ | EURO/$m^2$ | 168.00 | 168.00 |
| | BUILDING WALLS | $COST_3$ | EURO/$m^2$ | 23.00 | 23.00 |
| | BUILDING ROOF | $COST_4$ | EURO/$m^2$ | 25.00 | 25.00 |
| | UPRIGHT FRAMES | $COST_5$ | EURO/m | 30.00 | 30.00 |
| | BUYING RACK BEAMS | $COST_6$ | EURO/m | 23.00 | 23.00 |
| | BUYING BUFFERS | $COST_7$ | EURO/piece | 200.00 | 200.00 |
| | ASSEMBLY | $COST_8$ | EURO/PP | 10.00 | 10.00 |
| | FIRE SAFETY | $COST_9$ | EURO/PP | 5.00 | 5.00 |
| | AIR CONDITIONING | $COST_{10}$ | EURO/$m^3$ | 10.00 | 10.00 |
| | S/R MACHINE | $COST_{11}$ | EURO/piece | 1,500,000.00 | 1,500,000.00 |
| | PICKING AISLE | $COST_{12}$ | EURO/m | 50.00 | 50.00 |
| | CROSS AISLE | $COST_{13}$ | EURO/piece | 50.00 | 50.00 |
| OUTPUT | SYSTEM HEIGHT | $H_{total}$ | m | 26.2000 | 48.2000 |
| | SYSTEM WIDTH | $W_{total}$ | m | 23.5000 | 23.5000 |
| | SYSTEM LENGTH | $L_{total}$ | m | 37.0000 | 68.0000 |
| | SHAPE FACTOR | b | - | 0.7966 | 0.7667 |
| | NUMBER OF STORAGE CELLS | $N_{cells}$ | amount | 100.0000 | 400.0000 |
| | LAND AREA | $A_{land}$ | $m^2$ | 869.5000 | 1598.0000 |
| | CONSTRUCTED AREA | $A_{constructed}$ | $m^2$ | 344.1000 | 688.2000 |
| | TOTAL VOLUME | $V_{total}$ | $m^3$ | 22780.9000 | 77023.6000 |
| | STORAGE VOLUME | $V_{storage}$ | $m^3$ | 8292.8100 | 31726.0200 |
| | FLOOR COST | $COST_{floor}$ | EURO | 146,076.00 | 268,464.00 |
| | WALL COST | $COST_{walls}$ | EURO | 72,914.60 | 202,873.80 |
| | ROOF COST | $COST_{roof}$ | EURO | 21,737.50 | 39,950.00 |
| | UPFRAME COST | $COST_{upframe}$ | EURO | 8,646.00 | 30,366.00 |
| | SUPPORTING BEAM COST | $COST_{beam}$ | EURO | 25,300.00 | 101,200.00 |
| | BUFFER COST | $COST_{buffer}$ | EURO | 400.00 | 400.00 |
| | ASSEMBLY COST | $COST_{assembly}$ | EURO | 1,000.00 | 4,000.00 |
| | LAND COST | $COST_{land}$ | EURO | 612,323.94 | 1,051,315.79 |
| | WAREHOUSE BUILDING | $COST_{mh}$ | EURO | 240,728.10 | 511,287.80 |
| | STORAGE CONSTRUCTION | $COST_{warehouse}$ | EURO | 35,346.00 | 135,966.00 |
| | FIRE PROTECTION COST | $COST_{fireprot}$ | EURO | 500.00 | 2,000.00 |
| | AIR VENTILATION | $COST_{airvent}$ | EURO | 227,809.00 | 770,236.00 |
| | S/R MACHINE COST | $C_{sr}$ | EURO | 1,501,850.00 | 1,503,400.00 |
| | TOTAL COST | $TC$ | EURO | 2,618,157.04 | 3,973,805.59 |

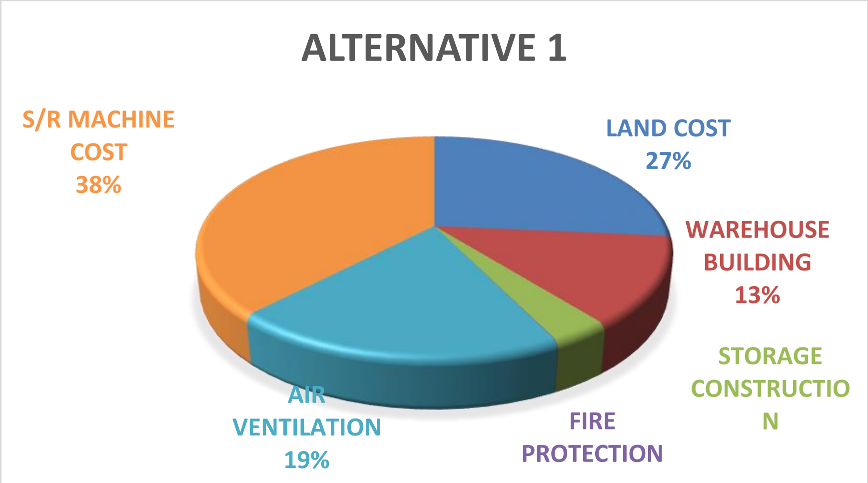


Figure 3.2: Cost distribution of alternative 1 for R-AS/RS.

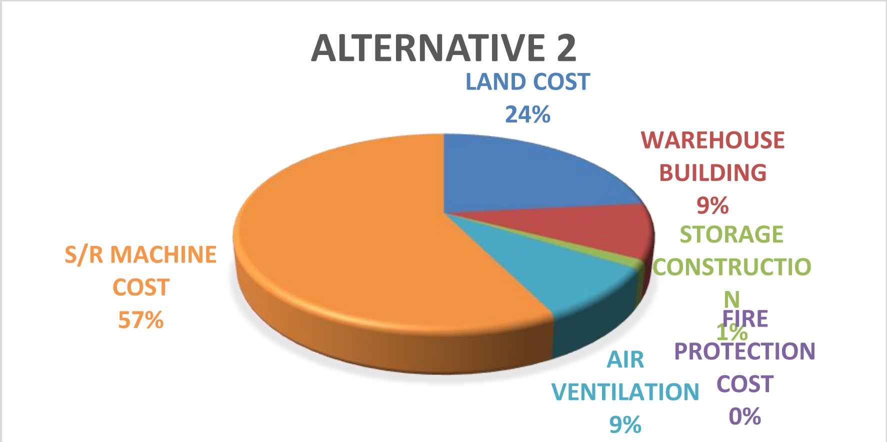


Figure 3.3: Cost distribution of alternative 2 for R-AS/RS.

From the pie charts, it can be understood that 38% of the total cost for the alternative 1, and 57% of the total cost for the alternative 2 depend on the S/R machine. Second highest value belong to land cost that is 57% for the alternative 1 and 13% for the alternative 2. S/R machine cost represents around 40% or more than 40% of the total cost of automated storage and retrieval system [72].

### 3.1.2 Travel Time Model of R-AS/RS

For the travel time model of R-AS/RS, various configurations limited with number of 99 and 399 products are created. Based on proposed configurations, shape factor (b) is found and then expected travel time is computed. Travel time model is adopted from Bozer, Y.A et. al. (1984). However, system is distinguished from the previous model in terms of number of storage capacity, system height, system width, system depth, horizontal and vertical speeds. In this model, travel times both vertical and horizontal direction, segment dimensions. This configuration also has got one I/O station and no drop-off station.

**Assumptions**

There can be variety of AS/RS configurations based on design variables such as number of rows, number of columns and crane speeds. In order to determine the configurations, proposed design considers several assumptions as follows.

1) Each segment capable of one product to be stored.
2) Vertical speed and horizontal speed of the system is same.
3) Width of the rack assumed as length of the storage cell, both in R-AS/RS and C-AS/RS.
4) The rack is considered to be a continuous rectangular pick face.
5) Platforms operate on both single command and dual command basis.
6) Unit loads are considered.
7) Randomly storage assignment policy is applied for the proposed system.
8) Configurations based on storage structure (ratio of length to height).
9) The effect of acceleration is compensated in dwell time.
10) Dwell point strategy “a” is applied. Dwell point strategies;

a. Return to the input station following the completion of a single command storage; remain at the output station following the completion of either a single command retrieval or a dual command cycle.
b. Remain at the storage location following the completion of a single command storage; remain at the output station following the completion of either a single command retrieval or a dual command cycle.
c. Travel to a midpoint location in the rack following the completion of any cycle.
d. Travel to the input station following the completion of any cycle.

Proposed R-AS/RS is consisting of a rectangular rack to accommodate SUV cars which has length of 5.200 m, height of 2.250 m and width of 2.200 m dimensional values. S/R machine is located at the base layer (1,1) and it moves along horizontal axis and vertical axis. travel time calculations will be calculated based on Cartesian coordinate system consisting different rectilinear movement. It is assumed that vertical speed, horizontal speed and radial speed of crane are equal. However, there can be many more configurations can be obtained by changing the crane speeds, hence variates cycle time for the storage and retrieval. Loading and unloading times are considered as z axis. Therefore, in order to complete one cycle in each operation, time spend to reach in specific row and time spent to reach a specific column and also loading and unloading time will be added together to find total one-way cycle time of the proposed R-AS/RS design.

N, number of product types is set as parameter in the system N=1. Therefore, if the N=1 and then from the relationship between number of product type and its proportion can be found that $\propto_i$ = 1. The proposed R-AS/RS contains 10 cells in the horizontal axis and 10 cells in the vertical axis. AS/RS's racks have got number of 99 items as cell capacity with an extra cell used as I/O station. Number of product types are shown with their proportion as follows: -1, -2, …, -N. After presentation of the physical configuration of the proposed AS/RS, results are obtained by using the mathematical model.

Let's $T_{vertical}$ indicate the travel time required for the vertical axis to go the farthest row from the base location point and $T_{horizontal}$, the travel time required for the horizontal axis to go to the farthest column from the base location point. b value represents shape factor of the rack in terms of time thus need to take as positive arbitrary value between 0 and 1 $(0 < b \leq 1)$. If the shape factor is equal to 1(b=1), then rack is square shape. Value of the shape factor can be found from the Equation (3.1.2.8). After completion of each operation, the S/R machine goes back to its base position.

### 3.1.2.2 Mathematical Model of R-AS/RS

$$Total_{length}=L_{total}=N_{columns}*(Cell_{width}+t_{concrete}) \quad (3.1.2.1)$$

$$Total_{height}=H_{total}=N_{rows}*(Cell_{height}+t_{concrete}) \quad (3.1.2.2)$$

$$T_{vertical}=\frac{N_{rows}*(Cell_{height}+t_{concrete})}{V_{vertical}}+Dwell_{vertical} \quad (3.1.2.3)$$

$$T_{horizontal}=\frac{H_{total}}{V_{horizontal}}+Dwell_{hotizontal} \quad (3.1.2.4)$$

$$T_{radial}=\frac{Cell_{length}+Cl_{crane}+Cl_{ext}}{V_{radial}}+Dwell_{radial} \quad (3.1.2.5)$$

$$T=\max(T_{vertical},T_{horizontal})+T_{radial} \quad (3.1.2.6)$$

$$N_{products}=N_{rows}*N_{columns}-1 \quad (3.1.2.7)$$

$$b=\frac{Min(T_{horizontal},T_{vertical})}{Max(T_{horizontal},T_{vertical})} \quad (3.1.2.8)$$

$$Land\ Area=A_{land}=2*L_{total}*Cell_{length} \quad (3.1.2.9)$$

$$Storage\ Area=A_{storage}=w*N_{rows}*W \quad (3.1.2.10)$$

$$Number\ of\ Products=N_{produts}=N_{rows}*N_{columns} \quad (3.1.2.11)$$

$$Volume=A_{storage}*Cell_{height}*N_{columns} \quad (3.1.2.12)$$

$$Utilization=\frac{Cell_{width}*Cell_{height}*Cell_{length}*N_{products}}{Volume}*100 \quad (3.1.2.13)$$

$$Longest_{trip}=2*T$$

$$E_{SC(continuous)}=(1+\frac{b^2}{3})*T \quad (3.1.2.14)$$

$$E_{DC(Condtinuous)}=\left(\frac{4}{3}+\frac{b^2}{2}-\frac{b^3}{30}\right)*T \quad (3.1.2.15)$$

$$E_{SC(Discrete)}=\frac{1}{N}*\sum_{i=1}^{N}2*t_{oi} \quad (3.1.2.16)$$

$$E_{DC(Discerete)}=\frac{2}{N*(N-1)}\sum_{i}^{N-1}\sum_{j=i+1}^{N}(t_{0i}+t_{ij}+t_{j0}) \quad (3.1.1.17)$$

$$\text{Throughput (SC)}=T_{SC}=\frac{60}{E_{SC}*x(3)} \quad (3.1.1.18)$$

$$\text{Throughput (DC)}=T_{DC}=\frac{60}{E_{DC}*x(3)} \quad (3.1.1.19)$$

Travel time model is conducted to proposed R-AS/RS design. Based on the cycle time, expected travel times and throughput capacity of the system is found. In order to find throughput capacity of the proposed system, $T_{shift}, n_{wd}, n_{weeks}$ are set as 16, 5, 50 respectively. Based on two different configuration travel time model performed and comparable results are presented in the Table 3.5. Design variables, parameters and output values are presented explicitly in the table due to provide better understanding.

Table 3.5: Travel time results for the proposed R-AS/RS design.

| | CONFIGURATION | SYMBOL | UNIT | R-AS/RS Alternative 1 | R-AS/RS Alternative 2 |
|---|---|---|---|---|---|
| VARIABLES | NUMBER OF COLUMNS | $N_{columns}$ | amount | 10 | 20 |
| | NUMBER OF ROWS | $N_{rows}$ | amount | 10 | 20 |
| | NUMBER OF PRODUCTS | $N_{products}$ | amount | 100 | 400 |
| | VERTICAL CRANE VELOCITY | $V_{vertical}$ | m/s | 1 | 1 |
| | HORIZONTAL CRANE VELOCITY | $V_{horizontal}$ | m/s | 1 | 1 |
| | RADIAL CRANE VELOCITY | $V_{radial}$ | m/s | 1 | 1 |
| PARAMETERS | CELL LENGTH | $CELL_{length}$ | m | 5.5000 | 5.5000 |
| | CELL HEIGHT | $CELL_{height}$ | m | 2.1000 | 2.1000 |
| | CELL WIDTH | $CELL_{width}$ | m | 3.0000 | 3.0000 |
| | CELL WEIGHT | $CELL_{weight}$ | m | 3200.0000 | 3200.0000 |
| | VERTICAL DWELL TIME | $T_{Dwellvertical}$ | s | 25.0000 | 25.0000 |
| | HORIZONTAL DWELL TIME | $T_{Dwellhorizontal}$ | s | 25.0000 | 25.0000 |
| | RADIAL DWELL TIME | $T_{Dwellradial}$ | s | 15.0000 | 15.0000 |
| OUTPUT | LONGEST TRIP | $T_{longest}$ | s | 206.0000 | 268.0000 |
| | EXPECTED TRAVEL TIME CONTINUOUS | $E_{SC}$ | s | 159.4802 | 195.6333 |
| | EXPECTED TRAVEL TIME CONTINUOUS | $E_{DC}$ | s | 228.3928 | 277.0981 |
| | EXPECTED TRAVEL TIME DISCRETE | $E_{Dsc}$ | s | 125.8060 | 155.4265 |
| | EXPECTED TRAVEL TIME DISCRETE | $E_{Ddc}$ | s | 189.6797 | 233.2168 |
| | VERTICAL LONGEST TRIP | $T_{vertical}$ | s | 47.0000 | 69.0000 |
| | HORIZONTAL LONGEST TRIP | $T_{rotational}$ | s | 59.0000 | 90.0000 |
| | RADIAL TRIP | $T_{radial}$ | s | 22.0000 | 22.0000 |
| | STORAGE TIME | T | s | 59.0000 | 90.0000 |
| | THROUGHPUT (SC) | $THROUGHPUT_{sc}$ | operation/hour | 22 | 18 |
| | THROUGHPUT FOR (DC) | $THROUGHPUT_{dc}$ | operation/hour | 15 | 12 |

### 3.1.3 Energy Efficiency Model for R-AS/RS

Generally, warehouse buildings, distribution centers and car parking buildings contribute in energy consumption and $CO_2$ emission. Therefore, one of the purpose of the study is to design an energy efficient AS/RS at reasonable levels while satisfying the middle size enterprises by reasonable total cost and enough number of products to store and retrieve.

In order to calculate energy efficiency of the system, specific assumptions are considered as follows:

1) Crane velocity is assumed to be constant velocity.
2) Aerodynamic drag is ignored for the calculation.
3) Motor power is found based on mechanical power calculation.
4) Crane weight is taken as 5000 kg due to the safety factor.
5) Radial direction neglected. Therefore, no motor power is considered.

Mechanical model is exist in the literature and it is explained well in Lerher, T. et al. (2014). Based on existing mathematical model from the literature, motor powers are found as follows:

$$P=\frac{Energy}{t},\ P=\frac{F*d}{t},\ P=F*v \tag{3.1.3.1}$$

$$\sum x=0, \sum y=0, \sum z=0 \tag{3.1.3.2}$$

$$\text{Rolling friction} = F_R=G*k_k \tag{3.1.3.3}$$

$$\text{Driving torque}=M_{Tv}=F*r \tag{3.1.3.4}$$

$$G=G_{crane}+G_{platform}+G_{safetyfactor} \tag{3.1.3.5}$$

$$P_{total}=P_{vertical}+P_{horizontal} \tag{3.1.3.6}$$

$$\text{Energy Consumption}=W=P*t_{shift}*n_{wd}*n_{weeks}*\varepsilon \tag{3.1.3.7}$$

$$CO_2 \text{ emission yearly}=W*\rho \tag{3.1.3.8}$$

Table 3.6: Energy efficiency of R-AS/RS.

| | CONFIGURATION | SYMBOL | UNIT | R-AS/RS |
|---|---|---|---|---|
| VARIABLES | NUMBER OF COLUMNS | $N_{columns}$ | amount | 10 |
| | NUMBER OF ROWS | $N_{rows}$ | amount | 10 |
| | NUMBER OF PRODUCTS | $N_{products}$ | amount | 100 |
| | VERTICAL CRANE VELOCITY | $V_{vertical}$ | m/s | 1 |
| | HORIZONTAL CRANE VELOCITY | $V_{horizontal}$ | m/s | 1 |
| | RADIAL CRANE VELOCITY | $V_{radial}$ | m/s | 1 |
| PARAMETERS | CELL LENGTH | $CELL_{length}$ | m | 5.5000 |
| | CELL HEIGHT | $CELL_{height}$ | m | 2.1000 |
| | CELL WIDTH | $CELL_{width}$ | m | 3.0000 |
| | CELL WEIGHT | $CELL_{weight}$ | m | 3200.0000 |
| | VERTICAL DWELL TIME | $T_{Dwellvertical}$ | s | 25.0000 |
| | HORIZONTAL DWELL TIME | $T_{Dwellhorizontal}$ | s | 25.0000 |
| | RADIAL DWELL TIME | $T_{Dwellradial}$ | s | 15.0000 |
| OUTPUT | REQUIRED MOTOR POWER VERTICAL DIRECTION | $POWER_{lifting}$ | kW | 49.0500 |
| | REQUIRED MOTOR POWER HORIZONTAL DIRECTION | $POWER_{rotational}$ | kW | 30.2150 |
| | TOTAL REQUIRED POWER | $POWER_{total}$ | kW | 79.2650 |
| | ENERGY CONSUMPTION | $W$ | kWh/yr | 215464.8000 |
| | $CO_2$ EMISSION | $E_{CO2}$ | kgCO2/yr | 146076.0000 |

Summerly, an AS/RS is proposed and its travel time model, total cost model and energy efficiency model created based on specific parameters. For the proposed system, which has ten number of rows and ten number of columns, configuration with one m/s crane speeds, requires 49 kW motor power in vertical direction and 30.215 kW motor power in horizontal direction. System requires 79.265 kW motor power to perform operations properly. Energy consumption and $CO_2$ emission analysis done by using Equation 3.1.3.7 and Equation 3.1.3.8. Analyze results presented in Table 3.6.

## 3.2 Circular Type AS/RS (C-AS/RS)

### 3.2.1 Cost Model of C-AS/RS

**Assumptions**

a. The number of the S/R machines, $N_{cranes}$ is equal to the number of picking aisles, $(N_{aisles})$.

b. The SR has a circular shape and it is located in the middle of the SR.

c. The S/R machine enables the operation of SC and DC.

d. The storage and retrieval operation is performed in the same picking aisle.

e. For the travel time calculation, acceleration of the crane is neglected.

f. The S/R machine travels in the picking aisle simultaneously in the vertical, radial and rotational directions.

g. System height and system length are having enough distance for the S/R machine to reach its maximum speed.

h. System inner diameter is large enough for SUV car length to be handled by the S/R machine.

i. Randomly assigned storage policy is utilized for the proposed system.

For the evidence of presented operational and physical parameters, the storage compartment and the storage rack are presented in Figure 3.6 and Figure 3.7.

$N_{rows}$, $N_{columns}$, $V_{vertical}$, $V_{rotational}$, $V_{radial}$ are taken as design variables for minimization of travel time as well as minimization of total cost.

**Operational Parameters of the Warehouse:**

Table 3.7: Operational parameters for C-AS/RS.

| Parameters | Symbol | Unit | Value |
|---|---|---|---|
| Cell height | $CELL_{height}$ | m | 2.1 |
| Cell length | $CELL_{length}$ | m | 5.5 |
| Cell width | $CELL_{width}$ | m | 3 |
| Cell weight | $CELL_{weight}$ | kg | 3200 |
| Clearance for roof | $CL_{roof}$ | m | 2.1 |
| Clearance for base | $CL_{base}$ | m | 2.1 |
| Clearance for crane | $CL_{crane}$ | m | 1 |
| Clearance for safety | $CL_{safety}$ | m | 5.5 |
| Clearance for extension | $CL_{ext}$ | m | 0.5 |
| Clearance for side | $CL_{side}$ | m | 3 |
| Dwell time for vertical axis | $T_{dwellvertical}$ | s | 25 |
| Dwell time for horizontal axis | $T_{dwellhorizontal}$ | s | 25 |
| Dwell time for radial direction | $T_{dwellradial}$ | s | 15 |

**Material Handling Equipment:**

the single-aisle S/R machine : $V_{radial}$ = 1 m/s, $V_{vertical}$ = 1 m/s, $V_{rotational} =$ 18 $degree/s$.

**Costs are presented as following [63]**

Table 3.8: Cost parameters.

| Parameters | Symbol | Unit | Value |
|---|---|---|---|
| Cost of the land | $COST_1$ | $EURO/m^2$ | 500 |
| Cost of foundation | $COST_2$ | $EURO/m^2$ | 168 |
| Cost of the construction walls | $COST_3$ | $EURO/m^2$ | 23 |
| Cost of construction roof | $COST_4$ | $EURO/m^2$ | 25 |
| Cost of upright frames | $COST_5$ | $EURO/m^2$ | 30 |
| Cost of rack beams | $COST_6$ | $EURO/m^2$ | 23 |
| Cost of buffers | $COST_7$ | $EURO/piece$ | 200 |
| Cost of assembly | $COST_8$ | $EURO/PP$ | 10 |
| Cost of fire safety | $COST_9$ | $EURO/PP$ | 5 |
| Cost of air conditioning | $COST_{10}$ | $EURO/m^3$ | 10 |
| Cost of S/R machine | $COST_{11}$ | $EURO/piece$ | 431 |
| Cost of the picking aisle | $COST_{12}$ | $EURO/m$ | 50 |

#### 3.2.1.1 Land Cost

Land cost can be differed in each city or in each country due to the land cost of place where the system to be set up. In the cost analysis of proposed system, Land cost is termed as $L_{Cost}$ and its value taken as 500 EURO/m$^2$. $D_z$ is representing the share for the warehouse building and its value is set to be 71 [71].

$$\text{Cost of Land } (COST_{land})=2*D_{total}^2*COST_1 \quad (3.2.1.1)$$

#### 3.2.1.2 Warehouse Building Cost

1) **Cost of Floor**

$$\text{Cost of Floor } (COST_{floor})=\pi*R_{total}^2*COST_2 \quad (3.2.1.2)$$

2) **Cost of Wall**

$$\text{Cost of walls } (COST_{walls})=\pi*R_{total}^2*H_{total}*2*COST_3 \quad (3.2.1.3)$$

3) **Cost of Roof**

$$\text{Cost of the roof } (COST_{roof})=\pi*R_{total}^2*COST_4 \quad (3.2.1.4)$$

### 3.2.1.3 Storage Construction Cost

1) **Cost of Up-frame**

$$\text{Cost of upright frames } (COST_{upframe}) = (N_{rows}+1)*N_{cranes}*(H_{total}-CL_{roof})*COST_5 \quad (3.2.1.5)$$

2) **Cost of Supporting Beam**

$$\text{Cost for the load supporting beams } (COST_{beam}) = N_{columns}*N_{rows}*2*N_{cranes}*(R_{total}-R_{inner})*C_{OST6} \quad (3.2.1.6)$$

3) **Cost of Buffer**

$$\text{Cost of Buffer } (COST_{buffer}) = 2*N_{aisles}*COST_7 \quad (3.2.1.7)$$

4) **Cost of Assembly**

$$\text{Cost of assembly } (COST_{assembly}) = N_{columns}*N_{rows}*N_{cranes}*COST_8 \quad (3.2.1.8)$$

### 3.2.1.4 Fire Safety Cost

$$\text{Cost of fireprot } (COST_{fireprot}) = N_{columns}*N_{rows}*N_{cranes}*COST_9 \quad (3.2.1.9)$$

### 3.2.1.5 Air Ventilation Cost

$$\text{Cost of Airvent } (COST_{airvent}) = \pi*R_{total}^2*H_{total}*COST_{10} \quad (3.2.1.10)$$

### 3.2.1.6 S/R Machine Cost

$$\text{Investment for single aisle S/R machine} (COST_{SR}) = S*COST_{11}+CELL_{length}*COST_{12}*N_{aisles} \quad (3.2.1.11)$$

### 3.2.1.7 Total Cost

$$\text{Total Cost (TC)} = COST_{land}+COST_{floor}+COST_{wall}+COST_{roof}+ COST_{upframe}+COST_{beam}+COST_{buffer}+ COST_{assembly}+COST_{fireprot}+COST_{airvent}+COST_{SR} \quad (3.2.1.12)$$

Cost analysis is applied to two different configurations in order to provide comparable cost values based on different configurations. The number of configuration alternatives can be increased due to the customer demand. However, two different alternatives are presented in the thesis as shown in the Table 3.9.

Table 3.9: Cost analysis for C-AS/RS.

| | CONFIGURATION | SYMBOL | UNIT | C-AS/RS | |
|---|---|---|---|---|---|
| | | | | Alternative 1 | Alternative 2 |
| VARIABLES | NUMBER OF COLUMNS | $N_{columns}$ | amount | 10 | 20 |
| | NUMBER OF ROWS | $N_{rows}$ | amount | 10 | 20 |
| | VERTICAL CRANE VELOCITY | $V_{vertical}$ | m/s | 1.0000 | 1.0000 |
| | ROTATIONAL CRANE VELOCITY | $V_{horizontal}$ | degree/s | 36.0000 | 36.0000 |
| | RADIAL CRANE VELOCITY | $V_{radial}$ | m/s | 1.0000 | 1.0000 |
| PARAMETERS | NUMBER OF PRODUCTS | $N_{products}$ | amount | 100 | 400.00 |
| | CELL LENGTH | $CELL_{length}$ | m | 5.5000 | 5.5000 |
| | CELL HEIGHT | $CELL_{height}$ | m | 2.1000 | 2.1000 |
| | CELL WIDTH | $CELL_{width}$ | m | 3.0000 | 3.0000 |
| | CELL WEIGHT | $CELL_{weight}$ | m | 3200.0000 | 3200.0000 |
| | ROOF | $CL_{roof}$ | m | 2.1000 | 2.1000 |
| | BASE | $CL_{base}$ | m | 2.1000 | 2.1000 |
| | CRANE RAILS | $CL_{rails}$ | m | 0.5000 | 0.5000 |
| | SAFETY | $CL_{safety}$ | m | 5.5000 | 5.5000 |
| | CRANE | $CL_{crane}$ | m | 1.0000 | 1.0000 |
| | EXTENSION | $CL_{ext}$ | m | 0.5000 | 0.5000 |
| | CONCRETE THICKNESS | $t_{concrete}$ | m | 0.1000 | 0.1000 |
| | BUYING LAND | $COST_1$ | EURO/$m^2$ | 150.00 | 150.00 |
| | LAYING FOUNDATION | $COST_2$ | EURO/$m^2$ | 160.00 | 160.00 |
| | BUILDING WALLS | $COST_3$ | EURO/$m^2$ | 50.00 | 50.00 |
| | BUILDING ROOF | $COST_4$ | EURO/$m^2$ | 50.00 | 50.00 |
| | UPRIGHT FRAMES | $COST_5$ | EURO/m | 30.00 | 30.00 |
| | BUYING RACK BEAMS | $COST_6$ | EURO/m | 35.00 | 35.00 |
| | BUYING BUFFERS | $COST_7$ | EURO/piece | 200.00 | 200.00 |
| | ASSEMBLY | $COST_8$ | EURO/PP | 5.00 | 5.00 |
| | FIRE SAFETY | $COST_9$ | EURO/PP | 5.00 | 5.00 |
| | AIR CONDITIONING | $COST_{10}$ | EURO/$m^3$ | 5.00 | 5.00 |
| | S/R MACHINE | $COST_{11}$ | EURO/piece | 1,500,000.00 | 1,500,000.00 |
| | PICKING AISLE | $COST_{12}$ | EURO/m | 50.00 | 50.00 |
| | CROSS AISLE | $COST_{13}$ | EURO/piece | 50.00 | 50.00 |
| OUTPUT | SYSTEM HEIGHT | $H_{total}$ | m | 26.2000 | 48.2000 |
| | SYSTEM DIAMETER | $D_{total}$ | m | 31.8676 | 41.4169 |
| | SYSTEM INNER DIAMETER | $D_{inner}$ | m | 9.8676 | 19.4169 |
| | TOTAL CIRCUMFERENCE | $CIR_{total}$ | m | 100.1150 | 130.1150 |
| | INNER CIRCUMFERENCE | $CIR_{inner}$ | m | 31.0000 | 61.0000 |
| | SHAPE FACTOR | b | - | 0.6383 | 0.4348 |
| | NUMBER OF STORAGE CELLS | $N_{cells}$ | amount | 100.0000 | 400.0000 |
| | LAND AREA | $A_{land}$ | $m^2$ | 797.6067 | 1347.2405 |
| | CONSTRUCTED AREA | $A_{constructed}$ | $m^2$ | 721.1327 | 1051.1327 |
| | TOTAL VOLUME | $V_{total}$ | $m^3$ | 20897.2945 | 64936.9913 |
| | STORAGE VOLUME | $V_{storage}$ | $m^3$ | 17379.2983 | 48457.2180 |
| | FLOOR COST | $COST_{floor}$ | EURO | 63,862.30 | 60,821.23 |
| | WALL COST | $COST_{walls}$ | EURO | 40,476.15 | 149,866.52 |
| | ROOF COST | $COST_{roof}$ | EURO | 25,388.61 | 85,767.99 |
| | UPFRAME COST | $COST_{upframe}$ | EURO | 8,646.00 | 30,366.00 |
| | SUPPORTING BEAM COST | $COST_{beam}$ | EURO | 25,300.00 | 154,000.00 |
| | BUFFER COST | $COST_{buffer}$ | EURO | 400.00 | 400.00 |
| | ASSEMBLY COST | $COST_{assembly}$ | EURO | 1,000.00 | 2,000.00 |
| | LAND COST | $COST_{land}$ | EURO | 715,172.07 | 338,557.87 |
| | WAREHOUSE BUILDING | $COST_{mh}$ | EURO | 129,727.06 | 296,455.75 |
| | STORAGE CONSTRUCTION | $COST_{warehouse}$ | EURO | 35,346.00 | 186,766.00 |
| | FIRE PROTECTION COST | $COST_{fireprot}$ | EURO | 500.00 | 2,000.00 |
| | AIR VENTILATION | $COST_{airvent}$ | EURO | 208,972.95 | 324,684.96 |
| | S/R MACHINE COST | $COST_{sr}$ | EURO | 1,501,550.00 | 1,501,550.00 |
| | TOTAL COST | $COST_{total}$ | EURO | 2,590,868.08 | 2,651,114.57 |

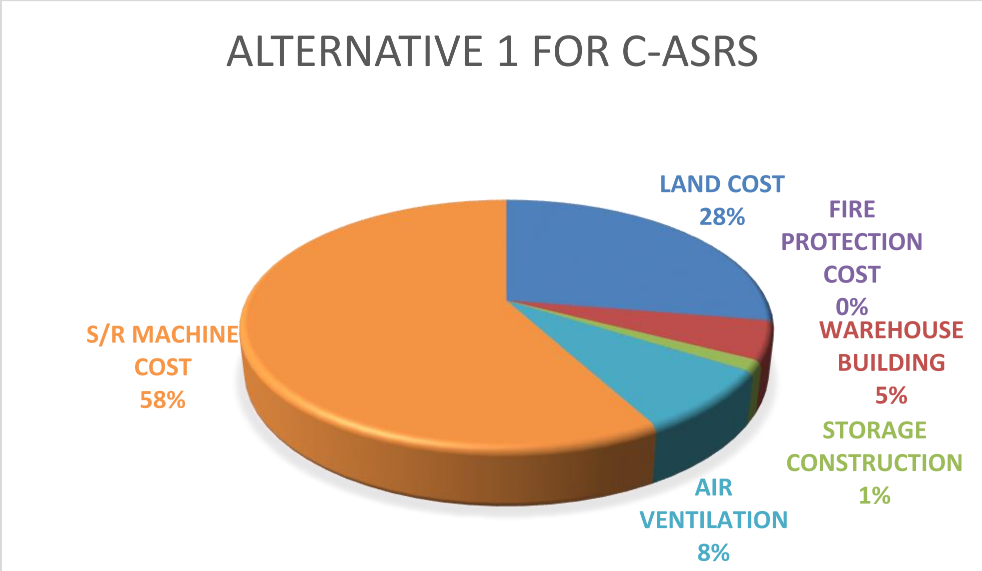



Figure 3.4: Cost distribution of alternative one for C-AS/RS.

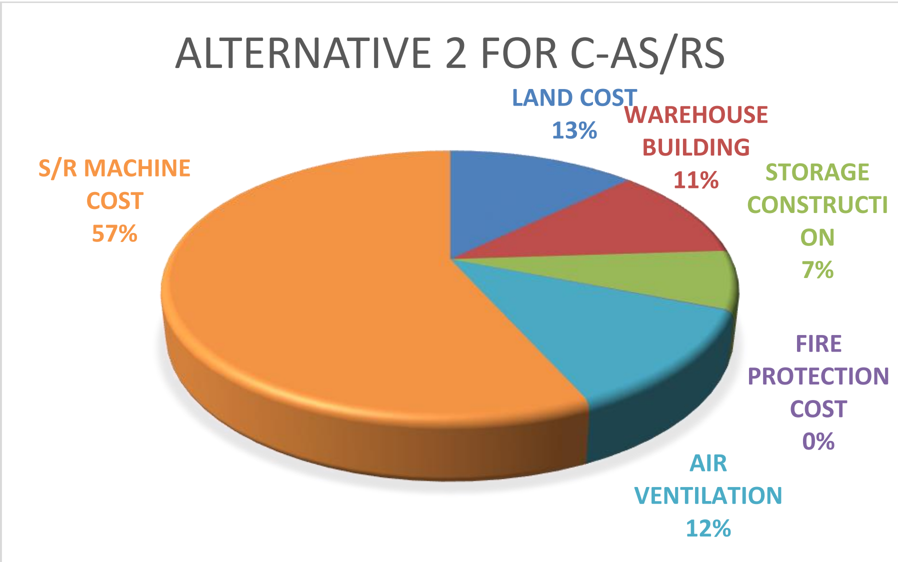



Figure 3.5: Cost distribution of alternative two for C-AS/RS.

From the pie charts, it can be understood that 58% of the total cost for the alternative 1, and 57% of the total cost for the alternative 2 depend on the S/R machine. Second highest value belong to land cost that is 28% for the alternative 1 and 13% for the alternative 2. S/R machine cost represents around 40% or more than 40% of the total cost of automated storage and retrieval system [72].

### 3.2.2 Travel Time Model of C-ASRS

For the proposed design of R-AS/RS is similar with the C-AS/RS except its shape. Rest of the parameters such as configuration, speed features, clearance values are same as the R-AS/RS. Therefore, new type of AS/RS design is proposed and then travel time model is created as follows:

$$\text{Circumference of a circle} = C_c = 2*\pi*r \qquad (3.2.2.1)$$

System capacity is calculated as shown in Equation (4.2.2). One storage cell is occupied by I/O location thus, we subtract 1 from overall number of storage cells.

$$\text{Overal capacity} = \text{No of loading high}*\text{No of aisles} - 1 \qquad (3.2.2.2)$$

**Assumptions for the Travel Time Model**

Travel time calculation, randomized storage assignment used to identify the storage cell coordinates for storing or retrieving. The product type is different in AS/RS models. Therefore, depth of the storage cells, acceleration, the time spent for product loading, the time spent for product unloading differ in each model and cause changes in travel time. In order to provide accurate comparison between models, variables affecting travel time is taken as same as proposed model of R-AS/RS. Therefore, calculation is done by evaluation of randomly assigned coordinates for both proposed designs R-AS/RS and C-AS/RS. Proposed models are then compared with each other to determine travel time performance of the systems. Assumptions for travel time model are as follows:

1) The rack is considered to be a continuous circular rack.

2) Cartesian coordinate system is used for assigning random storage allocations for evaluation of travel time in R-AS/RS, however this method does not work for C-AS/RS due to the rotational movement of the S/R machine. Therefore, randomly

assigned Cartesian coordinates (x, y, and z) are converted to cylindrical coordinate system $(\mathrm{P}, \Phi, z)$ for the proposed C-AS/RS design.

3) P is the radial distance and it is equivalent to x axis in the R-AS/RS.

4) Platforms operate on both single command and dual command basis.

5) Cells are located on rows and each row is divided into 10 equal stations. Each station capable to store only one product. System has got a single aisle located at the center of the circular rows.

6) Rest of the system properties, which are not mentioned in this section, will be the same as assumptions assigned for the proposed R-AS/RS design.

7) System has got single I/O station and located at the first row as shown in the Figure 3.6. Crane is located in the middle of the circular racks.

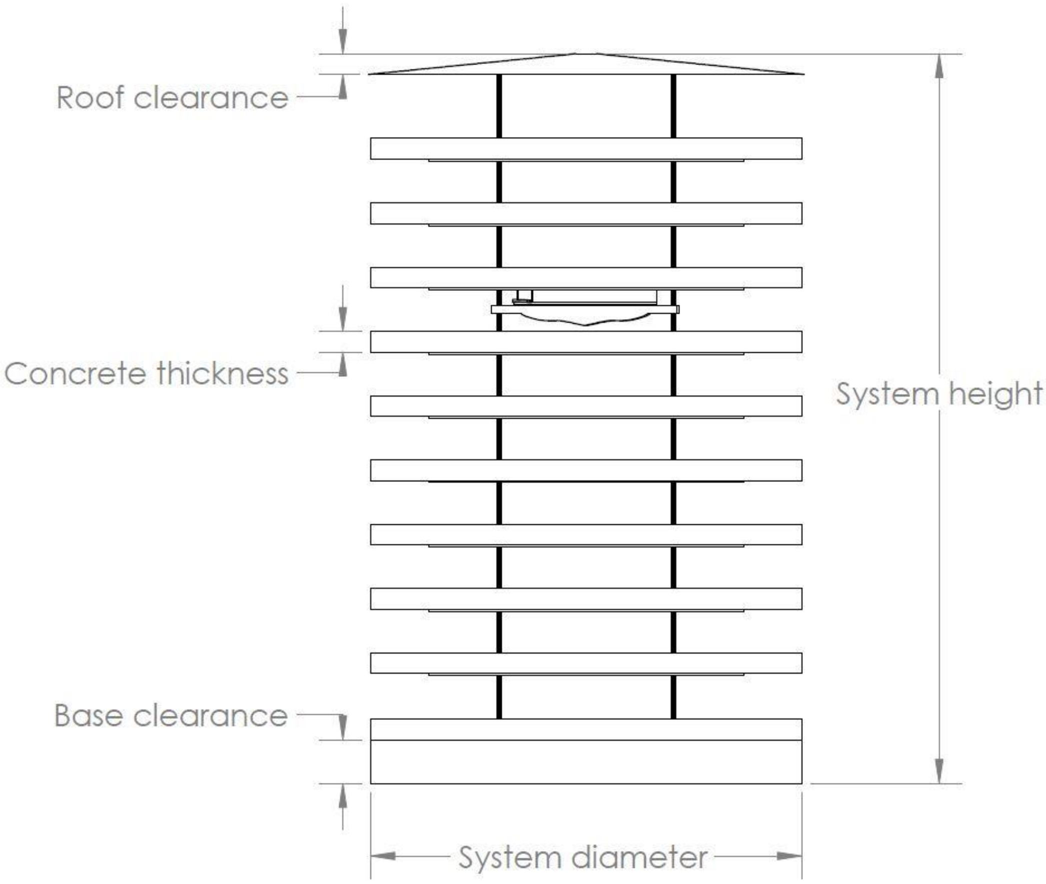



Figure 3.6: Circular racks and front view of the C-AS/RS.

C-AS/RS consist of circular racks including SUV cars inside the storage cells. S/R machine is located at the base layer and in the middle of the circle racks. S/R machine moves along $z$ and Φ axis and travel time calculations will be calculated based on cylindrical coordinate system. It is assumed that speeds in z and Φ axis are the same and motion in P axis presented to be loading and unloading time. Therefore, evaluation of waiting times and evaluation of loading/unloading times are given as parameter in the proposed designs. Notations of the variables are as follows:

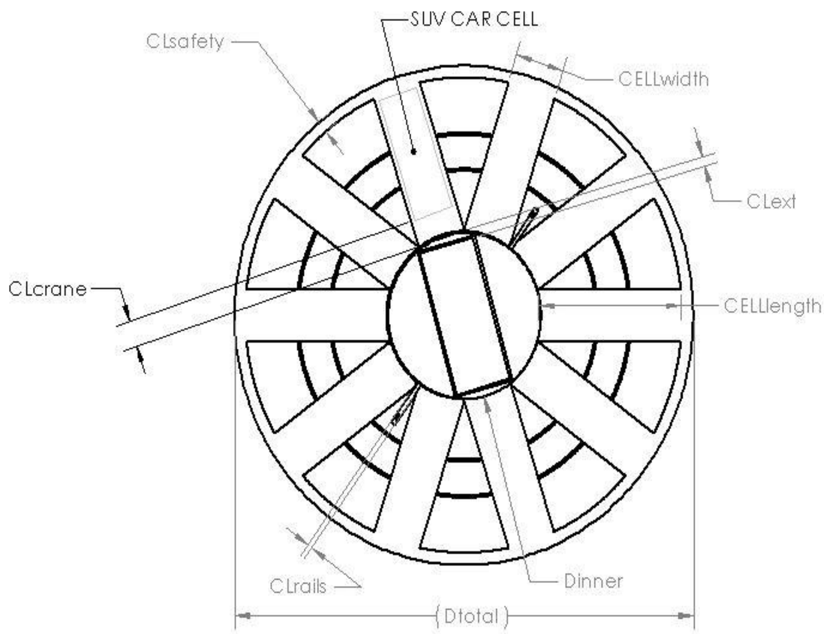


Figure 3.7: Top view of the C-AS/RS.

Number of product types is set as parameter in the system N=1, and SUV type cars are considered to accommodate in the circular storage racks. Therefore, if the N=1 and then from the relationship between number of product type and its proportion can be found that $\propto_i = 1$. The small scale R-AS/RS contains 10 cells per loading high and 10 cells per bay. AS/RS's racks have got number of 99 items as cell capacity with an extra cell used as I/O station.  After presentation of the physical configuration of the proposed AS/RS, results are obtained by using the mathematical model.

Let's $T_{vertical}$ indicate the travel time required for the z axis to go the farthest layer at the aisle from the base location point and $T_{rotational}$, the travel time required for the Φ axis to go to the highest loading high (circumference of the circular layer) from the base location point. b value represents the shape factor in terms of time thus need to set as positive arbitrary value between 0 and 1 $(0 < b \leq 1)$. If the shape factor is equal to 1(b=1), then rack is square in time.

**Mathematical Model of C-AS/RS**

For the proposed physical configurations, some parameters are considered as following; the load rate to be 0.9 and the number of product type N, and their proportions -1, -2, …, -N, and as system based on only one type of product that is SUV cars. Therefore, number of product type is considered as 1 $(N = 1, \propto = 1)$ for the mathematical calculation. For the proposed C-AS/RS design, based on obtained travel time model applied to find travel time with respect to single command and dual command. Evaluation is then utilized to find throughput. Model is presented at the below.

**Calculations,**

$$\text{Circumference}_{inner}=\text{Cir}_{inner}=\text{N}_{columns}*(\text{Cell}_{width}+\text{t}_{concrete})+\text{Cl}_{rails} \quad (3.2.2.3)$$

$$\text{Total}_{circumference}=\text{Cir}_{total}=2*\pi*\text{R}_{total} \quad (3.2.2.4)$$

$$\text{Total}_{radius}=\text{R}_{total}=\frac{\text{Cir}_{t}}{2*\pi} \quad (3.2.2.5)$$

$$\text{R}_{inner}=\frac{\text{Cir}_{inner}}{2*\pi} \quad (3.2.2.6)$$

$$\text{D}_{inner}=2*\text{R}_{inner} \quad (3.2.2.7)$$

$$\text{Total}_{diameter}=\text{D}_{t}=\text{x}(2)*\text{Cell}_{width}+2*\text{Cell}_{length}+2*\text{Cl}_{safety} \quad (3.2.2.8)$$

$$\text{T}_{vertical}=\frac{\text{N}_{rows}*(\text{Cell}_{height}+\text{t}_{concrete})}{\text{V}_{Vertical}}+\text{Dwell}_{vertical} \quad (3.2.2.9)$$

$$\text{T}_{rotational}=\frac{\text{Cir}_{inner}}{(\text{V}_{rotational})}+\text{Dwell}_{rotational} \quad (3.2.2.10)$$

$$\text{T}_{radial}=2*\frac{(\text{Cl}_{ext}+\text{Cl}_{crane}+\text{Cell}_{lenght})}{\text{V}_{radial}}+\text{Dwell}_{radial} \quad (3.2.2.11)$$

$$\text{Total}_{height}=\text{H}_{total}=\text{N}_{columns}*\left(\text{Cell}_{height}+\text{t}_{concrete}\right)+\text{Cl}_{roof}+\text{Cl}_{base} \quad (3.2.2.12)$$

$$\text{T}=\max(\text{T}_{vertical},\text{T}_{rotational}) \quad (3.2.2.13)$$

$$\text{Total}_{capacity}=\text{N}_{columns}*\text{N}_{rows}-1 \quad (3.2.2.14)$$

$$\text{b}=\frac{\text{Min}(\text{T}_{rotational},\text{T}_{vertical})}{\text{Max}(\text{T}_{rotational},\text{T}_{vertical})} \quad (3.2.2.15)$$

$$\text{Land Area}=\text{A}_{land}=2*\pi*(\text{R}_{total})^{2} \quad (3.2.2.16)$$

$$\text{Storage Area}=\text{A}_{storage}=2*\pi*(\text{R}_{total}\text{-R})^{2} \quad (3.2.2.17)$$

$$\text{Number of Products}=\text{N}_{products}=\text{x}(1)*\text{x}(2) \quad (3.2.2.18)$$

$$\text{Volume}=\text{A}_{storage}*\text{Total}_{height} \quad (3.2.2.19)$$

$$\text{Longest}_{trip}=2*(\text{T}_{vertical}+\text{T}_{radial}) \quad (3.2.2.20)$$

$$\text{E}_{SC(continuous)}=(1+\frac{\text{b}^{2}}{3})*\text{T} \quad (3.2.2.21)$$

$$E_{DC(Condtinuous)}=\left(\frac{4}{3}+\frac{b^2}{2}-\frac{b^3}{30}\right)*T \tag{3.2.2.22}$$

$$E_{SC(Discrete)}=\frac{1}{N}*\sum_{i=1}^{N} 2*t_{oi} \tag{3.2.2.23}$$

$$E_{DC(Discerete)}=\frac{2}{N*(N-1)}\sum_{i}^{N-1}\sum_{j=i+1}^{N}(t_{0i}+t_{ij}+t_{j0}) \tag{3.2.2.24}$$

$$Throughput_{(SC)}=T_{SC}=\frac{60}{E_{SC}*x(3)} \tag{3.2.2.25}$$

$$Throughput_{(DC)}=T_{DC}=\frac{60}{E_{DC}*x(3)} \tag{3.2.2.26}$$

Detailed cost analysis of the proposed C-AS/RS design with two different configuration is listed in Table 3.10. Design variables, parameters and output are categorized in the table. Alternative 1 and alternative 2 represents different configuration based on ratio height to diameter. Alternative 1 consist of $N_{rows}$=10 and $N_{columns}$= 10 whereas, Alternative 2 consist of $N_{rows}$=20 and $N_{columns}$= 20. Although, crane velocity for vertical, rotational and radial directions are kept as the same for alternative 1 and alternative 2.

Table 3.10: Parameters for proposed C-AS/RS.

| | CONFIGURATION | SYMBOL | UNIT | C-AS/RS | |
|---|---|---|---|---|---|
| | | | | **Alternative 1** | **Alternative 2** |
| **VARIABLES** | NUMBER OF COLUMNS | $N_{columns}$ | amount | 10 | 20 |
| | NUMBER OF ROWS | $N_{rows}$ | amount | 10 | 20 |
| | VERTICAL CRANE VELOCITY | $V_{vertical}$ | m/s | 1.0000 | 1.0000 |
| | ROTATIONAL CRANE VELOCITY | $V_{horizontal}$ | degree/s | 36.0000 | 36.0000 |
| | RADIAL CRANE VELOCITY | $V_{radial}$ | m/s | 1.0000 | 1.0000 |
| **PARAMETERS** | NUMBER OF PRODUCTS | $N_{products}$ | amount | 100.0000 | 400.0000 |
| | CELL LENGTH | $CELL_{length}$ | m | 5.5000 | 5.5000 |
| | CELL HEIGHT | $CELL_{height}$ | m | 2.1000 | 2.1000 |
| | CELL WIDTH | $CELL_{width}$ | m | 3.0000 | 3.0000 |
| | CELL WEIGHT | $CELL_{weight}$ | m | 3200.0000 | 3200.0000 |
| | VERTICAL | $T_{Dwellvertical}$ | s | 25.0000 | 25.0000 |
| | ROTATIONAL* / HORIZONTAL | $T_{Dwellrotational}$ | s | 10.0000 | 10.0000 |
| | RADIAL | $T_{Dwellradial}$ | s | 15.0000 | 15.0000 |
| **OUTPUT** | LONGEST TRIP | $T_{longest}$ | s | 182.0000 | 226.0000 |
| | EXPECTED TRAVEL TIME CONTINUOUS | $E_{SC}$ | s | 141.3830 | 161.3478 |
| | EXPECTED TRAVEL TIME CONTINUOUS | $E_{DC}$ | s | 203.8337 | 230.3327 |
| | EXPECTED TRAVEL TIME DISCRETE | $E_{Dsc}$ | s | 118.3200 | 136.1320 |
| | EXPECTED TRAVEL TIME DISCRETE | $E_{Ddc}$ | s | 172.5341 | 198.3606 |
| | VERTICAL LONGEST TRIP | $T_{vertical}$ | s | 47.0000 | 69.0000 |
| | ROTATIONAL LONGEST TRIP | $T_{rotational}$ | s | 30.0000 | 30.0000 |
| | RADIAL TRIP (LOADING/UNLOADING) | $T_{radial}$ | s | 22.0000 | 22.0000 |
| | STORAGE TIME | T | s | 47.0000 | 69.0000 |
| | THROUGHPUT (SC) | $THROUGHPUT_{sc}$ | operation/hour | 25 | 22 |
| | THROUGHPUT FOR (DC) | $THROUGHPUT_{dc}$ | operation/hour | 17 | 15 |

### 3.2.3 Energy Efficiency Model for the C-AS/RS

For the comprehensive study, energy consumption and $CO_2$ emission calculations are applied to the R-AS/RS as well as C-AS/RS. Calculation differs in each model because of the motor power calculation. Nevertheless, energy consumption values nearly the same, it is having essential effect on multi-objective optimization.

In order to calculate energy efficiency of the system, specific assumptions considered as follows:

1) Crane velocity is assumed to be constant velocity.
2) Aerodynamic drag is ignored for the calculation.
3) Motor power is found based on mechanical power calculation.
4) Crane weight is taken as 5000 kg due to the safety factor.

Motor power calculation is done by using mechanical power calculations in rigid body dynamics. After the calculation of required motor power for the system, $CO_2$ emission carried out with the help of $CO_2$ emission formula from the literature [2]. Based on existing mathematical model from the literature, motor powers found as follows:

$$P=\frac{Energy}{t},\ P=\frac{F*d}{t},\ P=F*v \tag{3.2.3.1}$$

$$\sum x=0, \sum y=0, \sum z=0 \tag{3.2.3.2}$$

$$\text{Rolling friction} = F_R=G*k_k \tag{3.2.3.3}$$

$$\text{Driving torque}=M_{Tv}=F*r \tag{3.2.3.4}$$

$$G=G_{crane}+G_{platform}+G_{safetyfactor} \tag{3.2.3.5}$$

$$M=F*d \tag{3.2.3.6}$$

$$G=G_{crane}+G_{platform}+G_{safetyfactor} \quad (3.2.3.7)$$

$$P_{total}=P_{vertical}+P_{horizontal} \quad (3.2.3.8)$$

$$\text{Energy Consumption}=W=P*t_{shift}*n_{wd}*n_{weeks}*\varepsilon \quad (3.2.3.9)$$

$$CO_2 \text{ emission yearly}=W*\rho \quad (3.2.3.10)$$

Table 3.11: Efficiency of the C-AS/RS.

| | CONFIGURATION | SYMBOL | UNIT | C-AS/RS |
|---|---|---|---|---|
| VARIABLES | NUMBER OF COLUMNS | $N_{columns}$ | amount | 10 |
| | NUMBER OF ROWS | $N_{rows}$ | amount | 10 |
| | VERTICAL CRANE VELOCITY | $V_{vertical}$ | m/s | 1 |
| | ROTATIONAL CRANE VELOCITY | $V_{horizontal}$ | degree/s | 18 |
| | RADIAL CRANE VELOCITY | $V_{radial}$ | m/s | 1 |
| PARAMETERS | NUMBER OF PRODUCTS | $N_{products}$ | amount | 100.0000 |
| | CELL LENGTH | $CELL_{length}$ | m | 5.5000 |
| | CELL HEIGHT | $CELL_{height}$ | m | 2.1000 |
| | CELL WIDTH | $CELL_{width}$ | m | 3.0000 |
| | CELL WEIGHT | $CELL_{weight}$ | m | 3200.0000 |
| | VERTICAL | $T_{Dwellvertical}$ | s | 25.0000 |
| | ROTATIONAL* / HORIZONTAL | $T_{Dwellrotational}$ | s | 10.0000 |
| | RADIAL | $T_{Dwellradial}$ | s | 15.0000 |
| OUTPUT | REQUIRED MOTOR POWER VERTICAL DIRECTION | $POWER_{lifting}$ | kW | 49.05 |
| | REQUIRED MOTOR POWER ROTATIONAL DIRECTION | $POWER_{rotational}$ | kW | 15.1074 |
| | TOTAL REQUIRED POWER | $POWER_{total}$ | kW | 64.1574 |
| | ENERGY CONSUMPTION | $W$ | kWh/yr | 272672.7 |
| | $CO_2$ EMISSION | $E_{CO2}$ | kgCO2/yr | 160876.9 |

C-AS/RS configuration is proposed and in order to create comprehensive results, same configuration with the R-AS/RS model applied to the C-AS/RS. Proposed C-AS/RS configuration's efficiency model created based on same parameters used for R-AS/RS. For the proposed system, which has ten number of rows and ten number of columns, configuration with one m/s crane speeds in vertical and radial directions and eighteen degree/s crane speed in rotational direction, requires 49.05 kW motor power in vertical direction and 15.1074 kW motor power in horizontal direction. System requires 64.1574 kW motor power to perform operations properly. Energy consumption and $CO_2$ emission analysis done by using Equation 3.2.3.9 and Equation 3.2.3.10. Analyze results presented in

Table 3.11.

# Chapter 4

# OPTIMIZATION OF PROPOSED CONFIGURATION FOR CAR PARKING C-AS/RS

## 4.1 GA Optimization

Genetic Algorithm has been used to find a feasible solution of this problem. Genetic algorithm is a search algorithm developed by John Holland in 1970. GA (Genetic Algorithm) is based on the Darwinian theory of evolution, "Survival of the fittest ". GA are search algorithms that imitate natural selection and natural genetic behavior. They combine survivors of the fittest among structures, with structured yet randomized information exchange to form a search algorithm. The basic GA is composed of a fitness function, a selection technique, a reproduction (cross over) and mutation operators with fixed probabilities. There are advantages of using GA for this problem are that GA is an intelligent random search method it searches in a feasible search area. The structure of functionality of GA allows a broader search in an area with feasible solutions. Necessary to use some simulation techniques to analyze material flow in the system in order to increase efficiency of the AS/RS. Results that are more accurate can be obtained without requiring highly costed and longtime consumed verifications for results [74]. Optimization is the determination of values for design variables, which minimize or maximize the objective, while satisfying all constraints [75]. For the proposed system, GA code is attached to the appendix chapter.

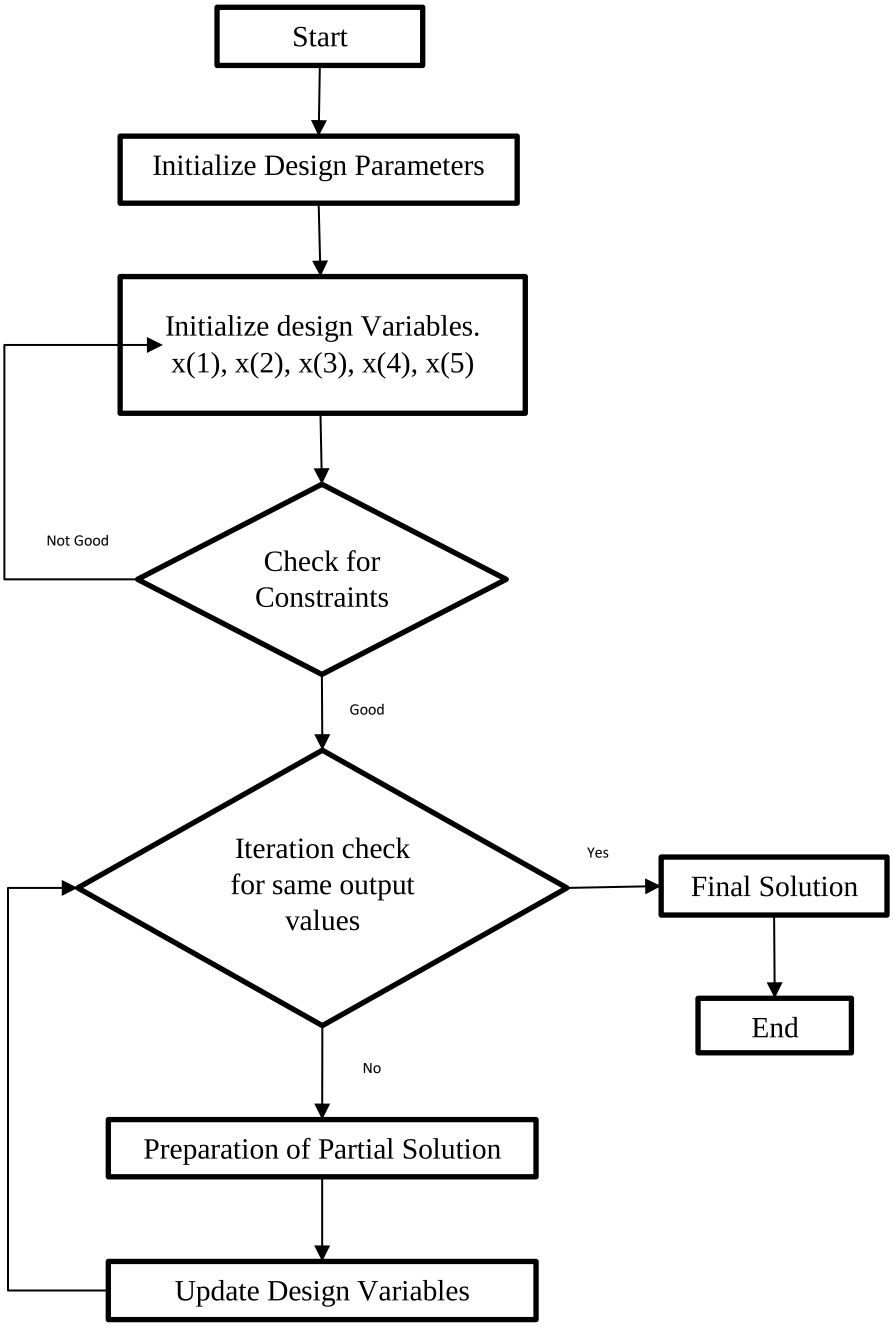



Figure 4.1: GA flowchart.

Specific design parameters and design variables are initialized to the MATLAB for optimization. After the satisfaction of the constrains that are mentioned in the chapter 3, variety of the iterations are created by MATLAB. Each iteration is representing different AS/RS configurations. Therefore, the user selects desired configuration that is providing enough number of SUV cars to retrieve and store in the system.

Multi-objective optimization with mixed integer optimization problem is carried out with the optimization of the decision variables x, $(N_{rows}, N_{columns}, V_{vertical}, V_{rotational}, V_{radial})$ in the minimum travel time and in the minimum total cost, where variables are:

$N_{rows}$ – Number of storage rows.

$N_{columns}$ – Number of storage columns.

$V_{vertical}$ – Vertical crane velocity.

$V_{rotational}$ – Rotational crane velocity.

$V_{radial}$ – Radial crane velocity.

It is aimed to search optimum configuration design related to specific crane velocities. The searched configuration design should satisfy the constraints presented below.

G1 - Constraint that limits the minimum storage capacity.

G2 - Constraint that limits the maximum storage capacity.

G3 - Constraint that limits the minimum length of the AS/RS

G4 - Constraint that limits the maximum length of the AS/RS.

G5 - Constraint that limits the minimum length of the AS/RS

G6 - Constraint that limits the maximum length of the AS/RS.

G7 - Constraint, which limits the crane space, respect to cell length.

The analysis for the proposed SUV car parking C-AS/RS determined by the specific parameters, which are:

**Geometric parameters:**

Table 4.1: Geometric parameters.

| Parameters | Symbol | Unit | Value |
|---|---|---|---|
| Maximum system height | $H_{max}$ | m | 70 |
| Minimum system height | $H_{min}$ | m | 20 |
| Maximum system diameter | $D_{max}$ | m | 60 |
| Minimum system diameter | $D_{min}$ | m | 20 |

Generally, system dimensions are determined with respect to loads that are being stored in the storage cells. Storage cell space is determined based on load dimensions and the space between load sides and cell walls called as clearance area. In the thesis, SUV car parking storage system designed. Therefore, for the load selection, SUV car dimensions taken as load dimension whereas, SUV car extensions such as baggage cover, doors and mirrors used to measure clearance areas between load and cell walls. As a result, maximum system dimension values created and presented in Table 4.1.

**Operational parameters of the storage rack and warehouse:**

Table 4.2: Operational parameters.

| Parameters | Symbol | Unit | Value |
|---|---|---|---|
| Maximum number of products | $N_{products}$ | amount | 110 |
| Minimum number of products | $N_{products}$ | amount | 90 |
| Number of cranes | $N_{cranes}$ | amount | 1 |
| Cell weight | $CELL_{weight}$ | kg | 3200 |
| Cell height | $CELL_{height}$ | m | 2.1 |
| Cell width | $CELL_{width}$ | m | 3 |
| Cell length | $CELL_{length}$ | m | 5.5 |
| Share for the warehouse | $D_z$ | % | 71 |
| Efficiency of the warehouse | $E$ | - | 0.8 |
| The emission factor | $p$ | - | 0.59 |
| Working hours in one shift | $T_{shift}$ | hours | 16 |
| Number of working days in one week | $n_{wd}$ | - | 5 |
| Number of weeks in a year | $n_{weeks}$ | - | 50 |
| Concrete thickness | $t_{concrete}$ | m | 0.1 |
| Clearance for roof | $CL_{roof}$ | m | 2.1 |
| Clearance for base | $CL_{base}$ | m | 2.1 |
| Clearance for rail | $CL_{raild}$ | m | 0.5 |
| Clearance for crane | $CL_{crane}$ | m | 1 |
| Clearance for safety | $CL_{safety}$ | m | 5.5 |
| Clearance for extension | $CL_{ext}$ | m | 0.5 |

Other operational parameters defined for the calculations. Warehouse and crane specifications imported from previous researches such as the emission factor and share of the warehouse. For the configuration design, a single crane utilized in the system that is practically enough to present how configuration design created in the study. Operational parameters shown in the Table 4.2.

**Cost parameters:**

Table 4.3: Cost parameters.

| Parameters | Symbol | Unit | Value |
|---|---|---|---|
| Cost of the land | $COST_1$ | $EURO/m^2$ | 500 |
| Cost of foundation | $COST_2$ | $EURO/m^2$ | 168 |
| Cost of the construction walls | $COST_3$ | $EURO/m^2$ | 23 |
| Cost of construction roof | $COST_4$ | $EURO/m^2$ | 25 |
| Cost of upright frames | $COST_5$ | $EURO/m^2$ | 30 |
| Cost of rack beams | $COST_6$ | $EURO/m^2$ | 23 |
| Cost of buffers | $COST_7$ | $EURO/piece$ | 200 |
| Cost of assembly | $COST_8$ | $EURO/PP$ | 10 |
| Cost of fire safety | $COST_9$ | $EURO/PP$ | 5 |
| Cost of air conditioning | $COST_{10}$ | $EURO/m^3$ | 10 |
| Cost of S/R machine | $COST_{11}$ | $EURO/piece$ | 431 |
| Cost of the picking aisle | $COST_{12}$ | $EURO/m$ | 50 |

Installation cost of the any type of system is essential for the manufacturers due to the economic issues. Although larger size enterprises can afford for more complex and costly high systems, middle size enterprises prefer low cost systems that are sufficient to their needs such as AS/RS. Therefore, total cost analysis created based on the cost parameters from the literature and they are representing the prices in 2017. By using the cost values, proposed design specifically created. Cost values presented in the Table 4.3.

The parameters used to create proposed design as well as finding optimized solution presented in Table 4.4.

## 4.2 Design Parameters

Table 4.4: Design Parameters for optimization.

| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Number of crane | $N_{crane}$ | amount | 1 |
| Number of aisle | $N_{aisle}$ | amount | 1 |
| Number of required crane | $S$ | amount | 1 |
| Number of items for a single storage compartment | $n$ | amount | 1 |
| Vertical speed | $T_{vertical}$ | m/s | 1 |
| Rotational speed | $T_{rotational}$ | degree/s | 18 |
| Radial speed | $T_{radial}$ | m/s | 1 |
| Share for warehouse building | $D_z$ | - | 71 |
| Warehouse efficiency | $E$ | - | 0.68 |
| Emission factor | $p$ | - | 0.59 |
| Working hours in one shift | $T_{shift}$ | hours | 16 |
| Number of working days in a week | $n_{wd}$ | days | 5 |
| Number of weeks in a year | $n_{weeks}$ | weeks | 50 |
| Required power for lifting | $POWER_{lifting}$ | kW | 30 |
| Required power for rotational | $POWER_{rotational}$ | kW | 1.5 |
| Required power for radial | $POWER_{radial}$ | kW | 1.5 |
| Land cost | $COST_1$ | EURO/m2 | 500.00 |
| Foundation cost | $COST_2$ | EURO/m2 | 168.00 |
| Wall cost | $COST_3$ | EURO/m2 | 23.00 |
| Roof cost | $COST_4$ | EURO/m2 | 25.00 |
| Upright frame cost | $COST_5$ | EURO/m | 30.00 |
| Supporting rack beam cost | $COST_6$ | EURO/m | 23.00 |
| Buffer cost | $COST_7$ | EURO/piece | 200.00 |
| Assembly cost | $COST_8$ | EURO/PP | 10.00 |
| Fire safety cost | $COST_9$ | EURO/PP | 5.00 |
| Air conditioning cost | $COST_{10}$ | EURO/m3 | 10.00 |
| Single aisle S/R machine cost | $COST_{11}$ | EURO/piece | 431,000.00 |
| Picking aisle cost | $COST_{12}$ | EURO/m | 50.00 |
| Cross aisle cost | $COST_{13}$ | EURO/piece | 50.00 |
| Clearance for roof | $CL_{roof}$ | m | 2.1 |
| Clearance for base | $CL_{base}$ | m | 2.1 |
| Clearance for crane | $CL_{crane}$ | m | 1 |
| Clearance for extension | $CL_{ext}$ | m | 0.5 |
| Clearance for rails | $CL_{rails}$ | m | 0.5 |
| Clearance for safety | $CL_{safety}$ | m | 5.5 |
| SUV car length | $SUV_{length}$ | m | 5.2 |
| SUV car height | $SUV_{height}$ | m | 2.25 |
| SUV car width | $SUV_{width}$ | m | 2 |
| SUV car weight | $SUV_{weight}$ | kg | 2200 |
| Cell length | $CELL_{length}$ | m | 5.5 |
| Cell height | $CELL_{height}$ | m | 2.1 |
| Cell width | $CELL_{width}$ | m | 3 |
| Dwell time at the vertical axis | $T_{dwellvertical}$ | s | 25 |
| Dwell time at the rotational axis | $T_{dwellrotational}$ | s | 10 |
| Dwell time at the radial axis | $T_{dwellradial}$ | s | 15 |

## 4.3 Design Variables

Table 4.5: Design variables for optimization.

| Variable | Symbol | Unit | Lower Bound | Upper Bound |
|---|---|---|---|---|
| Number of rows | $N_{rows}$ | amount | 1 | 100 |
| Number of columns | $N_{columns}$ | amount | 1 | 100 |
| Vertical Speed | $V_{vertical}$ | m/s | 0.1 | 1 |
| Rotational Speed*/ Horizontal Speed | $V_{rotational}$ * $/V_{horizontal}$ | degree/s* , m/s | 1* / 0.1 | 18* / 1 |
| Radial Speed | $V_{radial}$ | m/s | 0.1 | 3 |

## 4.4 Design Constraints

Table 4.6: Design constraints for optimization.

| Name | Symbol | Unit | Value |
|---|---|---|---|
| Min. required storage capacity | G1 | amount | $N_{rows}*N_{columns} \leq N_{products}$ |
| Max. required storage capacity | G2 | amount | $N_{rows}*N_{columns} \geq N_{products}$ |
| Min. system height | G3 | m | $H_{total} \leq H_{max}$ |
| Max. system height | G4 | m | $H_{min} \leq H_{total} \leq H_{max}$ |
| Min. system diameter*/width | G5 | m | $D_{min}(or\ W_{min}) \leq D_{total}(or\ W_{total})$ |
| Max. system diameter*/width | G6 | m | $D_{total}$(or $W_{total}$) ≤ D_ max (or $W_{max}$) |
| S/R machine space in the center* | G7 | m | $CELL_{length} \leq D_{inner}$ |

Design variables and design constraints are explicitly presented and the value of constraints are calculated due to the parameters. After constraint values calculated and they are satisfied for the proposed design, optimization is carried out by using GA technique.

Subject to the following constraints:

$$90 \leq x(1) * x(2) \qquad G1$$

$$x(1) * x(2) \leq 110 \qquad G2$$

$$24.2 - (x(1) * 2.1 + 0.5) = 0 \qquad G3$$

$$(x(1) * 2.1 + 0.5) - 66.8 = 0 \qquad G4$$

$$20 \leq \left(\frac{(2 * x(2) * 3.0 + 1)}{6.28} + 10.1\right) \qquad G5$$

$$\left(\frac{(2 * x(2) * 3 + 1)}{6.28} + 10.1\right) \leq 60 \qquad G6$$

$$5.818 - x(2) * 0.955 = 0 \qquad G7$$

Geometrical constraints are defined for the optimal design of AS/RS and presented as following.

## 4.5 Design Objective

Travel time in car parking systems relates to the movement of material handling devices such S/R machine with faster movement to provide faster and more efficient storage and retrieval. There are many ways of travel time calculation in the literature. For instance, some researchers have been used analytical travel time model approach and some others have been used discrete simulation approaches. Basically, travel time can be minimized whether by using efficient drives or by focusing on height to diameter configuration ratio. The design objective function is utilized to minimize expected travel time and stated as follows [3].

Travel time [minimize]:

$$E_{SC}=\left(1+\frac{b^2}{3}\right)*T \quad (4.5.1)$$

In car parking applications, Although the total cost mainly affected by floor, wall, roof, up-frame, buffer, assembly, fire protection and air ventilation costs, S/R machine cost is also affecting the total cost in terms of velocity features, capability to handle specific weight and motor specifications. Therefore, the design objective function is utilized to minimize total cost and stated as follows [63].

Total Cost [minimize]:

$$C_{total\ cost}=COST_{floor}+COST_{wall}+COST_{roof}+ COST_{upframe}+COST_{beam}+COST_{buffer}+ COST_{assembly}+COST_{fireprot}+COST_{airvent}+COST_{sr} \quad (4.5.2)$$

## 4.6 Result and Discussion

The analysis of genetic algorithm based optimization for the minimization of travel time and total cost presented above. Genetic algorithm is performed according to the given objectives (min. travel time, min. total cost), design variables, ($N_{rows}$, $N_{columns}$, $V_{vertical}$, $V_{rotational}$, $V_{radial}$ ) and parameters (G1, G2, G3, G4, G5, G6, G7). For the optimization, population size (n (pop) = 20, n (pop) = 40) and generation size (n (gen) = 100, n (gen) = 200) are set in the gaoptimset function. Obtained results from the GA optimization for min. travel time and min. total cost explicitly shown at the below. Min. travel time, minimum total cost and carbon footprint is presented in the thesis with the different population and generation sizes.

Table 4.7: Travel time optimization.

| | | PARAMETER | SYMBOL | UNIT | TRAVEL TIME OPTIMIZATION | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Population size=20, Generation size=100 | | | Population size=40, Generation size=200 | | |
| OBJECTIVES | | OPTIMIZED VALUE FOR OBJECTIVE | - | - | 118.9943558 | 119.0111794 | 118.9758617 | 118.97558 | 118.97649 | 118.97558 |
| | | EXPECTED TRAVEL TIME (SC) | E_SC | s | 118.9943558 | 119.0111794 | 118.9758617 | 118.97558 | 118.97649 | 118.97558 |
| | | EXPECTED TRAVEL TIME (DC) | E_DC | s | 170.8937252 | 170.915875 | 170.8678306 | 170.86744 | 170.86877 | 170.86744 |
| | | SINGLE COMMAND THROUGHPUT | THROUGHPUT_SC | operation/h | 30 | 30 | 30 | 30 | 30 | 30 |
| | | DUAL COMMAND THROUGHPUT | THROUGHPUT_DC | operation/h | 21 | 21 | 21 | 21 | 21 | 21 |
| | | TOTAL COST | TC | EUR | 2,376,161.50 | 2,671,642.04 | 3233232.069 | 2,735,862.44 | 2,671,642.04 | 3,814,298.58 |
| PARAMETERS | VARIABLES | NUMBER OF ROWS | N_rows | amount | 8 | 8 | 8 | 8 | 8 | 8 |
| | | NUMBER OF COLUMNS | N_columns | amount | 7 | 12 | 20 | 13 | 12 | 27 |
| | | VERTICAL VELOCITY | Vvertical | m/s | 0.99926 | 0.99827 | 1.00000 | 1.00000 | 0.99999 | 1.00000 |
| | | ROTATIONAL VELOCITY | Vrotational | degree/s | 17.99991 | 17.98951 | 17.99954 | 18.00000 | 17.99972 | 18.00000 |
| | | RADIAL VELOCITY | Vradial | m/s | 2.99748 | 2.99852 | 2.99999 | 3.00000 | 2.99979 | 3.00000 |
| | CLEARANCE | ROOF | CL_roof | m | 2.10000 | 2.10000 | 2.10000 | 2.10000 | 2.10000 | 2.10000 |
| | | BASE | CL_base | m | 2.10000 | 2.10000 | 2.10000 | 2.10000 | 2.10000 | 2.10000 |
| | | CRANE RAILS | CL_rails | m | 0.50000 | 0.50000 | 0.50000 | 0.50000 | 0.50000 | 0.50000 |
| | | SAFETY | CL_safety | m | 5.50000 | 5.50000 | 5.50000 | 5.50000 | 5.50000 | 5.50000 |
| | | CRANE | CL_crane | m | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | | EXTENSION | CL_ext | m | 0.50000 | 0.50000 | 0.50000 | 0.50000 | 0.50000 | 0.50000 |
| | | CONCRETE THICKNESS | t_concrete | m | 0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000 |
| | COST INITIALS | BUYING LAND | COST1 | EURO/m^2 | 500.00 | 500.00 | 500.00 | 500.00 | 500.00 | 500.00 |
| | | LAYING FOUNDATION | COST2 | EURO/m^2 | 168.00 | 168.00 | 168.00 | 168.00 | 168.00 | 168.00 |
| | | BUILDING WALLS | COST3 | EURO/m^2 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 |
| | | BUILDING ROOF | COST4 | EURO/m^2 | 25.00 | 25.00 | 25.00 | 25.00 | 25.00 | 25.00 |
| | | UPRIGHT FRAMES | COST5 | EURO/m | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 |
| | | BUYING RACK BEAMS | COST6 | EURO/m | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 |
| | | BUYING BUFFERS | COST7 | EURO/piece | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 |
| | | ASSEMBLY | COST8 | EURO/PP | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| | | FIRE SAFETY | COST9 | EURO/PP | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| | | AIR CONDITIONING | COST10 | EURO/m^3 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| | | S/R MACHINE COST | COST11 | EURO/piece | 1,500,000.00 | 1,500,000.00 | 1,500,000.00 | 1,500,000.00 | 1,500,000.00 | 1,500,000.00 |
| | | PICKING AISLE | COST12 | EURO/m | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 |
| | | CROSS AISLE | COST13 | EURO/piece | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 |
| OUTPUT | TRAVEL T. | LONGEST TRIP | T_longest | s | 154.56726 | 154.59907 | 154.53340 | 154.53333 | 154.53422 | 154.53333 |
| | | VERTICAL LONGEST TRAVEL TIME | T_vertical | s | 42.61304 | 42.63057 | 42.60003 | 42.60000 | 42.60011 | 42.60000 |
| | | ROTATIONAL LONGEST TRAVEL TIME | T_rotational | s | 30.00010 | 30.01165 | 30.00051 | 29.99999 | 30.00030 | 29.99999 |
| | | RADIAL LONGEST TRAVEL TIME | T_radial | s | 17.33529 | 17.33449 | 17.33334 | 17.33333 | 17.33350 | 17.33333 |
| | | STORAGE TIME | T | s | 42.61304 | 42.63057 | 42.60003 | 42.60000 | 42.60011 | 42.60000 |
| | CONFIGURATION | SYSTEM HEIGHT | H_total | m | 21.80000 | 21.80000 | 21.80000 | 21.80000 | 21.80000 | 21.80000 |
| | | SYSTEM DIAMETER | D_total | m | 29.00282 | 33.77747 | 41.41690 | 34.73240 | 33.77747 | 48.10141 |
| | | SYSTEM INNER DIAMETER | D_inner* | m | 7.00282 | 11.77747 | 19.41690 | 12.73240 | 11.77747 | 26.10141 |
| | | TOTAL CIRCUMFERENCE | CIR_total* | m | 91.11504 | 106.11504 | 130.11504 | 109.11504 | 106.11504 | 151.11504 |
| | | INNER CIRCUMFERENCE | CIR_inner* | m | 22.00000 | 37.00000 | 61.00000 | 40.00000 | 37.00000 | 82.00000 |
| | | SHAPE FACTOR | b | - | 0.70401 | 0.70399 | 0.70424 | 0.70423 | 0.70423 | 0.70423 |
| | | STORAGE CAPACITY | N_cells | amount | 56.00000 | 96.00000 | 160.00000 | 104.00000 | 96.00000 | 216.00000 |
| | | LAND AREA | A_land | m^2 | 660.64821 | 896.07427 | 1347.24048 | 947.45667 | 896.07427 | 1817.21163 |
| | | CONSTRUCTED AREA | A_constructed | m^2 | 622.13271 | 787.13271 | 1051.13271 | 820.13271 | 787.13271 | 1282.13271 |
| | | TOTAL VOLUME | V_total | m^3 | 14402.13092 | 19534.41908 | 29369.84252 | 20654.55531 | 19534.41908 | 39615.21353 |
| | | STORAGE VOLUME | V_storage | m^3 | 12256.01441 | 15506.51441 | 20707.31441 | 16156.61441 | 15506.51441 | 25258.01441 |
| | COST | FLOOR COST | COST_floor | EURO | 63,862.30 | 63,862.30 | 63,862.30 | 63,862.30 | 63,862.30 | 63,862.30 |
| | | WALL COST | COST_wall | EURO | 33,540.21 | 44,369.81 | 65,123.45 | 46,733.40 | 44,369.81 | 86,742.12 |
| | | ROOF COST | COST_roof | EURO | 21,029.09 | 28,522.93 | 42,884.00 | 30,158.48 | 28,522.93 | 57,843.64 |
| | | UPFRAME COST | COST_upframe | EURO | 5,232.00 | 8,502.00 | 13,734.00 | 9,156.00 | 8,502.00 | 18,312.00 |
| | | BEAM COST | COST_beam | EURO | 14,168.00 | 24,288.00 | 40,480.00 | 26,312.00 | 24,288.00 | 54,648.00 |
| | | BUFFER COST | COST_buffer | EURO | 400.00 | 400.00 | 400.00 | 400.00 | 400.00 | 400.00 |
| | | ASSEMBLY COST | COST_assembly | EURO | 560.00 | 960.00 | 1,600.00 | 1,040.00 | 960.00 | 2,160.00 |
| | | LAND COST | COST_land | EURO | 592,368.61 | 803,462.81 | 1,207,999.90 | 849,534.71 | 803,462.81 | 1,629,398.39 |
| | | WAREHOUSE COST | COST_warehouse | EURO | 118,431.59 | 136,755.03 | 171,869.74 | 140,754.17 | 136,755.03 | 208,448.06 |
| | | MATERIAL HANDLING COST | COST_mh | EURO | 20,360.00 | 34,150.00 | 56,214.00 | 36,908.00 | 34,150.00 | 75,520.00 |
| | | FIRE PROTECTION COST | COST_fireprot | EURO | 280.00 | 480.00 | 800.00 | 520.00 | 480.00 | 1,080.00 |
| | | AIR VENTILATION COST | COST_airvent | EURO | 144,021.31 | 195,344.19 | 293,698.43 | 206,545.55 | 195,344.19 | 396,152.14 |
| | | S/R MACHINE COST | COST_sr | EURO | 1,501,100.00 | 1,501,850.00 | 1,503,050.00 | 1,502,000.00 | 1,501,850.00 | 1,504,100.00 |
| CONSTRAINTS | | MIN. STORAGE CAPACITY | G1 | amount | -26.00000 | -6.00000 | -20.00000 | -233.00000 | -6.00000 | -164.00000 |
| | | MAX. STORAGE CAPACITY | G2 | amount | - | -6.27747 | - | - | -4.00000 | - |
| | | MIN SYSTEM HEIGHT | G3 | m | -2.45775 | -1.80000 | -9.14225 | -4.00000 | -1.80000 | -1.80000 |
| | | MAX. SYSTEM HEIGHT | G4 | m | -1.80000 | -48.20000 | -1.80000 | -46.00000 | -48.20000 | -48.20000 |
| | | MIN SYSTEM DIAMETER | G5 | m | -48.20000 | -13.77747 | -48.20000 | -37.65071 | -13.77747 | -33.83099 |
| | | MAX. SYSTEM DIAMETER | G6 | m | -9.95775 | -26.22253 | -16.64225 | -2.34929 | -26.22253 | -6.16901 |
| | | MIN. INNER DIAMETER | G7 | m | -30.04225 | -4.00000 | -23.35775 | -30.15071 | -6.27747 | -26.33099 |

If we look at the total cost optimization that is presented in Table 4.9. It is east to see that optimized value is total cost of the proposed design of AS/RS. Out of three different configuration, configuration of 10 x 6 has lowest total cost, which is 2,354,151.40 EURO. Depend on customer demand and number of products, appropriate design can be selected from the table.

Table 4.9table.

Table 4.10: Energy efficiency optimization.

| | PARAMETER | SYMBOL | UNIT | ENERGY CONSUMPTION OPTIMIZATION | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Population size=20, Generation size=10 | | | Population size=40, Generation size=20 | | |
| OBJECTIVES | OPTIMIZED VALUE FOR OBJECTIVE | W | kWh/yr | 13569.89372 | 13571.11437 | 13569.88896 | 14105.32247 | 13570.11873 | 13598.56214 |
| | EXPECTED TRAVEL TIME (SC) | E_SC | s | 3953.672602 | 3689.011366 | 3695.367563 | 1743.40554 | 3689.07532 | 3870.92972 |
| | TOTAL COST | TC | EUR | 2,376,161.50 | 2,590,868.08 | 4586526.471 | 2,370,132.26 | 2,434,055.67 | 2,887,257.44 |
| | ENERGY CONSUMPTION | W | kWh/yr | 8,006.24 | 8,006.96 | 8006.234489 | 8,322.14 | 8,006.37 | 8,023.15 |
| VARIABLES | NUMBER OF ROWS | N_rows | amount | 8 | 10 | 17 | 11 | 15 | 28 |
| | NUMBER OF COLUMNS | N_columns | amount | 7 | 10 | 30 | 6 | 6 | 9 |
| | VERTICAL VELOCITY | Vvertical | m/s | 0.10000 | 0.10000 | 0.10000 | 0.10172 | 0.10000 | 0.10021 |
| | ROTATIONAL VELOCITY | Vrotational | degree/s | 0.10000 | 0.10038 | 0.10000 | 0.23394 | 0.10005 | 0.10035 |
| | RADIAL VELOCITY | Vradial | m/s | 0.10001 | 1.03511 | 2.62440 | 0.23392 | 2.98031 | 0.15939 |
| OUTPUT | VERTICAL REQUIRED POWER | POWER_lifting | Kw | 4.91 | 4.91 | 4.91 | 4.99 | 4.91 | 4.92 |
| | ROTATIONAL REQUIRED POWER | POWER_rotational | Kw | 0.08 | 0.08 | 0.08 | 0.20 | 0.08 | 0.08 |
| | TOTAL REQUIRED POWER | POWER_total | Kw | 4.99 | 4.99 | 4.99 | 5.19 | 4.99 | 5.00 |
| | ENERGY CONSUMPTION | W | kWh/yr | 13,569.89 | 13,571.11 | 13,569.89 | 14,105.32 | 13,570.12 | 13,598.56 |
| | $CO_2$ EMISSION | CO2 | kg $CO_2$/yr | 8006.23730 | 8006.95748 | 8006.23449 | 8322.14026 | 8006.37005 | 8023.15166 |
| CONSTRAINTS | MIN. STORAGE CAPACITY | G1 | amount | -36.00000 | -9.00000 | -899.00000 | -34.00000 | 0.00000 | -65.00000 |
| | MAX. STORAGE CAPACITY | G2 | amount | -0.54789 | -5.32254 | -30.15071 | -1.50282 | -0.54789 | -5.32254 |
| | MIN SYSTEM HEIGHT | G3 | m | -4.00000 | -4.00000 | -43.60000 | -1.80000 | -17.20000 | -17.20000 |
| | MAX. SYSTEM HEIGHT | G4 | m | -46.00000 | -46.00000 | -6.40000 | -48.20000 | -32.80000 | -32.80000 |
| | MIN SYSTEM DIAMETER | G5 | m | -8.04789 | -12.82254 | -37.65071 | -9.00282 | -8.04789 | -12.82254 |
| | MAX. SYSTEM DIAMETER | G6 | m | -31.95211 | -27.17746 | -2.34929 | -30.99718 | -31.95211 | -27.17746 |
| | MIN. INNER DIAMETER | G7 | m | 0.00000 | -1.00000 | 0.00000 | 0.00000 | -10.00000 | 0.00000 |

Different C-AS/RS configurations obtained with different design variables. In order to minimize energy efficiency of the system, parameters that has essential impact on energy consumption minimized in proposed configurations. Therefore, configurations cannot be practically suitable for industrial proposes. However, C-AS/RS design optimized in term of energy efficiency and energy consumption and CO2 e mission values presented in Table 4.10.

Single objective optimization usually becomes insufficient for the automotive industry. Therefore, the aim is to create a system in which number of required products will accommodate and storage and retrieval times will be enough to operate certain number of products will be stored and retrieved in a certain time period whereas, installation cost will be less and affordable for the middle size enterprises. For this purpose, multi-objective optimization created and results presented in the Table 4.11. It can be seen that objective is to minimize weighted cost function which is including travel time and total cost.

Table 4.11In one hand, number of generations are set as 100 whereas; population size is set as 20. In this condition, there are three different configurations are created. If each configuration is reviewed in detail. It is easy to understand that optimized value is single command expected travel time and its value is 118.9943 seconds at minimum, shown as in Table 4.8.

# Table 4.8: Travel time optimization.

| | | PARAMETER | SYMBOL | UNIT | TRAVEL TIME OPTIMIZATION | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Population size=20, Generation size=100 | | | Population size=40, Generation size=200 | | |
| OBJECTIVES | | OPTIMIZED VALUE FOR OBJECTIVE | - | - | 118.9943558 | 119.0111794 | 118.9758617 | 118.97558 | 118.97649 | 118.97558 |
| | | EXPECTED TRAVEL TIME (SC) | E_SC | s | 118.9943558 | 119.0111794 | 118.9758617 | 118.97558 | 118.97649 | 118.97558 |
| | | EXPECTED TRAVEL TIME (DC) | E_DC | s | 170.8937252 | 170.915875 | 170.8678306 | 170.86744 | 170.86877 | 170.86744 |
| | | SINGLE COMMAND THROUGHPUT | THROUGHPUT_SC | operation/h | 30 | 30 | 30 | 30 | 30 | 30 |
| | | DUAL COMMAND THROUGHPUT | THROUGHPUT_DC | operation/h | 21 | 21 | 21 | 21 | 21 | 21 |
| | | TOTAL COST | TC | EUR | 2,376,161.50 | 2,671,642.04 | 3233232.069 | 2,735,862.44 | 2,671,642.04 | 3,814,298.58 |
| PARAMETERS | VARIABLES | NUMBER OF ROWS | N_rows | amount | 8 | 8 | 8 | 8 | 8 | 8 |
| | | NUMBER OF COLUMNS | N_columns | amount | 7 | 12 | 20 | 13 | 12 | 27 |
| | | VERTICAL VELOCITY | Vvertical | m/s | 0.99926 | 0.99827 | 1.00000 | 1.00000 | 0.99999 | 1.00000 |
| | | ROTATIONAL VELOCITY | Vrotational | degree/s | 17.99991 | 17.98951 | 17.99954 | 18.00000 | 17.99972 | 18.00000 |
| | | RADIAL VELOCITY | Vradial | m/s | 2.99748 | 2.99852 | 2.99999 | 3.00000 | 2.99979 | 3.00000 |
| | CLEARANCE | ROOF | CL_roof | m | 2.10000 | 2.10000 | 2.10000 | 2.10000 | 2.10000 | 2.10000 |
| | | BASE | CL_base | m | 2.10000 | 2.10000 | 2.10000 | 2.10000 | 2.10000 | 2.10000 |
| | | CRANE RAILS | CL_rails | m | 0.50000 | 0.50000 | 0.50000 | 0.50000 | 0.50000 | 0.50000 |
| | | SAFETY | CL_safety | m | 5.50000 | 5.50000 | 5.50000 | 5.50000 | 5.50000 | 5.50000 |
| | | CRANE | CL_crane | m | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | | EXTENSION | CL_ext | m | 0.50000 | 0.50000 | 0.50000 | 0.50000 | 0.50000 | 0.50000 |
| | | CONCRETE THICKNESS | t_concrete | m | 0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000 |
| | COST INITIALS | BUYING LAND | COST1 | EURO/m^2 | 500.00 | 500.00 | 500.00 | 500.00 | 500.00 | 500.00 |
| | | LAYING FOUNDATION | COST2 | EURO/m^2 | 168.00 | 168.00 | 168.00 | 168.00 | 168.00 | 168.00 |
| | | BUILDING WALLS | COST3 | EURO/m^2 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 |
| | | BUILDING ROOF | COST4 | EURO/m^2 | 25.00 | 25.00 | 25.00 | 25.00 | 25.00 | 25.00 |
| | | UPRIGHT FRAMES | COST5 | EURO/m | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 |
| | | BUYING RACK BEAMS | COST6 | EURO/m | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 |
| | | BUYING BUFFERS | COST7 | EURO/piece | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 |
| | | ASSEMBLY | COST8 | EURO/PP | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| | | FIRE SAFETY | COST9 | EURO/PP | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| | | AIR CONDITIONING | COST10 | EURO/m^3 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| | | S/R MACHINE COST | COST11 | EURO/piece | 1,500,000.00 | 1,500,000.00 | 1,500,000.00 | 1,500,000.00 | 1,500,000.00 | 1,500,000.00 |
| | | PICKING AISLE | COST12 | EURO/m | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 |
| | | CROSS AISLE | COST13 | EURO/piece | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 |
| OUTPUT | TRAVEL T. | LONGEST TRIP | T_longest | s | 154.56726 | 154.59907 | 154.53340 | 154.53333 | 154.53422 | 154.53333 |
| | | VERTICAL LONGEST TRAVEL TIME | T_vertical | s | 42.61304 | 42.63057 | 42.60003 | 42.60000 | 42.60011 | 42.60000 |
| | | ROTATIONAL LONGEST TRAVEL TIME | T_rotational | s | 30.00010 | 30.01165 | 30.00051 | 29.99999 | 30.00030 | 29.99999 |
| | | RADIAL LONGEST TRAVEL TIME | T_radial | s | 17.33529 | 17.33449 | 17.33334 | 17.33333 | 17.33350 | 17.33333 |
| | | STORAGE TIME | T | s | 42.61304 | 42.63057 | 42.60003 | 42.60000 | 42.60011 | 42.60000 |
| | CONFIGURATION | SYSTEM HEIGHT | H_total | m | 21.80000 | 21.80000 | 21.80000 | 21.80000 | 21.80000 | 21.80000 |
| | | SYSTEM DIAMETER | D_total | m | 29.00282 | 33.77747 | 41.41690 | 34.73240 | 33.77747 | 48.10141 |
| | | SYSTEM INNER DIAMETER | D_inner* | m | 7.00282 | 11.77747 | 19.41690 | 12.73240 | 11.77747 | 26.10141 |
| | | TOTAL CIRCUMFERENCE | CIR_total* | m | 91.11504 | 106.11504 | 130.11504 | 109.11504 | 106.11504 | 151.11504 |
| | | INNER CIRCUMFERENCE | CIR_inner* | m | 22.00000 | 37.00000 | 61.00000 | 40.00000 | 37.00000 | 82.00000 |
| | | SHAPE FACTOR | b | - | 0.70401 | 0.70399 | 0.70424 | 0.70423 | 0.70423 | 0.70423 |
| | | STORAGE CAPACITY | N_cells | amount | 56.00000 | 96.00000 | 160.00000 | 104.00000 | 96.00000 | 216.00000 |
| | | LAND AREA | A_land | m^2 | 660.64821 | 896.07427 | 1347.24048 | 947.45667 | 896.07427 | 1817.21163 |
| | | CONSTRUCTED AREA | A_constructed | m^2 | 622.13271 | 787.13271 | 1051.13271 | 820.13271 | 787.13271 | 1282.13271 |
| | | TOTAL VOLUME | V_total | m^3 | 14402.13092 | 19534.41908 | 29369.84252 | 20654.55531 | 19534.41908 | 39615.21353 |
| | | STORAGE VOLUME | V_storage | m^3 | 12256.01441 | 15506.51441 | 20707.31441 | 16156.61441 | 15506.51441 | 25258.01441 |
| | COST | FLOOR COST | COST_floor | EURO | 63,862.30 | 63,862.30 | 63,862.30 | 63,862.30 | 63,862.30 | 63,862.30 |
| | | WALL COST | COST_wall | EURO | 33,540.21 | 44,369.81 | 65,123.45 | 46,733.40 | 44,369.81 | 86,742.12 |
| | | ROOF COST | COST_roof | EURO | 21,029.09 | 28,522.93 | 42,884.00 | 30,158.48 | 28,522.93 | 57,843.64 |
| | | UPFRAME COST | COST_upframe | EURO | 5,232.00 | 8,502.00 | 13,734.00 | 9,156.00 | 8,502.00 | 18,312.00 |
| | | BEAM COST | COST_beam | EURO | 14,168.00 | 24,288.00 | 40,480.00 | 26,312.00 | 24,288.00 | 54,648.00 |
| | | BUFFER COST | COST_buffer | EURO | 400.00 | 400.00 | 400.00 | 400.00 | 400.00 | 400.00 |
| | | ASSEMBLY COST | COST_assembly | EURO | 560.00 | 960.00 | 1,600.00 | 1,040.00 | 960.00 | 2,160.00 |
| | | LAND COST | COST_land | EURO | 592,368.61 | 803,462.81 | 1,207,999.90 | 849,534.71 | 803,462.81 | 1,629,398.39 |
| | | WAREHOUSE COST | COST_warehouse | EURO | 118,431.59 | 136,755.03 | 171,869.74 | 140,754.17 | 136,755.03 | 208,448.06 |
| | | MATERIAL HANDLING COST | COST_mh | EURO | 20,360.00 | 34,150.00 | 56,214.00 | 36,908.00 | 34,150.00 | 75,520.00 |
| | | FIRE PROTECTION COST | COST_fireprot | EURO | 280.00 | 480.00 | 800.00 | 520.00 | 480.00 | 1,080.00 |
| | | AIR VENTILATION COST | COST_airvent | EURO | 144,021.31 | 195,344.19 | 293,698.43 | 206,545.55 | 195,344.19 | 396,152.14 |
| | | S/R MACHINE COST | COST_sr | EURO | 1,501,100.00 | 1,501,850.00 | 1,503,050.00 | 1,502,000.00 | 1,501,850.00 | 1,504,100.00 |
| CONSTRAINTS | | MIN. STORAGE CAPACITY | G1 | amount | -26.00000 | -6.00000 | -20.00000 | -233.00000 | -6.00000 | -164.00000 |
| | | MAX. STORAGE CAPACITY | G2 | amount | - | -6.27747 | - | - | -4.00000 | - |
| | | MIN SYSTEM HEIGHT | G3 | m | -2.45775 | -1.80000 | -9.14225 | -4.00000 | -1.80000 | -1.80000 |
| | | MAX. SYSTEM HEIGHT | G4 | m | -1.80000 | -48.20000 | -1.80000 | -46.00000 | -48.20000 | -48.20000 |
| | | MIN SYSTEM DIAMETER | G5 | m | -48.20000 | -13.77747 | -48.20000 | -37.65071 | -13.77747 | -33.83099 |
| | | MAX. SYSTEM DIAMETER | G6 | m | -9.95775 | -26.22253 | -16.64225 | -2.34929 | -26.22253 | -6.16901 |
| | | MIN. INNER DIAMETER | G7 | m | -30.04225 | -4.00000 | -23.35775 | -30.15071 | -6.27747 | -26.33099 |

If we look at the total cost optimization that is presented in Table 4.9. It is east to see that optimized value is total cost of the proposed design of AS/RS. Out of three different configuration, configuration of 10 x 6 has lowest total cost, which is 2,354,151.40 EURO. Depend on customer demand and number of products, appropriate design can be selected from the table.

Table 4.9: Total cost optimization.

| | | PARAMETER | SYMBOL | UNIT | TOTAL COST OPTIMIZATION | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Population size=20, Generation size=100 | | | Population size=40, Generation size=200 | | |
| OBJECTIVES | | OPTIMIZED VALUE FOR OBJECTIVE | - | - | 2,354,151.40 | 2,434,055.67 | 2,466,017.38 | 2,322,189.70 | 2434055.669 | 2,466,017.38 |
| | | EXPECTED SINGLE COMMAND TRAVEL TIME | E_SC | s | 168.2685195 | 156.4479416 | 169.9362105 | 134.48906 | 187.03225 | 156.47742 |
| | | EXPECTED DUAL COMMAND TRAVEL TIME | E_DC | s | 237.3563996 | 221.6738652 | 241.6170163 | 193.06055 | 266.95034 | 221.99797 |
| | | SINGLE COMMAND THROUGHPUT | THROUGHPUT_SC | operation/h | 21 | 23 | 21 | 26 | 19 | 23 |
| | | DUAL COMMAND THROUGHPUT | THROUGHPUT_DC | operation/h | 15 | 16 | 14 | 18 | 13 | 16 |
| | | TOTAL COST | TC | EUR | 2,354,151.40 | 2,434,055.67 | 2,466,017.38 | 2,322,189.70 | 2,434,055.67 | 2,466,017.38 |
| PARAMETERS | VARIABLES | NUMBER OF ROWS | N_rows | amount | 10 | 15 | 17 | 8 | 15 | 17 |
| | | NUMBER OF COLUMNS | N_columns | amount | 6 | 6 | 6 | 6 | 6 | 6 |
| | | VERTICAL VELOCITY | Vvertical | m/s | 0.95895 | 0.78900 | 0.72069 | 0.85301 | 0.64338 | 0.84179 |
| | | ROTATIONAL VELOCITY | Vrotational | degree/s | 4.65160 | 6.80101 | 10.67253 | 11.78275 | 8.25357 | 8.01083 |
| | | RADIAL VELOCITY | Vradial | m/s | 2.31231 | 2.83777 | 1.13127 | 1.66238 | 0.73337 | 2.22976 |
| | CLEARANCE | ROOF | CL_roof | m | 2.10000 | 2.10000 | 2.10000 | 2.10000 | 2.10000 | 2.10000 |
| | | BASE | CL_base | m | 2.10000 | 2.10000 | 2.10000 | 2.10000 | 2.10000 | 2.10000 |
| | | CRANE RAILS | CL_rails | m | 0.50000 | 0.50000 | 0.50000 | 0.50000 | 0.50000 | 0.50000 |
| | | SAFETY | CL_safety | m | 5.50000 | 5.50000 | 5.50000 | 5.50000 | 5.50000 | 5.50000 |
| | | CRANE | CL_crane | m | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | | EXTENSION | CL_ext | m | 0.50000 | 0.50000 | 0.50000 | 0.50000 | 0.50000 | 0.50000 |
| | | CONCRETE THICKNESS | t_concrete | m | 0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000 |
| | COST INITIALS | BUYING LAND | COST1 | EURO/m^2 | 500.00 | 500.00 | 500.00 | 500.00 | 500.00 | 500.00 |
| | | LAYING FOUNDATION | COST2 | EURO/m^2 | 168.00 | 168.00 | 168.00 | 168.00 | 168.00 | 168.00 |
| | | BUILDING WALLS | COST3 | EURO/m^2 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 |
| | | BUILDING ROOF | COST4 | EURO/m^2 | 25.00 | 25.00 | 25.00 | 25.00 | 25.00 | 25.00 |
| | | UPRIGHT FRAMES | COST5 | EURO/m | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 |
| | | BUYING RACK BEAMS | COST6 | EURO/m | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 |
| | | BUYING BUFFERS | COST7 | EURO/piece | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 |
| | | ASSEMBLY | COST8 | EURO/PP | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| | | FIRE SAFETY | COST9 | EURO/PP | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| | | AIR CONDITIONING | COST10 | EURO/m^3 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| | | S/R MACHINE COST | COST11 | EURO/piece | 1,500,000.00 | 1,500,000.00 | 1,500,000.00 | 1,500,000.00 | 1,500,000.00 | 1,500,000.00 |
| | | PICKING AISLE | COST12 | EURO/m | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 |
| | | CROSS AISLE | COST13 | EURO/piece | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 |
| OUTPUT | TRAVEL T. | LONGEST TRIP | T_longest | s | 167.99283 | 203.51674 | 238.54085 | 168.10883 | 250.76323 | 211.41520 |
| | | VERTICAL LONGEST TRAVEL TIME | T_vertical | s | 47.94185 | 66.82492 | 76.89491 | 45.63276 | 76.29168 | 69.42891 |
| | | ROTATIONAL LONGEST TRAVEL TIME | T_rotational | s | 87.39276 | 62.93333 | 43.73144 | 40.55313 | 53.61747 | 54.93914 |
| | | RADIAL LONGEST TRAVEL TIME | T_radial | s | 18.02728 | 17.46673 | 21.18776 | 19.21083 | 24.54497 | 18.13935 |
| | | STORAGE TIME | T | s | 87.39276 | 66.82492 | 76.89491 | 45.63276 | 76.29168 | 69.42891 |
| | CONFIGURATION | SYSTEM HEIGHT | H_total | m | 26.20000 | 37.20000 | 41.60000 | 21.80000 | 37.20000 | 41.60000 |
| | | SYSTEM DIAMETER | D_total | m | 28.04789 | 28.04789 | 28.04789 | 28.04789 | 28.04789 | 28.04789 |
| | | SYSTEM INNER DIAMETER | D_inner* | m | 6.04789 | 6.04789 | 6.04789 | 6.04789 | 6.04789 | 6.04789 |
| | | TOTAL CIRCUMFERENCE | CIR_total* | m | 88.11504 | 88.11504 | 88.11504 | 88.11504 | 88.11504 | 88.11504 |
| | | INNER CIRCUMFERENCE | CIR_inner* | m | 19.00000 | 19.00000 | 19.00000 | 19.00000 | 19.00000 | 19.00000 |
| | | SHAPE FACTOR | b | - | 0.54858 | 0.94176 | 0.56872 | 0.88868 | 0.70280 | 0.79130 |
| | | STORAGE CAPACITY | N_cells | amount | 60.00000 | 90.00000 | 102.00000 | 48.00000 | 90.00000 | 102.00000 |
| | | LAND AREA | A_land | m^2 | 617.86018 | 617.86018 | 617.86018 | 617.86018 | 617.86018 | 617.86018 |
| | | CONSTRUCTED AREA | A_constructed | m^2 | 589.13271 | 589.13271 | 589.13271 | 589.13271 | 589.13271 | 589.13271 |
| | | TOTAL VOLUME | V_total | m^3 | 16187.93667 | 22984.39863 | 25702.98342 | 13469.35189 | 22984.39863 | 25702.98342 |
| | | STORAGE VOLUME | V_storage | m^3 | 14198.09834 | 20678.55816 | 23270.74209 | 11605.91441 | 20678.55816 | 23270.74209 |
| | COST | FLOOR COST | COST_floor | EURO | 63,862.30 | 63,862.30 | 63,862.30 | 63,862.30 | 63,862.30 | 63,862.30 |
| | | WALL COST | COST_wall | EURO | 32,207.82 | 33,797.46 | 34,433.32 | 31,571.96 | 33,797.46 | 34,433.32 |
| | | ROOF COST | COST_roof | EURO | 19,667.10 | 19,667.10 | 19,667.10 | 19,667.10 | 19,667.10 | 19,667.10 |
| | | UPFRAME COST | COST_upframe | EURO | 5,502.00 | 7,812.00 | 8,736.00 | 4,578.00 | 7,812.00 | 8,736.00 |
| | | BEAM COST | COST_beam | EURO | 15,180.00 | 22,770.00 | 25,806.00 | 12,144.00 | 22,770.00 | 25,806.00 |
| | | BUFFER COST | COST_buffer | EURO | 400.00 | 400.00 | 400.00 | 400.00 | 400.00 | 400.00 |
| | | ASSEMBLY COST | COST_assembly | EURO | 600.00 | 900.00 | 1,020.00 | 480.00 | 900.00 | 1,020.00 |
| | | LAND COST | COST_land | EURO | 554,002.83 | 554,002.83 | 554,002.83 | 554,002.83 | 554,002.83 | 554,002.83 |
| | | WAREHOUSE COST | COST_warehouse | EURO | 115,737.21 | 117,326.86 | 117,962.72 | 115,101.35 | 117,326.86 | 117,962.72 |
| | | MATERIAL HANDLING COST | COST_mh | EURO | 21,682.00 | 31,882.00 | 35,962.00 | 17,602.00 | 31,882.00 | 35,962.00 |
| | | FIRE PROTECTION COST | COST_fireprot | EURO | 300.00 | 450.00 | 510.00 | 240.00 | 450.00 | 510.00 |
| | | AIR VENTILATION COST | COST_airvent | EURO | 161,879.37 | 229,843.99 | 257,029.83 | 134,693.52 | 229,843.99 | 257,029.83 |
| | | S/R MACHINE COST | COST_sr | EURO | 1,500,950.00 | 1,500,950.00 | 1,500,950.00 | 1,500,950.00 | 1,500,950.00 | 1,500,950.00 |
| CONSTRAINTS | | MIN. STORAGE CAPACITY | G1 | amount | -42.00000 | 18.00000 | -87.00000 | -42.00000 | 0.00000 | -2.00000 |
| | | MAX. STORAGE CAPACITY | G2 | amount | - | -3.41268 | - | - | -10.00000 | - |
| | | MIN SYSTEM HEIGHT | G3 | m | -0.54789 | -1.80000 | -5.32254 | -1.80000 | -17.20000 | -21.60000 |
| | | MAX. SYSTEM HEIGHT | G4 | m | -1.80000 | -48.20000 | -21.60000 | -48.20000 | -32.80000 | -28.40000 |
| | | MIN SYSTEM DIAMETER | G5 | m | -48.20000 | -10.91268 | -28.40000 | -8.04789 | -8.04789 | -8.04789 |
| | | MAX. SYSTEM DIAMETER | G6 | m | -8.04789 | -29.08732 | -12.82254 | -31.95211 | -31.95211 | -31.95211 |
| | | MIN. INNER DIAMETER | G7 | m | -31.95211 | -28.00000 | -27.17746 | -0.54789 | -0.54789 | -0.54789 |

Table 4.10: Energy efficiency optimization.

| | PARAMETER | SYMBOL | UNIT | ENERGY CONSUMPTION OPTIMIZATION | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Population size=20, Generation size=10 | | | Population size=40, Generation size=20 | | |
| OBJECTIVES | OPTIMIZED VALUE FOR OBJECTIVE | W | kWh/yr | 13569.89372 | 13571.11437 | 13569.88896 | 14105.32247 | 13570.11873 | 13598.56214 |
| | EXPECTED TRAVEL TIME (SC) | E_SC | s | 3953.672602 | 3689.011366 | 3695.367563 | 1743.40554 | 3689.07532 | 3870.92972 |
| | TOTAL COST | TC | EUR | 2,376,161.50 | 2,590,868.08 | 4586526.471 | 2,370,132.26 | 2,434,055.67 | 2,887,257.44 |
| | ENERGY CONSUMPTION | W | kWh/yr | 8,006.24 | 8,006.96 | 8006.234489 | 8,322.14 | 8,006.37 | 8,023.15 |
| VARIABLES | NUMBER OF ROWS | N_rows | amount | 8 | 10 | 17 | 11 | 15 | 28 |
| | NUMBER OF COLUMNS | N_columns | amount | 7 | 10 | 30 | 6 | 6 | 9 |
| | VERTICAL VELOCITY | Vvertical | m/s | 0.10000 | 0.10000 | 0.10000 | 0.10172 | 0.10000 | 0.10021 |
| | ROTATIONAL VELOCITY | Vrotational | degree/s | 0.10000 | 0.10038 | 0.10000 | 0.23394 | 0.10005 | 0.10035 |
| | RADIAL VELOCITY | Vradial | m/s | 0.10001 | 1.03511 | 2.62440 | 0.23392 | 2.98031 | 0.15939 |
| OUTPUT | VERTICAL REQUIRED POWER | POWER_lifting | Kw | 4.91 | 4.91 | 4.91 | 4.99 | 4.91 | 4.92 |
| | ROTATIONAL REQUIRED POWER | POWER_rotational | Kw | 0.08 | 0.08 | 0.08 | 0.20 | 0.08 | 0.08 |
| | TOTAL REQUIRED POWER | POWER_total | Kw | 4.99 | 4.99 | 4.99 | 5.19 | 4.99 | 5.00 |
| | ENERGY CONSUMPTION | W | kWh/yr | 13,569.89 | 13,571.11 | 13,569.89 | 14,105.32 | 13,570.12 | 13,598.56 |
| | $CO_2$ EMISSION | CO2 | kg $CO_2$/yr | 8006.23730 | 8006.95748 | 8006.23449 | 8322.14026 | 8006.37005 | 8023.15166 |
| CONSTRAINTS | MIN. STORAGE CAPACITY | G1 | amount | -36.00000 | -9.00000 | -899.00000 | -34.00000 | 0.00000 | -65.00000 |
| | MAX. STORAGE CAPACITY | G2 | amount | -0.54789 | -5.32254 | -30.15071 | -1.50282 | -0.54789 | -5.32254 |
| | MIN SYSTEM HEIGHT | G3 | m | -4.00000 | -4.00000 | -43.60000 | -1.80000 | -17.20000 | -17.20000 |
| | MAX. SYSTEM HEIGHT | G4 | m | -46.00000 | -46.00000 | -6.40000 | -48.20000 | -32.80000 | -32.80000 |
| | MIN SYSTEM DIAMETER | G5 | m | -8.04789 | -12.82254 | -37.65071 | -9.00282 | -8.04789 | -12.82254 |
| | MAX. SYSTEM DIAMETER | G6 | m | -31.95211 | -27.17746 | -2.34929 | -30.99718 | -31.95211 | -27.17746 |
| | MIN. INNER DIAMETER | G7 | m | 0.00000 | -1.00000 | 0.00000 | 0.00000 | -10.00000 | 0.00000 |

Different C-AS/RS configurations obtained with different design variables. In order to minimize energy efficiency of the system, parameters that has essential impact on energy consumption minimized in proposed configurations. Therefore, configurations cannot be practically suitable for industrial proposes. However, C-AS/RS design optimized in term of energy efficiency and energy consumption and $CO_2$ e mission values presented in Table 4.10.

Single objective optimization usually becomes insufficient for the automotive industry. Therefore, the aim is to create a system in which number of required products will accommodate and storage and retrieval times will be enough to operate certain number of products will be stored and retrieved in a certain time period whereas, installation cost will be less and affordable for the middle size enterprises. For this purpose, multi-objective optimization created and results presented in the Table 4.11. It can be seen that objective is to minimize weighted cost function which is including travel time and total cost.

Table 4.11: Multi-objective optimization.

| | | PARAMETER | SYMBOL | UNIT | MULTI OBJECTIVE OPTIMIZATION | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Population size=20, Generation size=100 | | | Population size=40, Generation size=200 | | |
| OBJECTIVES | | OPTIMIZED VALUE FOR OBJECTIVE | - | - | 9225.168331 | 9229.100317 | 9227.652483 | 9,320.11053 | 9317.463932 | 9225.176136 |
| | | EXPECTED SINGLE COMMAND TRAVEL TIME | E_SC | s | 122.7167199 | 123.5569136 | 128.53036 | 217.65892 | 211.9205286 | 122.7245248 |
| | | EXPECTED DUAL COMMAND TRAVEL TIME | E_DC | s | 175.8342755 | 176.9843053 | 183.5489389 | 302.36540 | 295.0680508 | 175.8452474 |
| | | SINGLE COMMAND THROUGHPUT | THROUGHPUT_SC | operation/h | 29 | 29 | 28 | 16 | 16 | 29 |
| | | DUAL COMMAND THROUGHPUT | THROUGHPUT_DC | operation/h | 20 | 20 | 19 | 11 | 12 | 20 |
| | | TOTAL COST | TC | EURO | 2529032.21966 | 2590868.07514 | 2462442.45310 | 2529032.21966 | 2590868.07514 | 2529032.21966 |
| | | ENERGY CONSUMPTION | | | 89760.00000 | 89760.00000 | 89760.00000 | 89760.00000 | 89760.00000 | 89760.00000 |
| | | $CO_2$ EMISSION | | | 52,958.40 | 52,958.40 | 52,958.40 | 52,958.40 | 52,958.40 | 52,958.40 |
| PARAMETERS | VARIABLES | NUMBER OF ROWS | N_rows | amount | 10 | 10 | 13 | 10 | 10 | 10 |
| | | NUMBER OF COLUMNS | N_columns | amount | 9 | 10 | 7 | 9 | 10 | 9 |
| | | VERTICAL VELOCITY | Vvertical | m/s | 0.99999 | 0.96881 | 1.00000 | 0.18414 | 0.76907 | 0.99995 |
| | | ROTATIONAL VELOCITY | Vrotational | degree/s | 17.99958 | 17.90356 | 17.99999 | 17.73912 | 2.87561 | 17.98604 |
| | | RADIAL VELOCITY | Vradial | m/s | 2.99998 | 2.94266 | 3.00000 | 2.52935 | 2.90322 | 2.99976 |
| | CLEARANCE | ROOF | CL_roof | m | 2.10000 | 2.10000 | 2.10000 | 2.10000 | 2.10000 | 2.10000 |
| | | BASE | CL_base | m | 2.10000 | 2.10000 | 2.10000 | 2.10000 | 2.10000 | 2.10000 |
| | | CRANE RAILS | CL_rails | m | 0.50000 | 0.50000 | 0.50000 | 0.50000 | 0.50000 | 0.50000 |
| | | SAFETY | CL_safety | m | 5.50000 | 5.50000 | 5.50000 | 5.50000 | 5.50000 | 5.50000 |
| | | CRANE | CL_crane | m | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| | | EXTENSION | CL_ext | m | 0.50000 | 0.50000 | 0.50000 | 0.50000 | 0.50000 | 0.50000 |
| | | CONCRETE THICKNESS | t_concrete | m | 0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000 | 0.10000 |
| | COST INITIALS | BUYING LAND | COST1 | EURO/m^2 | 500.00 | 500.00 | 500.00 | 500.00 | 500.00 | 500.00 |
| | | LAYING FOUNDATION | COST2 | EURO/m^2 | 168.00 | 168.00 | 168.00 | 168.00 | 168.00 | 168.00 |
| | | BUILDING WALLS | COST3 | EURO/m^2 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 |
| | | BUILDING ROOF | COST4 | EURO/m^2 | 25.00 | 25.00 | 25.00 | 25.00 | 25.00 | 25.00 |
| | | UPRIGHT FRAMES | COST5 | EURO/m | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 |
| | | BUYING RACK BEAMS | COST6 | EURO/m | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 |
| | | BUYING BUFFERS | COST7 | EURO/piece | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 |
| | | ASSEMBLY | COST8 | EURO/PP | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| | | FIRE SAFETY | COST9 | EURO/PP | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| | | AIR CONDITIONING | COST10 | EURO/m^3 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| | | S/R MACHINE | COST11 | EURO/piece | 1,500,000.00 | 1,500,000.00 | 1,500,000.00 | 1,500,000.00 | 1,500,000.00 | 1,500,000.00 |
| | | PICKING AISLE | COST12 | EURO/m | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 |
| | | CROSS AISLE | COST13 | EURO/piece | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 |
| OUTPUT | TRAVEL T. | LONGEST TRIP | T_longest | s | 163.33376 | 164.93169 | 176.53336 | 360.01291 | 176.85628 | 163.33609 |
| | | VERTICAL LONGEST TRAVEL TIME | T_vertical | s | 47.00019 | 47.70824 | 53.60001 | 144.47145 | 53.60590 | 47.00101 |
| | | ROTATIONAL LONGEST TRAVEL TIME | T_rotational | s | 30.00046 | 30.10773 | 30.00000 | 30.29412 | 135.19078 | 30.01551 |
| | | RADIAL LONGEST TRAVEL TIME | T_radial | s | 17.33335 | 17.37880 | 17.33333 | 17.76750 | 17.41112 | 17.33352 |
| | | STORAGE TIME | T | s | 47.00019 | 47.70824 | 53.60001 | 144.47145 | 135.19078 | 47.00101 |
| | CONFIGURATION | SYSTEM HEIGHT | H_total | m | 26.20000 | 26.20000 | 32.80000 | 26.20000 | 26.20000 | 26.20000 |
| | | SYSTEM DIAMETER | D_total | m | 30.91268 | 31.86761 | 29.00282 | 30.91268 | 31.86761 | 30.91268 |
| | | SYSTEM INNER DIAMETER | D_inner* | m | 8.91268 | 9.86761 | 7.00282 | 8.91268 | 9.86761 | 8.91268 |
| | | TOTAL CIRCUMFERENCE | CIR_total* | m | 97.11504 | 100.11504 | 91.11504 | 97.11504 | 100.11504 | 97.11504 |
| | | INNER CIRCUMFERENCE | CIR_inner* | m | 28.00000 | 31.00000 | 22.00000 | 28.00000 | 31.00000 | 28.00000 |
| | | SHAPE FACTOR | b | - | 0.63830 | 0.63108 | 0.55970 | 0.20969 | 0.39652 | 0.63861 |
| | | STORAGE CAPACITY | N_cells | amount | 90.00000 | 100.00000 | 91.00000 | 90.00000 | 100.00000 | 90.00000 |
| | | LAND AREA | A_land | m^2 | 750.52145 | 797.60666 | 660.64821 | 750.52145 | 797.60666 | 750.52145 |
| | | CONSTRUCTED AREA | A_constructed | m^2 | 688.13271 | 721.13271 | 622.13271 | 688.13271 | 721.13271 | 688.13271 |
| | | TOTAL VOLUME | V_total | m^3 | 19663.66196 | 20897.29452 | 21669.26120 | 19663.66196 | 20897.29452 | 19663.66196 |
| | | STORAGE VOLUME | V_storage | m^3 | 16583.99834 | 17379.29834 | 19099.47423 | 16583.99834 | 17379.29834 | 16583.99834 |
| | COST | FLOOR COST | COST_floor | EURO | 63,862.30 | 63,862.30 | 63,862.30 | 63,862.30 | 63,862.30 | 63,862.30 |
| | | WALL COST | COST_wall | EURO | 38,310.23 | 40,476.15 | 35,129.85 | 38,310.23 | 40,476.15 | 38,310.23 |
| | | ROOF COST | COST_roof | EURO | 23,889.84 | 25,388.61 | 21,029.09 | 23,889.84 | 25,388.61 | 23,889.84 |
| | | UPFRAME COST | COST_upframe | EURO | 7,860.00 | 8,646.00 | 7,872.00 | 7,860.00 | 8,646.00 | 7,860.00 |
| | | BEAM COST | COST_beam | EURO | 22,770.00 | 25,300.00 | 23,023.00 | 22,770.00 | 25,300.00 | 22,770.00 |
| | | BUFFER COST | COST_buffer | EURO | 400.00 | 400.00 | 400.00 | 400.00 | 400.00 | 400.00 |
| | | ASSEMBLY COST | COST_assembly | EURO | 900.00 | 1,000.00 | 910.00 | 900.00 | 1,000.00 | 900.00 |
| | | LAND COST | COST_land | EURO | 672,953.23 | 715,172.07 | 592,368.61 | 672,953.23 | 715,172.07 | 672,953.23 |
| | | WAREHOUSE COST | COST_warehouse | EURO | 126,062.37 | 129,727.06 | 120,021.23 | 126,062.37 | 129,727.06 | 126,062.37 |
| | | MATERIAL HANDLING COST | COST_mh | EURO | 31,930.00 | 35,346.00 | 32,205.00 | 31,930.00 | 35,346.00 | 31,930.00 |
| | | FIRE PROTECTION COST | COST_fireprot | EURO | 450.00 | 500.00 | 455.00 | 450.00 | 500.00 | 450.00 |
| | | AIR VENTILATION COST | COST_airvent | EURO | 196,636.62 | 208,972.95 | 216,692.61 | 196,636.62 | 208,972.95 | 196,636.62 |
| | | S/R MACHINE COST | COST_sr | EURO | 1,501,400.00 | 1,501,550.00 | 1,501,100.00 | 1,501,400.00 | 1,501,550.00 | 1,501,400.00 |
| CONSTRAINTS | | MIN. STORAGE CAPACITY | G1 | amount | 0.00000 | 0.00000 | -1.00000 | 0.00000 | 9.00000 | 0.00000 |
| | | MAX. STORAGE CAPACITY | G2 | amount | -3.41268 | -3.41268 | -1.50282 | -3.41268 | -3.41268 | -3.41268 |
| | | MIN SYSTEM HEIGHT | G3 | m | -6.20000 | -6.20000 | -12.80000 | -6.20000 | -4.00000 | -6.20000 |
| | | MAX. SYSTEM HEIGHT | G4 | m | -43.80000 | -43.80000 | -37.20000 | -43.80000 | -46.00000 | -43.80000 |
| | | MIN SYSTEM DIAMETER | G5 | m | -10.91268 | -10.91268 | -9.00282 | -10.91268 | -10.91268 | -10.91268 |
| | | MAX. SYSTEM DIAMETER | G6 | m | -29.08732 | -29.08732 | -30.99718 | -29.08732 | -29.08732 | -29.08732 |
| | | MIN. INNER DIAMETER | G7 | Operation/h | 0.00000 | -10.00000 | -9.00000 | -10.00000 | -19.00000 | -10.00000 |

In the other hand, number of generations selected as 200 whereas, population size selected as 40. Therefore, there are three more configuration design of AS/RS is being created and presented above in the tables. Generation and population sizes affect the non-gradient direct search detail. In other words, as the number of generation and population changes, exploration and exploitation border increases or decreases.

In the Table 4.8, travel time values are same in each configuration. Therefore, we can conclude that for the travel time optimization, there is no need to deep search. However, Table 4.9 shows that optimized total cost found as 2,322,189.70 EURO, Table 4.11 displays that optimized value found as 9225.1761 in which number of generations is 200 and population size is 40.

Proposed SUV car parking C-AS/RS configurations created with respect to weighted cost function. Weighted cost function consist of three objectives that are travel time, total cost and energy consumption. The aim is to find appropriate configuration for SUV car parking C-AS/RS in the industrial enterprises. Comparison between C-AS/RS and R-AS/RS in terms of travel time, total cost and $CO_2$ emission shown in Table 4.12, Table 4.13. From the tables, we can conclude that 10 number of rows and 10 number of columns configuration of C-AS/RS requires 2,618,157.04 EURO to install. It is able to perform 25 number of operations for single command, 17 number of operations for dual command in one hour. Therefore, System can perform operations with the travel time of 141.3830 seconds. System creates 160,876.9 kg.$CO_2$/year $CO_2$ emission every year to the atmosphere. After the optimization of the 10 number of rows and 10 number of columns configuration, total cost minimized to 2,590,868.07 EURO, travel time minimized to 118.32 seconds and $CO_2$ emission minimized to 52,958.40 kg.CO/year. In other words, total cost, travel time and $CO_2$ emission is minimized %1.05, %16.31 and %67 respectively. For the detailed information and optimization values, plot matrices and pareto charts are presented in the appendices chapter.

Table 4.12: R-AS/RS, C-AS/RS and optimized C-AS/RS comparison in term of travel time.

| | CONFIGURATION | SYMBOL | UNIT | R-AS/RS | | C-AS/RS | | OPTIMIZED SYSTEM CONFIGURATION OF C-AS/RS | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Alternative 1 | Alternative 2 | Alternative 1 | Alternative 2 | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 | Alternative 6 |
| VARIABLES | NUMBER OF COLUMNS | N_columns | amount | 10 | 20 | 10 | 20 | 8 | 8 | 8 | 8 | 8 | 8 |
| | NUMBER OF ROWS | N_rows | amount | 10 | 20 | 10 | 20 | 7 | 12 | 20 | 13 | 12 | 27 |
| | NUMBER OF PRODUCTS | N_products | amount | 100 | 400 | 100 | 400 | 56 | 96 | 160 | 104 | 96 | 216 |
| | VERTICAL CRANE VELOCITY | V_vertical | m/s | 1 | 1 | 1 | 1 | 0.99926 | 0.99827 | 1.00000 | 1.00000 | 0.99999 | 1.00000 |
| | HORIZONTAL CRANE VELOCITY | V_horizontal | m/s | 1 | 1 | 36 | 36 | 17.99991 | 17.98951 | 17.99954 | 18.00000 | 17.99972 | 18.00000 |
| | RADIAL CRANE VELOCITY | V_radial | m/s | 1 | 1 | 1 | 1 | 2.99748 | 2.99852 | 2.99999 | 3.00000 | 2.99979 | 3.00000 |
| PARAMETERS | CELL LENGTH | CELL_length | m | 5.5000 | 5.5000 | 5.5000 | 5.5000 | 5.5000 | 5.5000 | 5.5000 | 5.5000 | 5.5000 | 5.5000 |
| | CELL HEIGHT | CELL_height | m | 2.1000 | 2.1000 | 2.1000 | 2.1000 | 2.1000 | 2.1000 | 2.1000 | 2.1000 | 2.1000 | 2.1000 |
| | CELL WIDTH | CELL_width | m | 3.0000 | 3.0000 | 3.0000 | 3.0000 | 3.0000 | 3.0000 | 3.0000 | 3.0000 | 3.0000 | 3.0000 |
| | CELL WEIGHT | CELL_weight | m | 3200 | 3200 | 3200 | 3200 | 3200 | 3200 | 3200 | 3200 | 3200 | 3200 |
| | VERTICAL DWELL TIME | T_Dwellvertical | s | 25.0000 | 25.0000 | 25.0000 | 25.0000 | 25.0000 | 25.0000 | 25.0000 | 25.0000 | 25.0000 | 25.0000 |
| | HORIZONTAL DWELL TIME | T_Dwellhorizontal | s | 25.0000 | 25.0000 | 10.0000 | 10.0000 | 10.0000 | 10.0000 | 10.0000 | 10.0000 | 10.0000 | 10.0000 |
| | RADIAL DWELL TIME | T_Dwellradial | s | 15.0000 | 15.0000 | 15.0000 | 15.0000 | 15.0000 | 15.0000 | 15.0000 | 15.0000 | 15.0000 | 15.0000 |
| OUTPUT | LONGEST TRIP | | s | 206.0000 | 268.0000 | 182.0000 | 226.0000 | 154.56726 | 154.59907 | 154.53340 | 154.53333 | 154.53422 | 154.53333 |
| | EXPECTED TRAVEL TIME CONTINUOUS | E_SC | s | 159.4802 | 195.6333 | 141.3830 | 161.3478 | 118.9943558 | 119.0111794 | 118.9758617 | 118.97558 | 118.97649 | 118.97558 |
| | EXPECTED TRAVEL TIME CONTINUOUS | E_DC | s | 228.3928 | 277.0981 | 203.8337 | 230.3327 | 170.8937252 | 170.915875 | 170.8678306 | 170.86744 | 170.86877 | 170.86744 |
| | VERTICAL LONGEST TRIP | T_vertical | s | 47.0000 | 69.0000 | 47.0000 | 69.0000 | 42.61304 | 42.63057 | 42.60003 | 42.60000 | 42.60011 | 42.60000 |
| | HORIZONTAL LONGEST TRIP | T_rotational | s | 59.0000 | 90.0000 | 30.0000 | 30.0000 | 30.00010 | 30.01165 | 30.00051 | 29.99999 | 30.00030 | 29.99999 |
| | RADIAL TRIP (LOADING/UNLOADING) | T_radial | s | 22.0000 | 22.0000 | 22.0000 | 22.0000 | 17.33529 | 17.33449 | 17.33334 | 17.33333 | 17.33350 | 17.33333 |
| | STORAGE TIME | T | s | 59.0000 | 90.0000 | 47.0000 | 69.0000 | 42.61304 | 42.63057 | 42.60003 | 42.60000 | 42.60011 | 42.60000 |
| | THROUGHPUT FOR SINGLE COMMAND | THROUGHPUTsc | operation/h | 22 | 18 | 25 | 22 | 30 | 30 | 30 | 30 | 30 | 30 |
| | THROUGHPUT FOR DUAL COMMAND | THROUGHPUTdc | operation/h | 15 | 12 | 17 | 15 | 21 | 21 | 21 | 21 | 21 | 21 |
| | TOTAL COST | TC | EURO | 2,618,157.04 | 3,973,805.59 | 2,590,868.08 | 2,651,114.57 | 2,376,161.50 | 2,671,642.04 | 3,233,232.07 | 2,735,862.44 | 2,671,642.04 | 3,814,298.58 |

Table 4.13: R-AS/RS, C-AS/RS and optimized C-AS/RS comparison in term of total cost.

| | CONFIGURATION | SYMBOL | UNIT | R-AS/RS | | C-AS/RS | | OPTIMIZED SYSTEM CONFIGURATION OF C-AS/RS | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Alternative 1 | Alternative 2 | Alternative 1 | Alternative 2 | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 | Alternative 6 |
| VARIABLES | NUMBER OF COLUMNS | N_columns | amount | 10 | 20 | 10 | 20 | 10 | 15 | 17 | 8 | 15 | 17 |
| | NUMBER OF ROWS | N_rows | amount | 10 | 20 | 10 | 20 | 6 | 6 | 6 | 6 | 6 | 6 |
| | VERTICAL CRANE VELOCITY | V_vertical | m/s | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 0.95895 | 0.78900 | 0.72069 | 0.85301 | 0.64338 | 0.84179 |
| | HORIZONTAL CRANE VELOCITY | V_horizontal | m/s | 1.0000 | 1.0000 | 36.0000 | 36.0000 | 4.65160 | 6.80101 | 10.67253 | 11.78275 | 8.25357 | 8.01083 |
| OUTPUT | RADIAL CRANE VELOCITY | V_radial | m/s | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 2.31231 | 2.83777 | 1.13127 | 1.66238 | 0.73337 | 2.22976 |
| | SYSTEM HEIGHT | H_total | m | 26.2000 | 48.2000 | 26.2000 | 48.2000 | 26.20000 | 37.20000 | 41.60000 | 21.80000 | 37.20000 | 41.60000 |
| | SYSTEM WIDTH, SYSTEM DIAMETER | W_total | m | 23.5000 | 23.5000 | - | - | - | - | - | - | - | - |
| | SYSTEM LENGTH | L_total, D_total | m | 37.0000 | 68.0000 | 31.8676 | 41.4169 | 28.04789 | 28.04789 | 28.04789 | 28.04789 | 28.04789 | 28.04789 |
| | SHAPE FACTOR | b | - | 0.7966 | 0.7667 | 0.6383 | 0.4348 | 0.54858 | 0.94176 | 0.56872 | 0.88868 | 0.70280 | 0.79130 |
| | NUMBER OF STORAGE CELLS | N_cells | amount | 100 | 400 | 100 | 400 | 60.00000 | 90.00000 | 102.00000 | 48.00000 | 90.00000 | 102.00000 |
| | LAND AREA | A_land | m^2 | 869.5000 | 1598.0000 | 797.6067 | 1347.2405 | 617.86018 | 617.86018 | 617.86018 | 617.86018 | 617.86018 | 617.86018 |
| | CONSTRUCTED AREA | A_constructed | m^2 | 344.1000 | 688.2000 | 721.1327 | 1051.1327 | 589.13271 | 589.13271 | 589.13271 | 589.13271 | 589.13271 | 589.13271 |
| | TOTAL VOLUME | V_total | m^3 | 22780.9000 | 77023.6000 | 20897.2945 | 64936.9913 | 16187.93667 | 22984.39863 | 25702.98342 | 13469.35189 | 22984.39863 | 25702.98342 |
| | STORAGE VOLUME | V_storage | m^3 | 8292.8100 | 31726.0200 | 17379.2983 | 48457.2180 | 14198.09834 | 20678.55816 | 23270.74209 | 11605.91441 | 20678.55816 | 23270.74209 |
| | FLOOR COST | C_floor | EURO | 146,076.00 | 268,464.00 | 63,862.30 | 60,821.23 | 63,862.30 | 63,862.30 | 63,862.30 | 63,862.30 | 63,862.30 | 63,862.30 |
| | WALL COST | C_walls | EURO | 72,914.60 | 202,873.80 | 40,476.15 | 149,866.52 | 32,207.82 | 33,797.46 | 34,433.32 | 31,571.96 | 33,797.46 | 34,433.32 |
| | ROOF COST | C_roof | EURO | 21,737.50 | 39,950.00 | 25,388.61 | 85,767.99 | 19,667.10 | 19,667.10 | 19,667.10 | 19,667.10 | 19,667.10 | 19,667.10 |
| | UPFRAME COST | C_upframe | EURO | 8,646.00 | 30,366.00 | 8,646.00 | 30,366.00 | 5,502.00 | 7,812.00 | 8,736.00 | 4,578.00 | 7,812.00 | 8,736.00 |
| | SUPPORTING BEAM COST | C_beam | EURO | 25,300.00 | 101,200.00 | 25,300.00 | 154,000.00 | 15,180.00 | 22,770.00 | 25,806.00 | 12,144.00 | 22,770.00 | 25,806.00 |
| | BUFFER COST | C_buffer | EURO | 400.00 | 400.00 | 400.00 | 400.00 | 400.00 | 400.00 | 400.00 | 400.00 | 400.00 | 400.00 |
| | ASSEMBLY COST | C_assembly | EURO | 1,000.00 | 4,000.00 | 1,000.00 | 2,000.00 | 600.00 | 900.00 | 1,020.00 | 480.00 | 900.00 | 1,020.00 |
| | LAND COST | C_land | EURO | 612,323.94 | 1,051,315.79 | 715,172.07 | 338,557.87 | 554,002.83 | 554,002.83 | 554,002.83 | 554,002.83 | 554,002.83 | 554,002.83 |
| | WAREHOUSE BUILDING | C_mh | EURO | 240,728.10 | 511,287.80 | 129,727.06 | 296,455.75 | 115,737.21 | 117,326.86 | 117,962.72 | 115,101.35 | 117,326.86 | 117,962.72 |
| | STORAGE CONSTRUCTION | C_warehouse | EURO | 35,346.00 | 135,966.00 | 35,346.00 | 186,766.00 | 21,682.00 | 31,882.00 | 35,962.00 | 17,602.00 | 31,882.00 | 35,962.00 |
| | FIRE PROTECTION COST | C_fireprot | EURO | 500.00 | 2,000.00 | 500.00 | 2,000.00 | 300.00 | 450.00 | 510.00 | 240.00 | 450.00 | 510.00 |
| | AIR VENTILATION | C_airvent | EURO | 227,809.00 | 770,236.00 | 208,972.95 | 324,684.96 | 161,879.37 | 229,843.99 | 257,029.83 | 134,693.52 | 229,843.99 | 257,029.83 |
| | S/R MACHINE COST | C_sr | EURO | 1,501,850.00 | 1,503,400.00 | 1,501,550.00 | 1,503,050.00 | 1,500,950.00 | 1,500,950.00 | 1,500,950.00 | 1,500,950.00 | 1,500,950.00 | 1,500,950.00 |
| | TOTAL COST | C_total | EURO | 2,618,157.04 | 3,973,805.59 | 2,590,868.08 | 2,651,114.57 | 2,354,151.40 | 2,434,055.67 | 2,466,017.38 | 2,322,189.70 | 2,434,055.67 | 2,466,017.38 |

Design objectives affected by design variables with same ratio. In other words, objectives equally covered by the design variables. Sensitivity graphs are presented in appendices. It can be seen from the sensitivity graphs that travel time, total cost and $CO_2$ objectives are having almost the rectangular shape in the histogram. Rectangular trend displays that each variable has the equal amount of effect on travel time, total cost and $CO_2$.

In addition, pareto matrix for travel time and total cost is presented in Figure 4.2. Best configuration solution is highlighted in the figure.

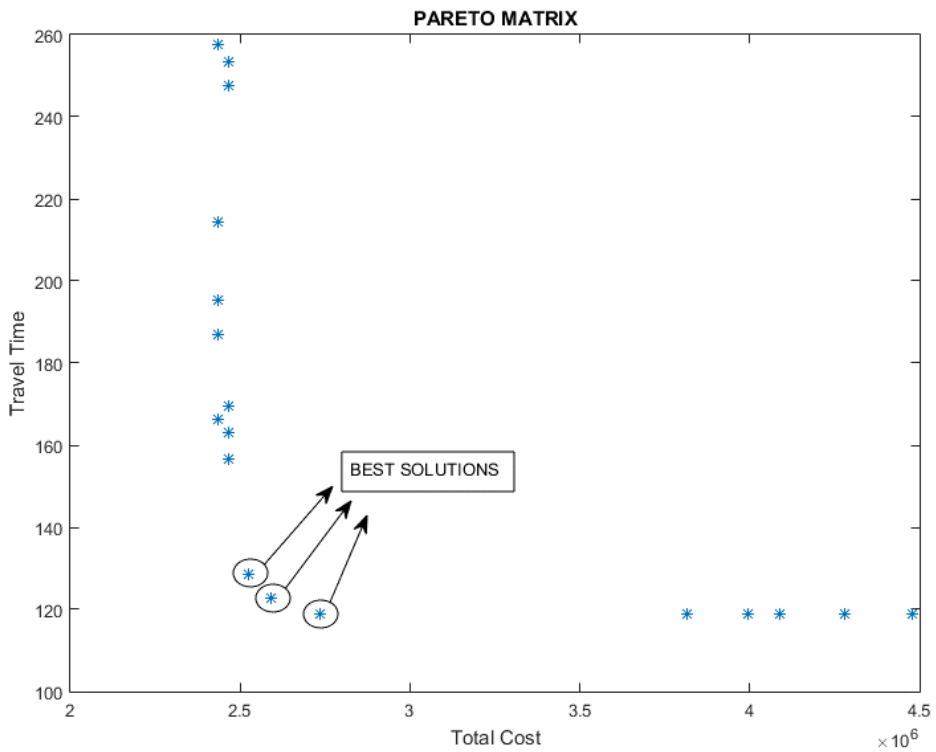



Figure 4.2: Pareto matrix.

# Chapter 5

# CONCLUSION

## 5.1 Impact of the Research

Optimization of various AS/RS configurations has been carried out by many researches around the world. Storage systems are broadly utilized in distribution centers as subsystem for production area. Previous research efforts have mainly focused on the design and optimization of rectangular AS/RS configurations, however, there is still a gap of research on the design and optimization of circular AS/RS especially  for car parking applications. Recently AS/RSs are implemented in the automotive factories due to improved safety, better inventory control, effective landscape utilization, minimal cost and improved efficiency resulting in a net decrease in the travel time of the cranes and increase of  the throughput capacity.

Generally, AS/RS installation is preferred to overcome three major problems; First, reduction in inventory levels of AS/RS while satisfying the customer requirements in a way that is forced to adopt various and continuously developing technologies by manufacturing enterprises. Second, space consumption design problem that brings out minimization on investment cost, discounted operation cost and maintenance costs under volumetric, space and environmental constraints. The last problem is minimization in travel time and carbon footprint consumption in order to provide sustainable system. Due to the high installation cost and inflexibility of the AS/RS, configuration design is critical for optimal AS/RS.

Various AS/RS configurations for car parking have been analyzed. The proposed configuration is based on a single aisle; single S/R machine; single deep rack storage system. Random storage assignment policy is applied for the proposed system. Configuration of the storage structure (ratio of lenght to height) is used for design decisions in order to create travel time and cost model of the C-AS/RS. The design objectives are to minimize travel time, minimize carbon footprint, and minimize the total cost, under the constraints for system height, system diameter and storage capacity. The number of rows, number of columns, vertical, rotational and radial velocities of the S/R machine are taken as the decision variables.

A mixed integer multi-objective optimization problem for the proposed SUV car parking is formulated to be optimized using Genetic Algorithm (GA), which is a non-gradient, direct search. a metaheuristic optimization method, well suited for this class of problems. Different configurations are created and then compared in terms of continuous rack. Optimization results show that travel time, throughput capacity, and the total cost have been optimized.

## 5.2 Future Research

One of the important AS/RS problem is Storage and retrieval operations to be completed in a faster way with less land occupation. The proposed C-AS/RS design carried out in this thesis to minimize SUV car storage and retrieval time while minimizing the land occupation and minimize the installation cost while maximizing the throughput. SUV Car Parking C-AS/RS can be utilized at car distribution centers, airports, cities and automotive industries as it's proposed in the thesis. C-AS/RS configuration can be modified depend on the demanding requirements. In the study, one aisle and a single S/R machine serving for the storage and retrieval process. However, number of aisles and number of S/R machines can be taken as design variables and dwell point policy can be modified by class based storage system with single or dual sided aisle for optimization in order to create system that is more complex. Moreover, there can be different cranes in each row and with the load transfer between cranes, storage and retrieval operations can be more complex for the AS/RS system in which various type of products can be stored based on class based storage system. Travel time optimization can be carried out by optimizing scheduling as well and it can be done as a future work. System can be transformed to flow rack C-AS/RS. As an optimization technique, Ant Colony Optimization (ACO) is recommended and can be applied as further research to proposed car parking C-AS/RS model.

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# APPENDICES

# Appendix A: GA Optimization Results and Histograms

## Travel Time Minimization

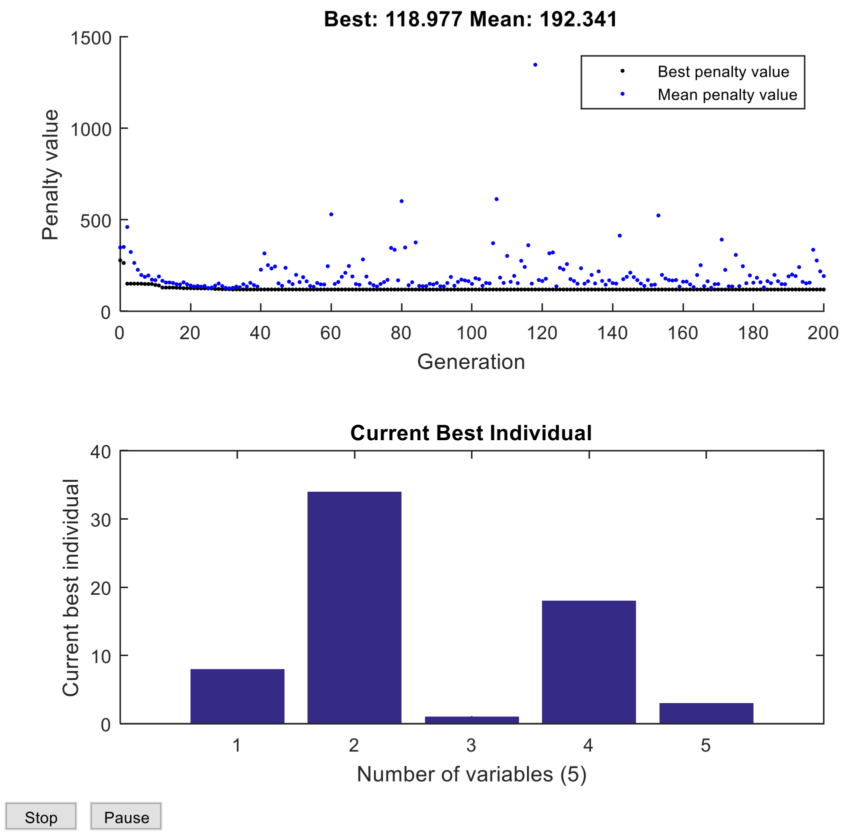


Figure A.1: Travel time optimization run: 1.

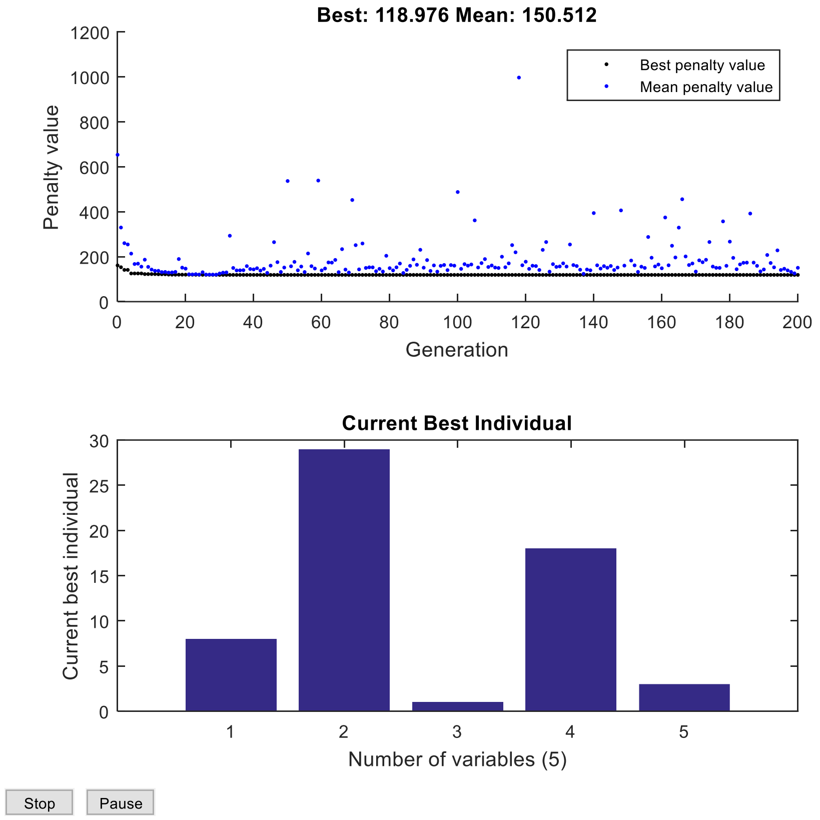


Figure A.2: Travel time optimization run: 2.

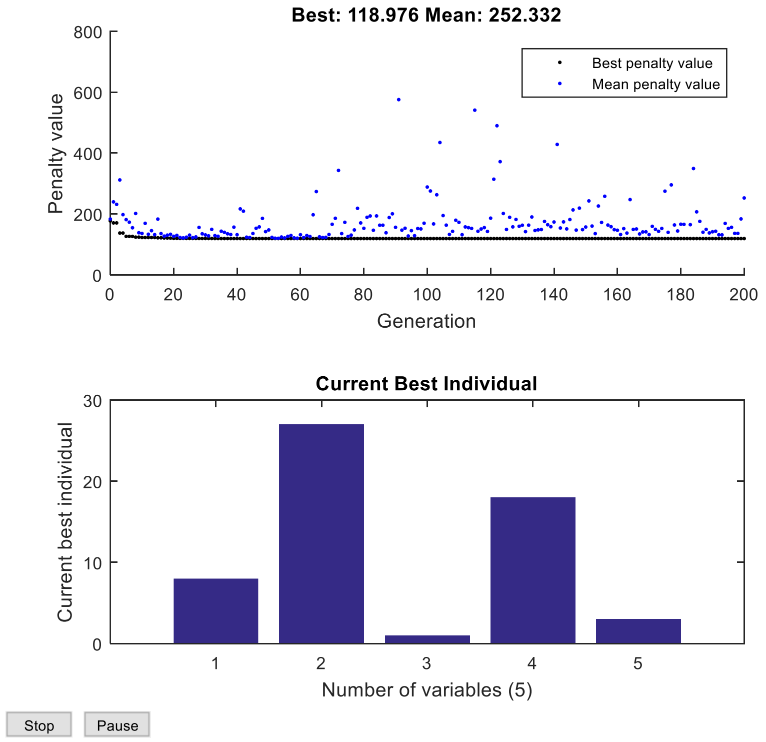


Figure A.3: Travel time optimization run: 3.

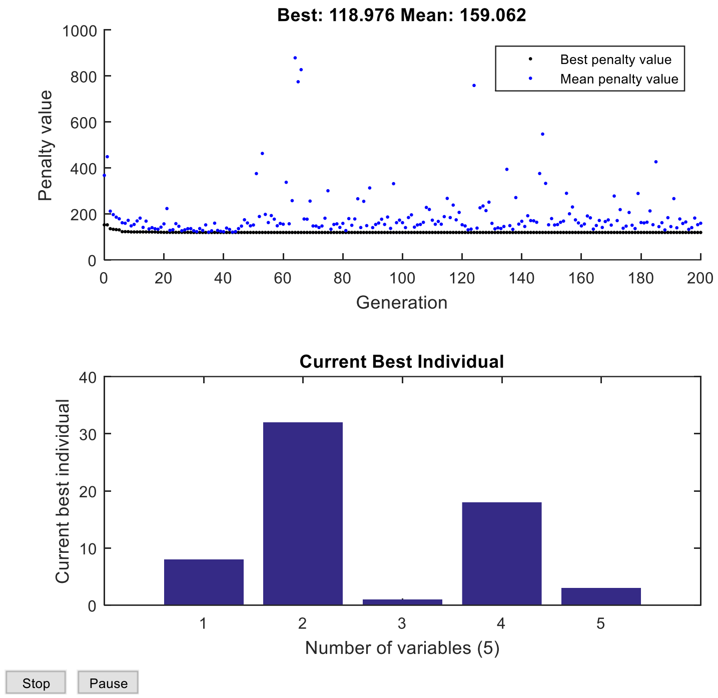

Figure A.4: Travel time optimization run: 4.

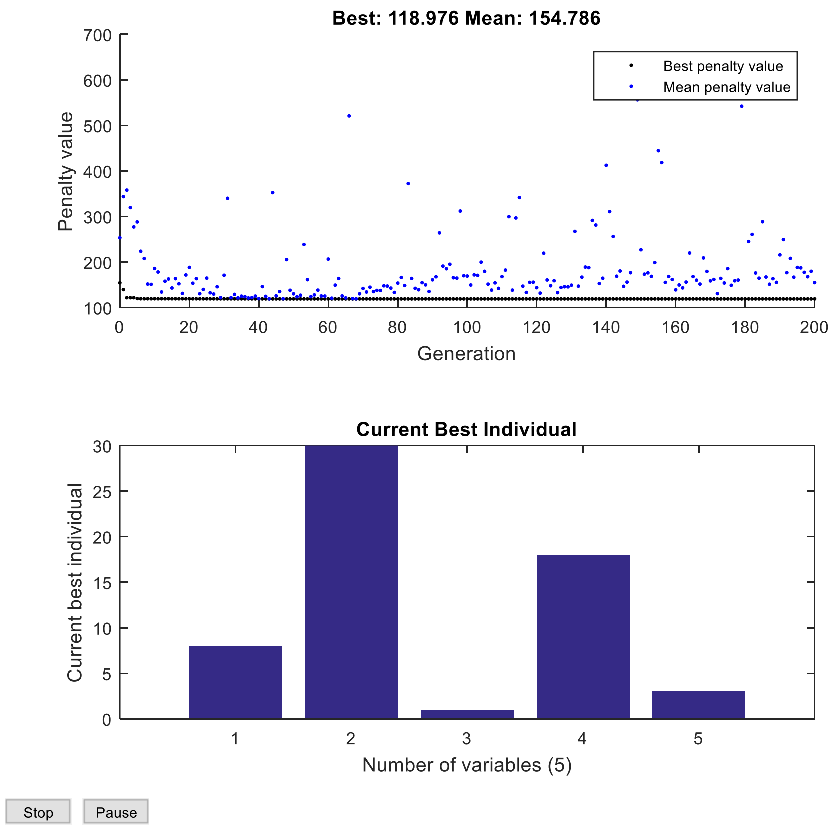

Figure A.5: Travel time optimization run: 5.

# Throughput Maximization

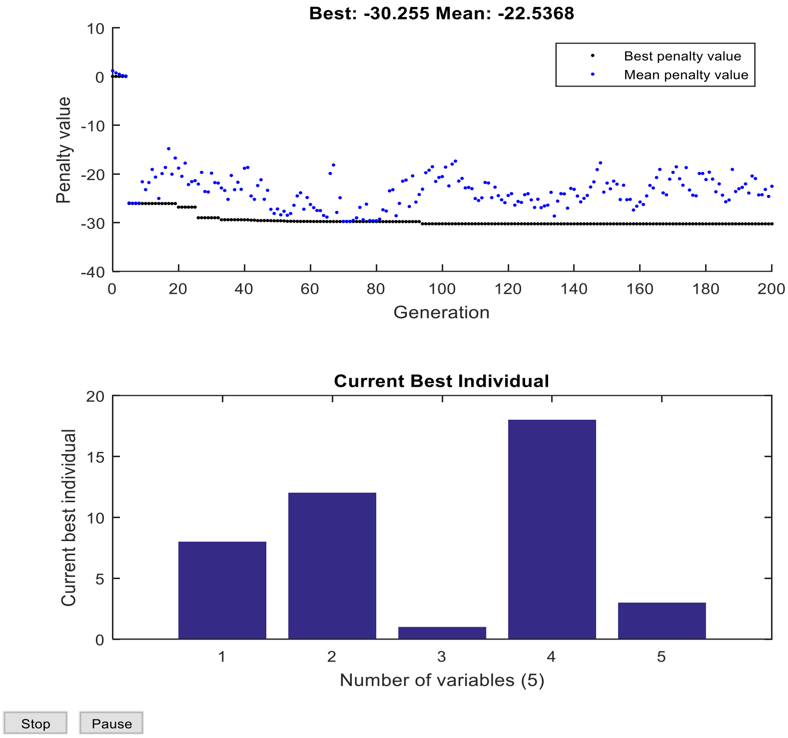


Figure A.6: Throughput optimization run: 1.

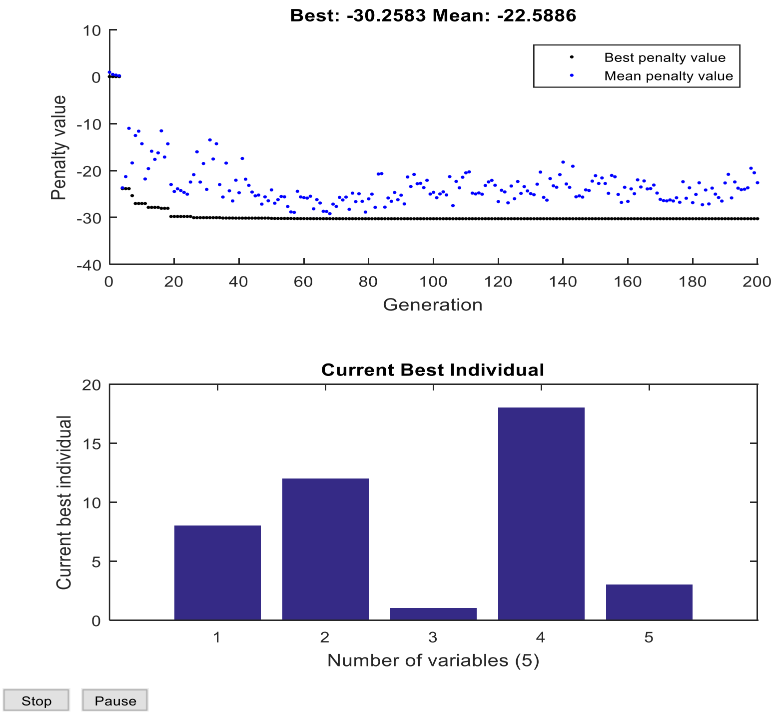


Figure A.7: Throughput optimization run: 2.

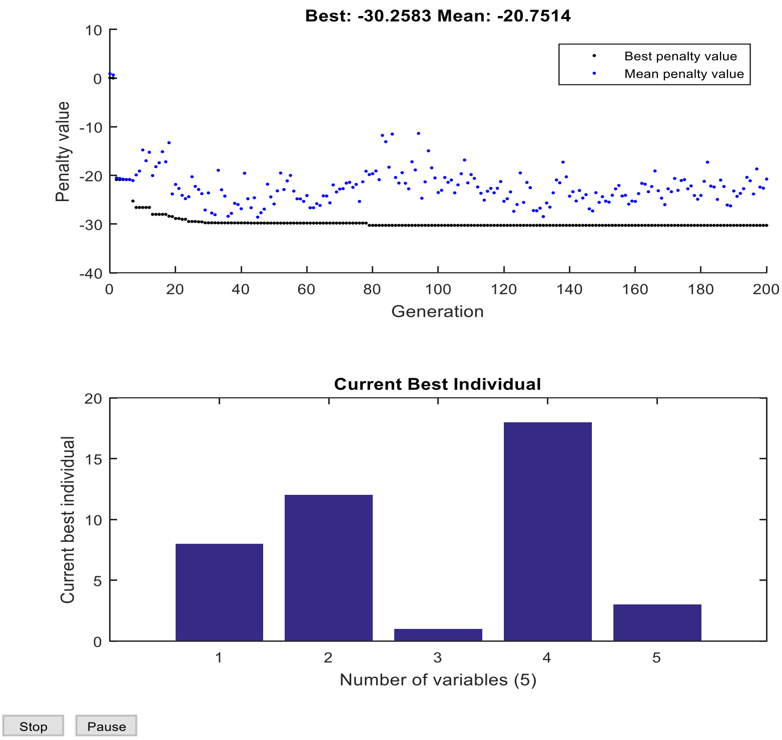


Figure A.8: Throughput optimization run: 3.

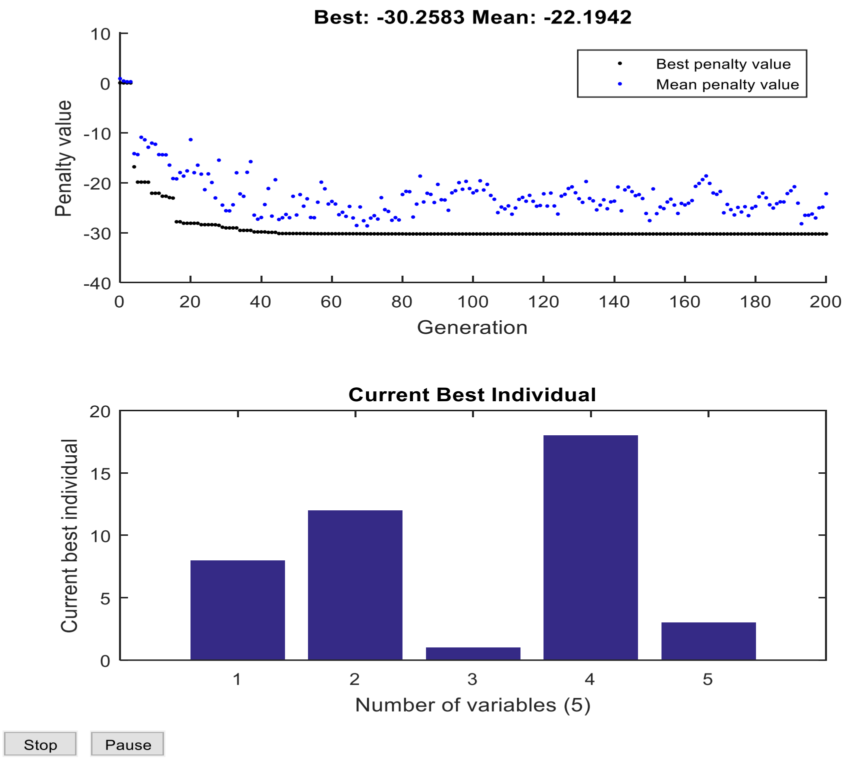


Figure A.9: Throughput optimization run: 4.

## Total Cost Minimization

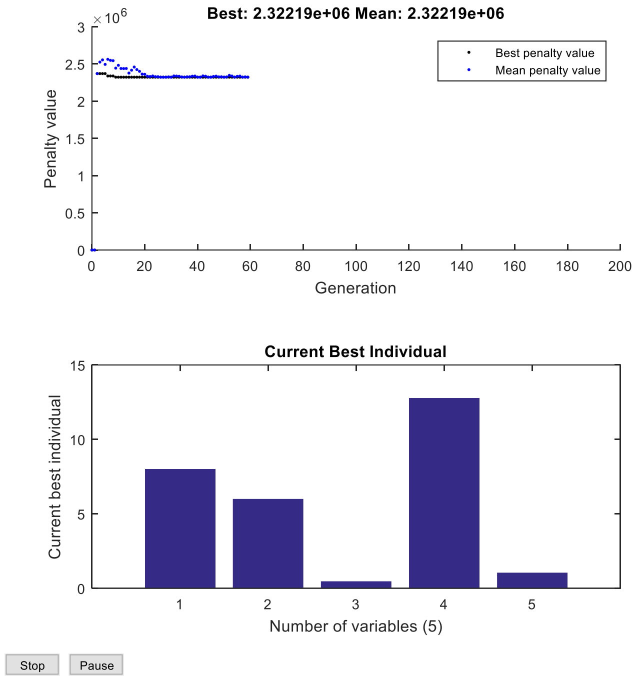


Figure A.10: Total cost optimization run: 1.

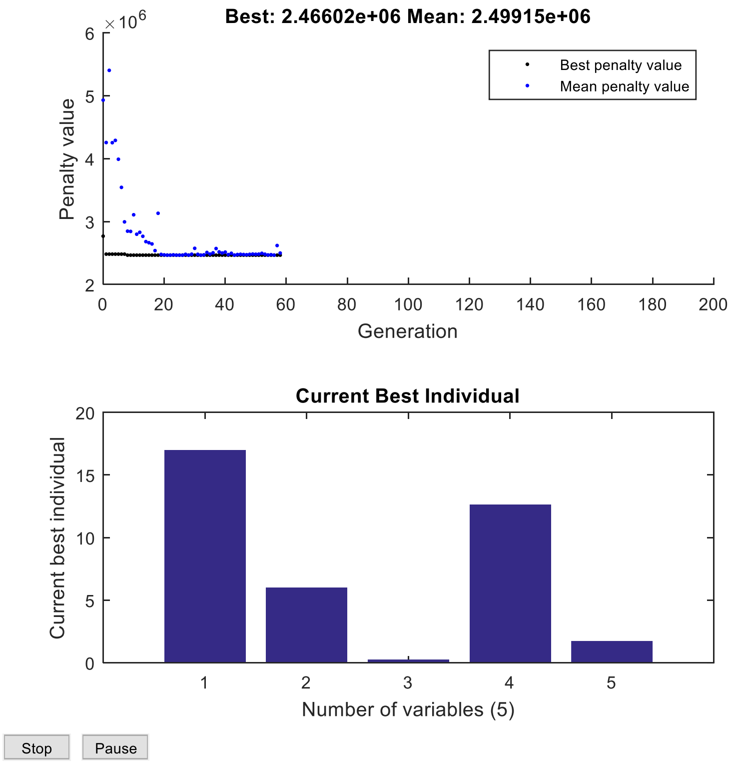


Figure A.11: Total cost optimization run: 2.

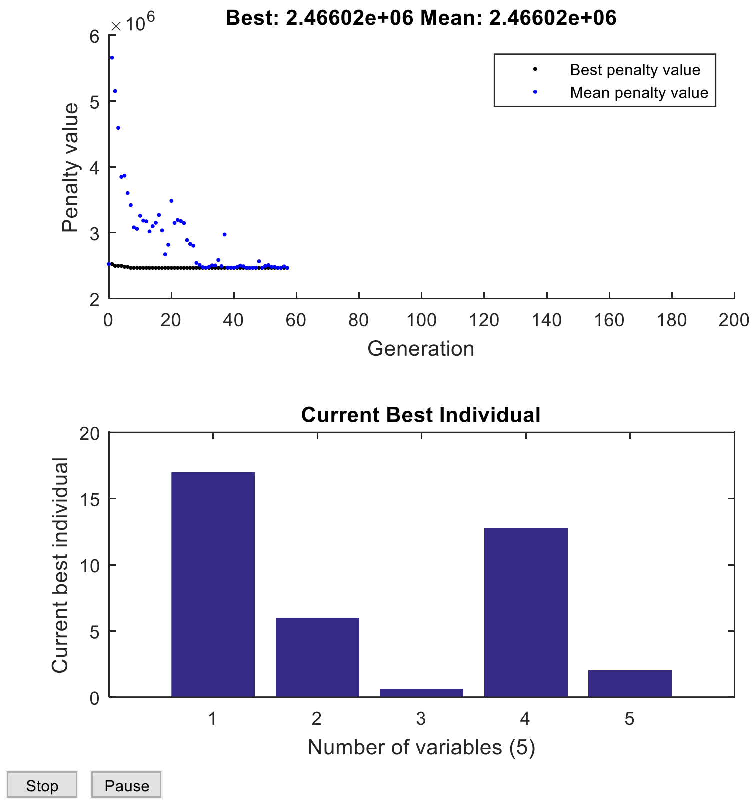

Figure A.12: Total cost optimization run: 3.

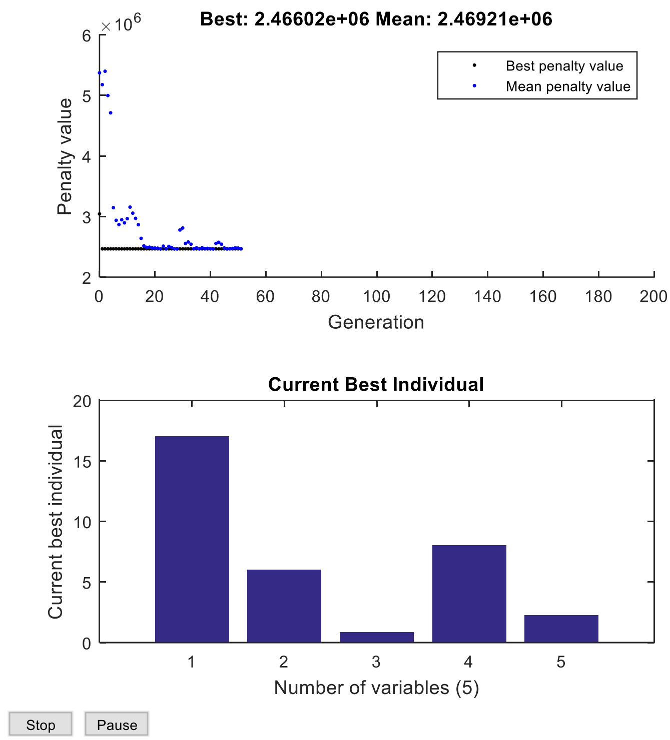

Figure A.13: Total cost optimization run: 4.

# Multi-objective Optimization of Travel Time & Total Cost

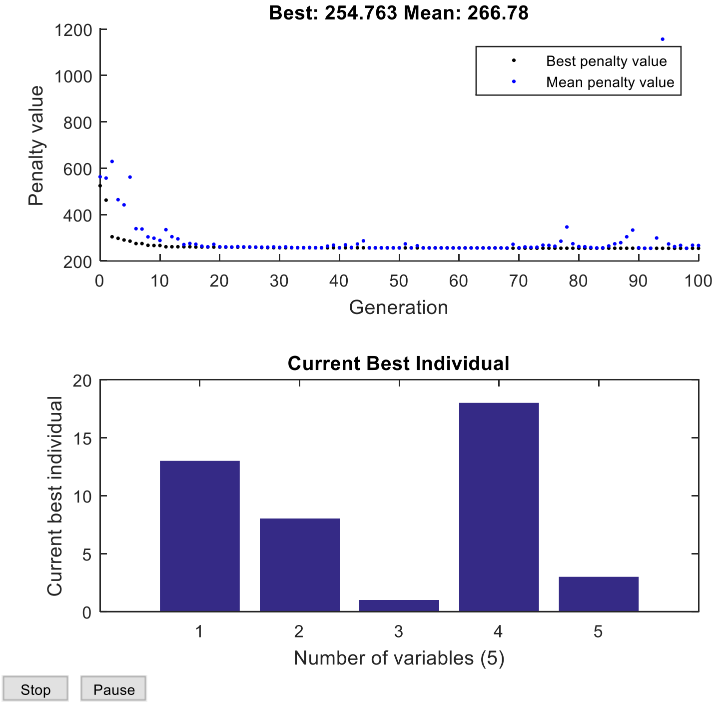


Figure A.14: Multi-objective optimization run:1.

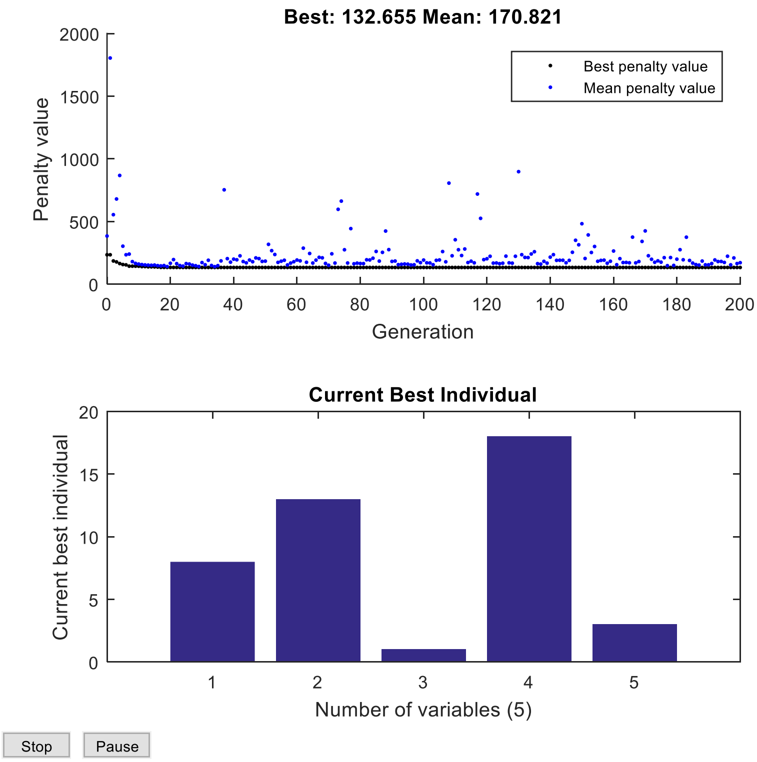


Figure A.15: Multi-objective optimization run: 2.

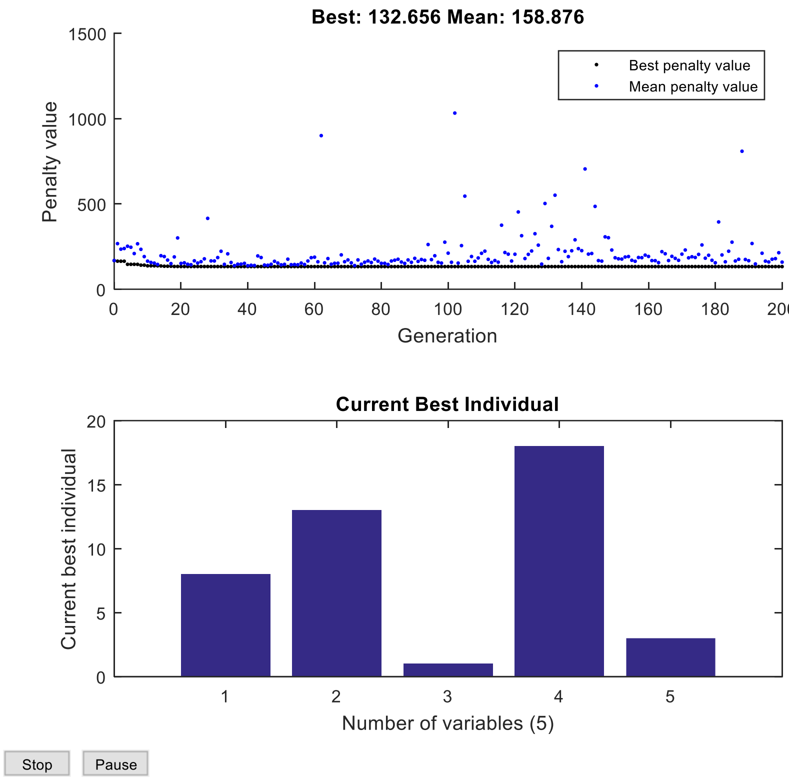


Figure A.16: Multi-objective optimization run:3.

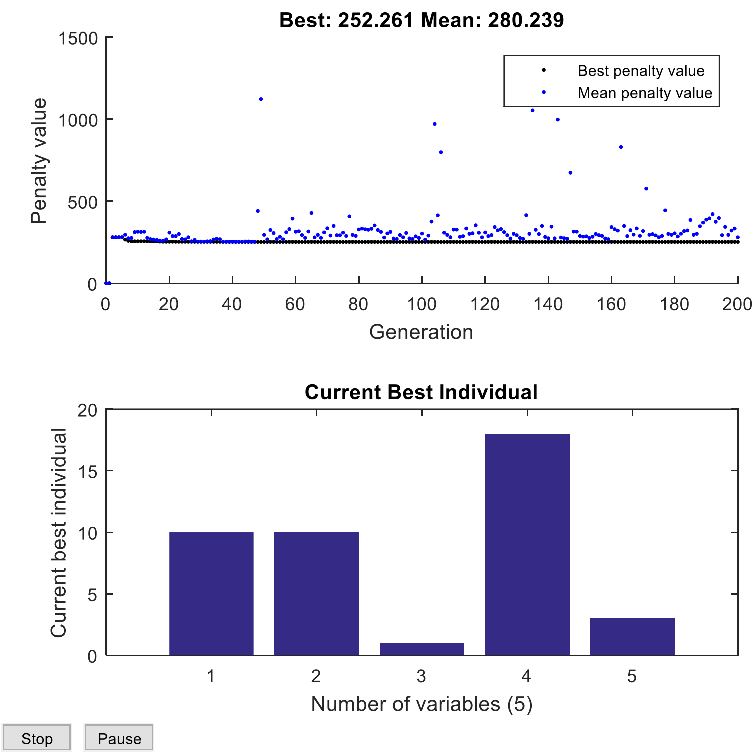


Figure A.17: Multi-objective optimization run: 4.

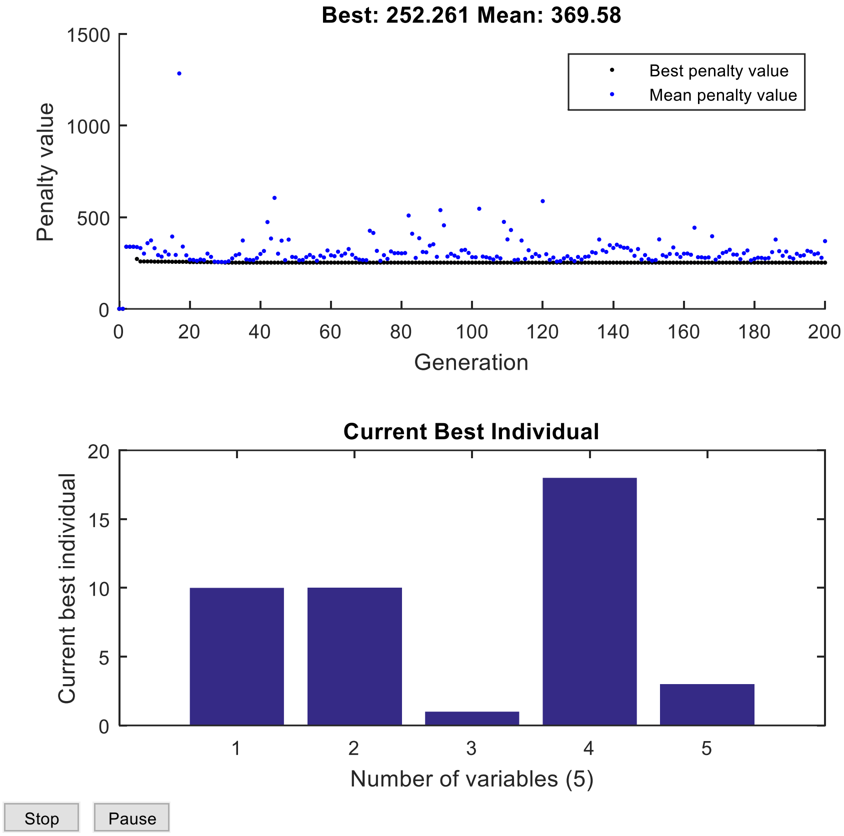

Figure A.18: Multi-objective optimization run: 5.

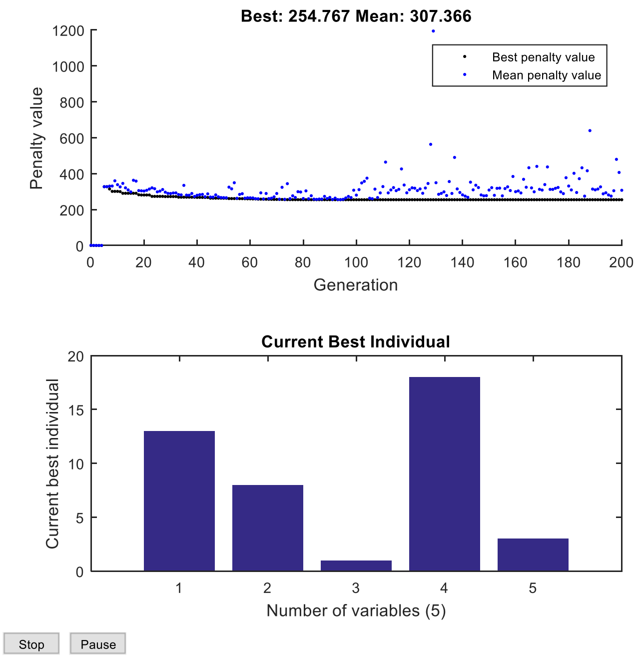

Figure A.19: Multi-objective optimization run: 6.

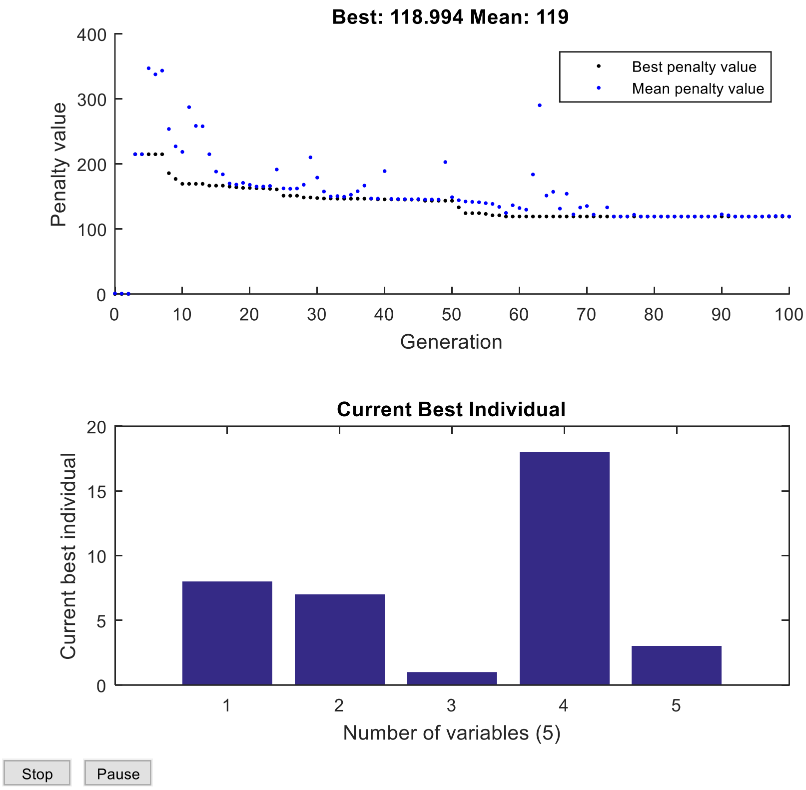


Figure A.20: Multi-objective optimization run: 7.

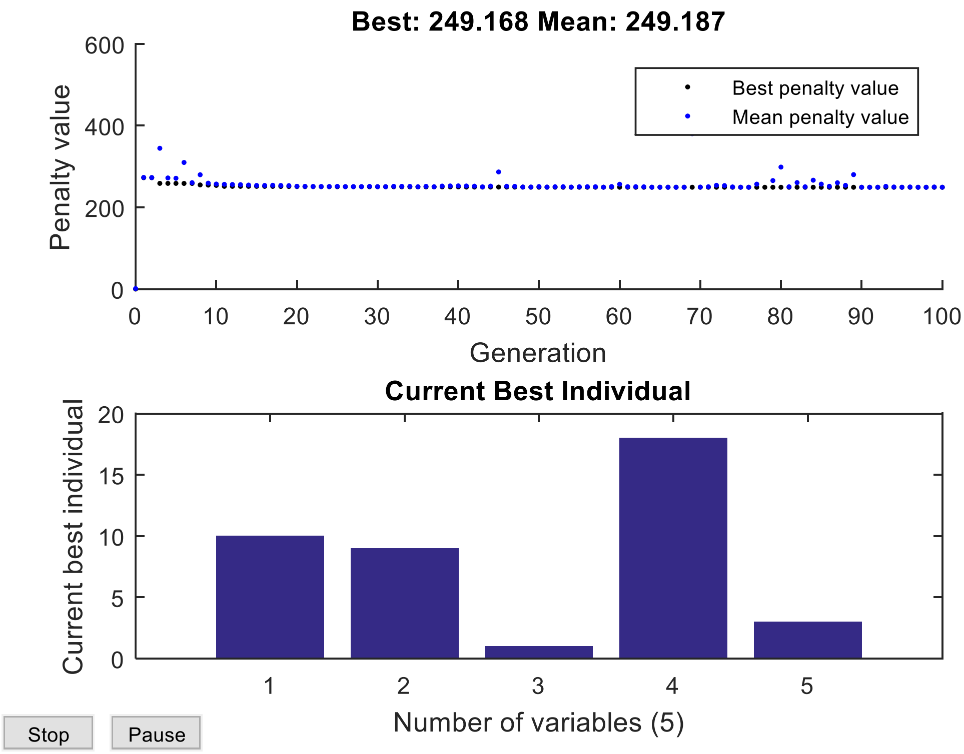


Figure A.21: Multi-objective optimization run: 8.

**Sensitivity Analysis of Variables**

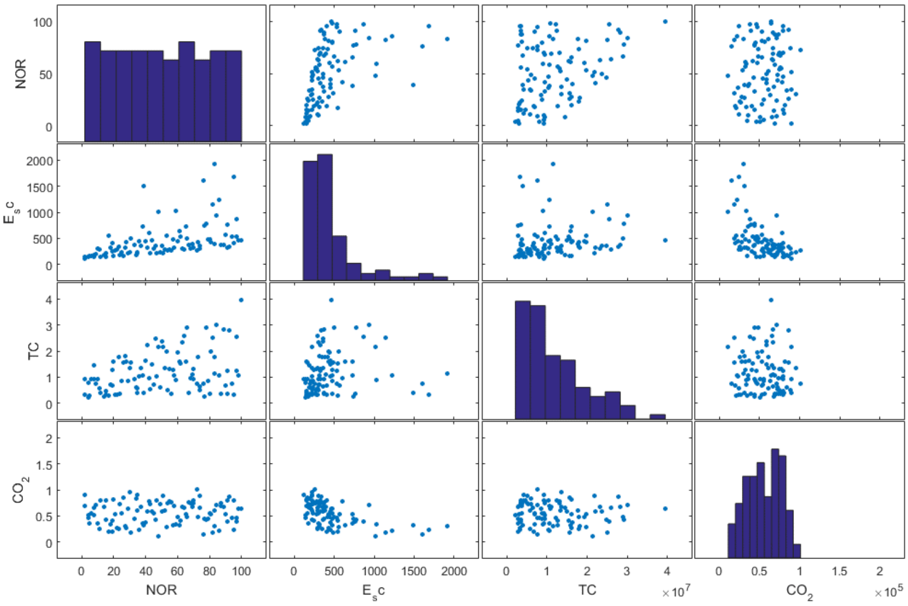


Figure A.22: Sensitivity of x(1), number of rows.

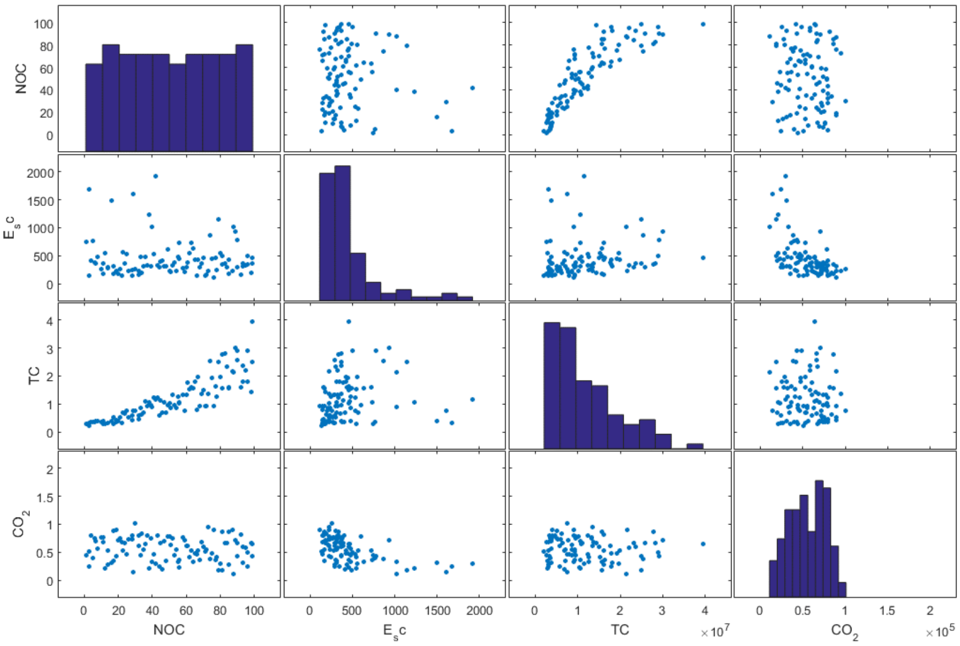


Figure A.23: Sensitivity of x(2), number of columns.

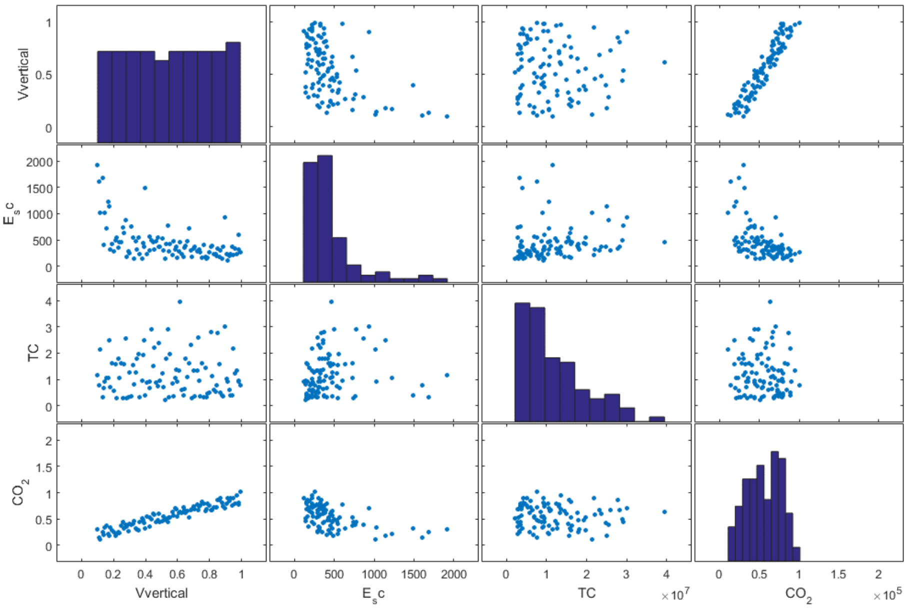


Figure A.24: Sensitivity of x(3), vertical crane velocity.

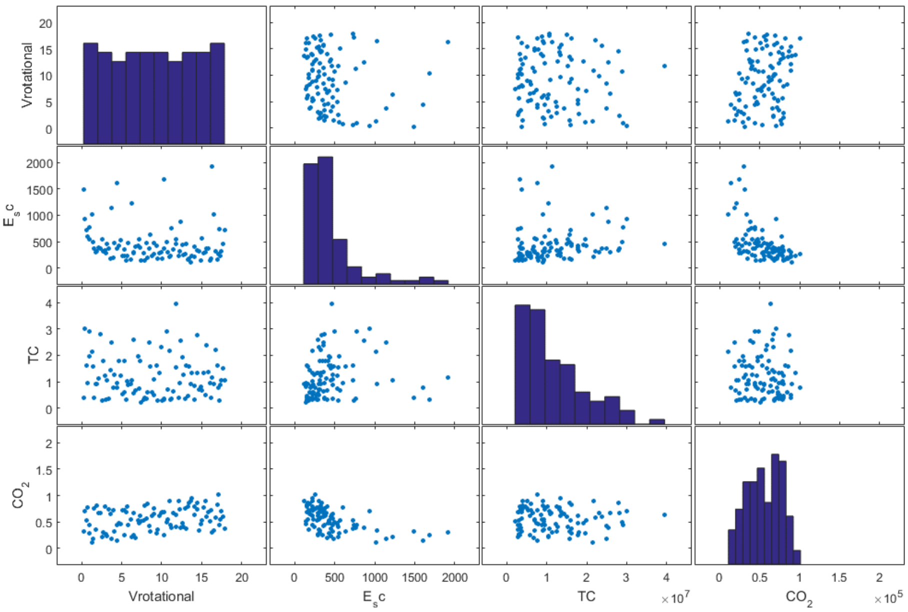


Figure A.25: Sensitivity of x(4), rotational crane velocity.

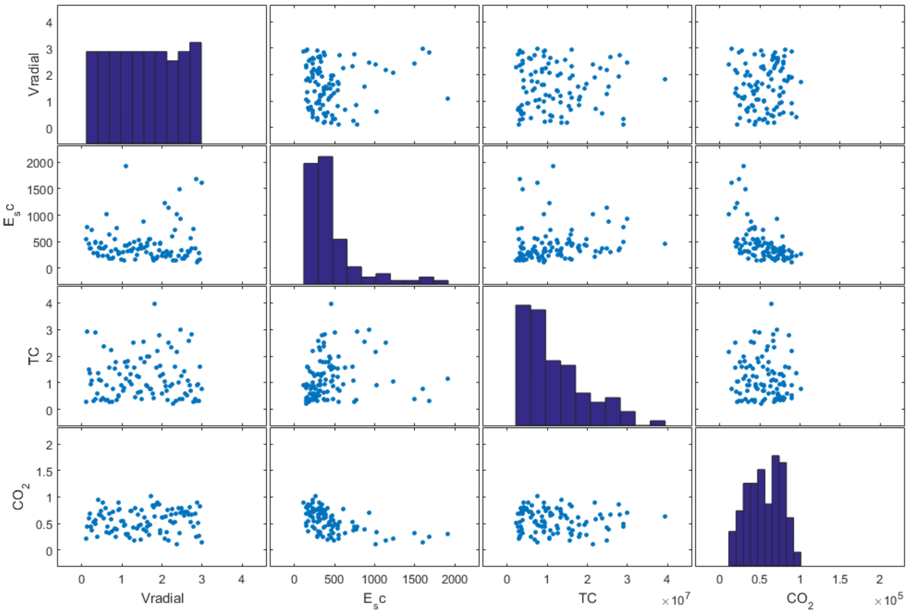


Figure A.26: Sensitivity of x(5), radial crane velocity.

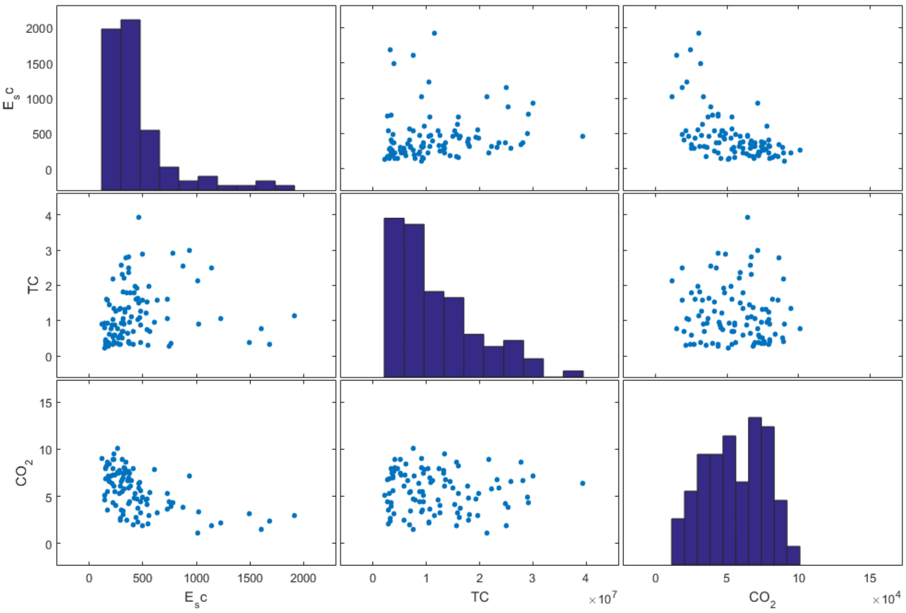


Figure A.27: Objectives in histogram.

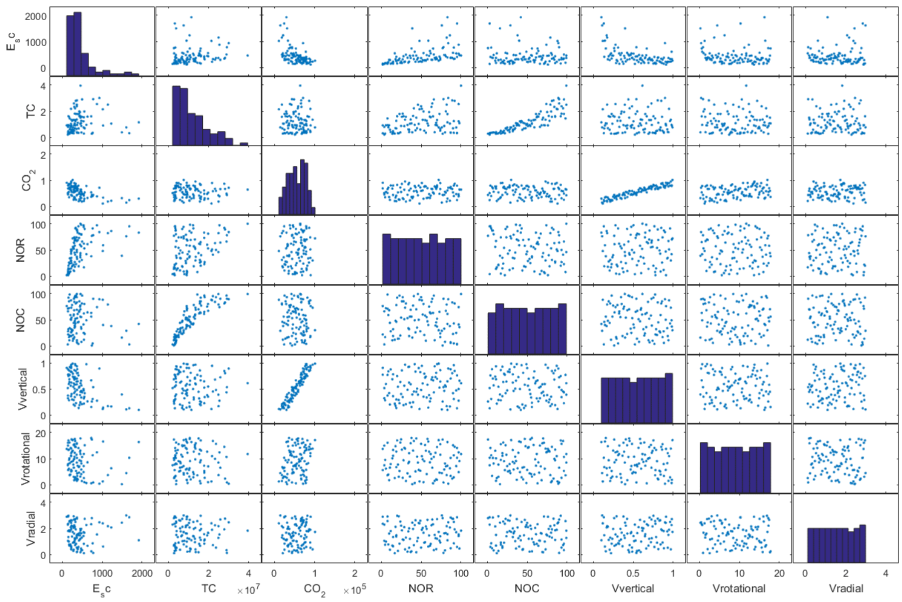


Figure A.28: Travel time & other objectives and design variables.

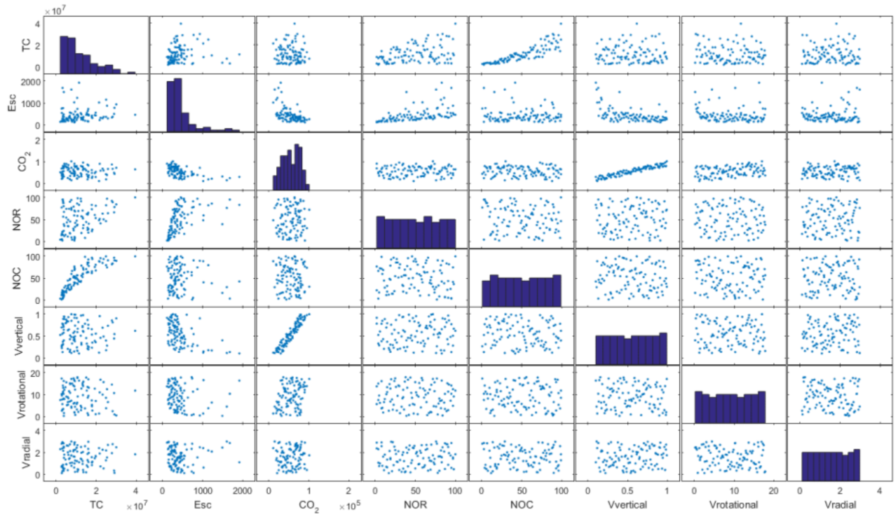


Figure A.29: Total cost & other objectives and design variables.

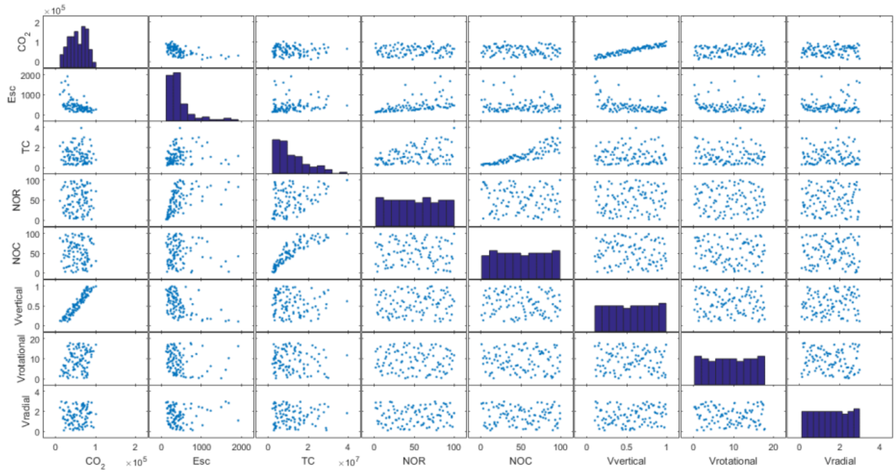


Figure A.30: $CO_2$ & other objectives and design variables.

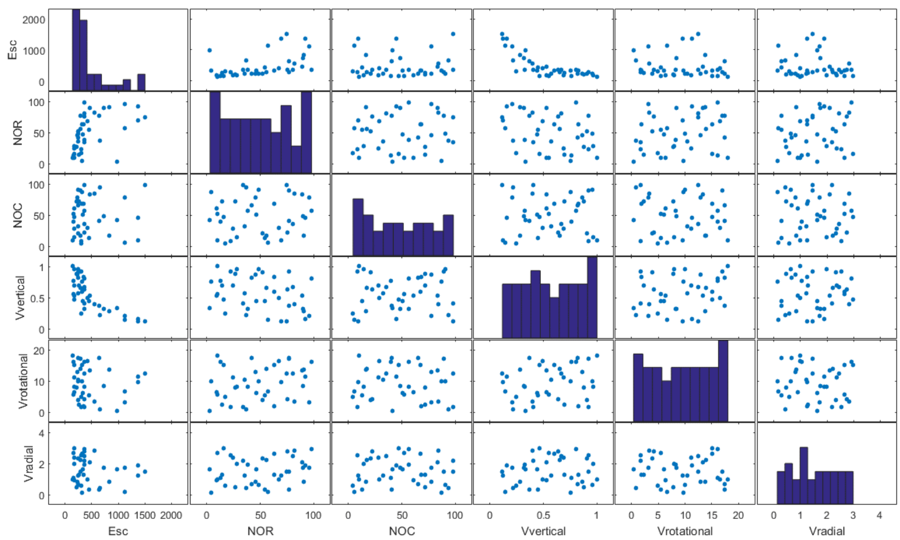


Figure A.31: Travel time & design variables.

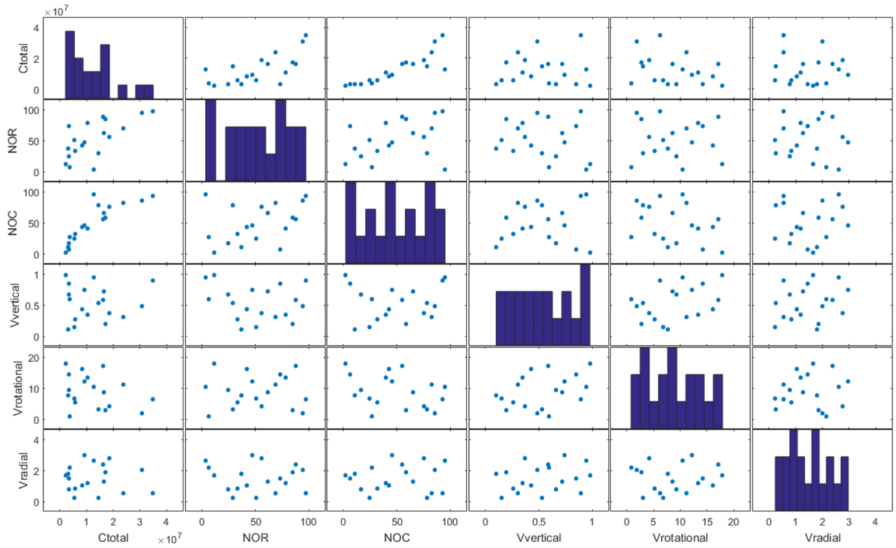


Figure A.32: Total cost & design variables.

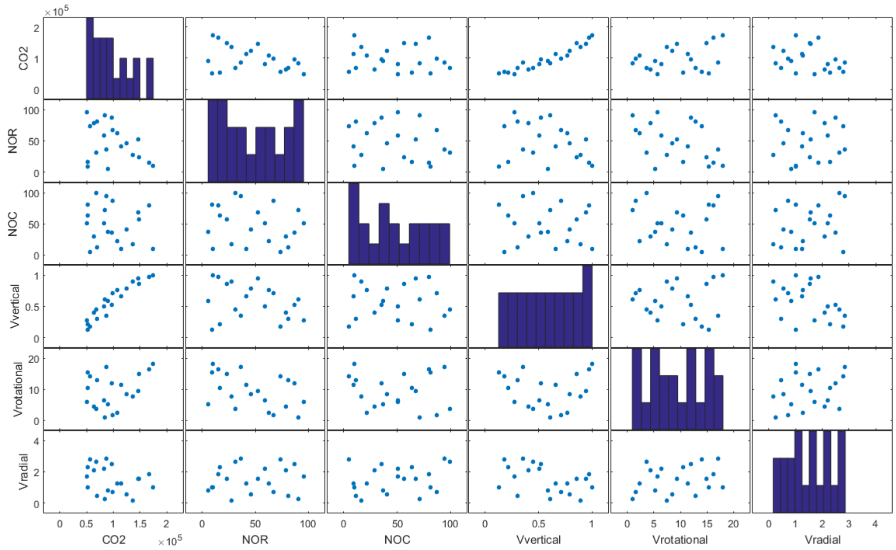


Figure A.33: CO & design variables.

# Appendix B: MATLAB Code

## Constraints

```
function [c,ceq]=CASRS_const_ga(x)
double STORAGEcapacity;
double tconcrete  ;
double CELLlength ;
double CELLheight;
double CLroof;
double CLbase ;
double CELLwidth;
double CLsafety;
double CLrails;

ceq=[];
c = zeros(7,1);
%   Non-equality constraints
% c(1)=   1*x(1)*x(2)*1
- 90;                                  % storage capacity should be less
than 90.
c(1)=   -1*x(1)*x(2)*1
+ 100;                                  % storage capacity should be
more than 100.

% c(2)=   -2*((x(2)*CELLwidth+2*CLrails)/(2*pi))
+ CELLlength;                          % Inner Diameter should be
greater than CELLlength
c(2)=-(x(2)*3.000+2*0.5)/(2*pi)*2
+5.500;

% c(3)=   -x(1)*(CELLheight+tconcrete)+ CLbase+CLroof
+20 ;                                  %Htotal should be higher than 20m
c(3)=-(x(1)*(2.100+0.1)+2.100+2.100)
+20;

% c(4)=   x(1)*(CELLheight+tconcrete)+CLbase+CLroof
-70;                                   %Htotal should be less than 70m
c(4)=(x(1)*(2.100+0.1)+2.100+2.100)
-70;

% c(5)=   -
2*(((x(2)*CELLwidth+2*CLrails)/(2*pi))+CELLlength+CLsafety)   +20;
%Dtotal should be greater than 20m
c(5)=-((x(2)*3+2*0.5)/(2*pi)+5.5+5.5)*2
+20;

% c(6)=
2*(((x(2)*CELLwidth+2*CLrails)/(2*pi))+CELLlength+CLsafety)    -60;
%Dtotal should be less than 60m
c(6)=((x(2)*3+2*0.5)/(2*pi)+5.5+5.5)*2
-60;

% c(7)=   1*x(1)*x(2)*1
-100;                                  % storage capacity should be LESS
than100.
```

```
%   CONSTRAINTS = [c(1) c(2) c(3) c(4) c(5) c(6) x(1) x(2) x(3) x(4)
x(5) ];
  CONSTRAINTS = [c(1) c(2) c(3) c(4) c(5) c(6) c(7)];

    dlmwrite('CONSTRAINTS.txt', CONSTRAINTS,'-append', 'delimiter',
'\t', 'precision', 14,'newline','pc');
end
```

## Objective Function

```
function Fval=ObjectiveFunction_CarParking_CASRS_Travel_Time(x)
%%                                INITIALIZATION
format long
% x
% gloval x;
% global Fval;
global Nproducts;
global CELLlength;
global CELLheight;
global CELLwidth;
global CELLweight;
global CLroof;
global CLbase;
global CLrails;
global CLsafety;
global CLcrane ;
global CLext ;
global tconcrete  ;
global Tdwellvertical ;
global Tdwellrotational ;
global Tdwellradial ;
global $COST_1$ ;
global $COST_2$ ;
global $COST_3$ ;
global $COST_4$ ;
global $COST_5$ ;
global $COST_6$ ;
global $COST_7$ ;
global $COST_8$ ;
global $COST_9$ ;
global $COST_{10}$ ;
global $COST_{11}$ ;
global $COST_{12}$ ;
global $COST_{13}$      ;
global Longesttrip   ;
global Edc ;
global Tvertical ;
global Trotational ;
global Tradial ;
global T ;
global Htotal ;
global Dtotal ;
global Dinner ;
global CIRtotal ;
global CIRinner ;
global b ;
global Nproducts  ;
```

```
global Aland ;
global Aconstructed ;
global Vtotal ;
global Vstorage ;
global Utilization ;
global Throughputsc ;
global Throughputdc ;
global POWERlifting ;
global POWERradial ;
global POWERrotational ;
global POWERtotal ;
global W ;
global CO2 ;
global COSTfloor;
global COSTwall ;
global COSTroof ;
global COSTupframe;
global COSTbeam ;
global COSTbuffer ;
global COSTassembly ;
global COSTland ;
global COSTwarehouse ;
global COSTmh;
global COSTfireprot;
global COSTairvent ;
global COSTsr;
global TC;
% global c;
% global ceq;
global STORAGEcapacity;

%Speed initials
%--------------------------------------------------------------------
----------
    global Tradial;          %travel spent for farthest radial cell
    global Tvertical;        %travel spent for farthest vertical cell
    global Trotational;      %travel spent for farthest rotational
cell
    global b;                %shape factor

%Configuration initials
%--------------------------------------------------------------------
----------
    global CELLlength;       %cell length
    global CELLheight;       %cell height
    global CELLwidth;        %cell width
    global CELLweight;       %cell weight
    global CLroof;
    global CLbase;
    global CLext;
    global CLcrane;



%Energy Efficiency Initials
%--------------------------------------------------------------------
----------
    POWERlifting=30;         %kw
    POWERrotational=1.5;        %kW
    POWERradial=1.5;      %kW
```

```
    E=0.68;              %efficiency of the warehouse calculated from
(SUVlength*SUVheight*SUVwidth/CELLwidth*CELLlength*CELLheight)
    p=0.59;              % emmission factor
    Tshift=16;
    nwd=5;
    nweeks=50;


%Cost initials
%---------------------------------------------------------------------
----------
    Ncrane=1;            %number of cranes (8)
    Naisles=1;           %number of aisles (4)
    S=1;                 %number of required cranes (4)
    n=1;                 %number of items for a single storge
compartment (3)
    Dz=71;               %Lerher, T. et al. (2012) share for the
warehouse building

% % COST INITIALS FOR LETHER,T.2012
%     Ncrane=8;            %number of cranes (8)
%     Naisles=4;           %number of aisles (4)
%     S=4;                 %number of required cranes (4)
%     n=3;                 %number of items for a single storge
compartment (3)
%     Dz=71;               %Lerher, T. et al. (2012) share for the
warehouse building

% % COSTS FOR 2016
    COST1 = 500.00;         % EURO/m2,
    COST2 = 168.00;         % EURO/m2,
    COST3 = 23.00;          %EURO/m2,
    COST4 = 25.00;          %EURO/m2,
    COST5 = 30.00;          %EURO/m,
    COST6 = 23.00;          %EURO/m,
    COST7 = 200.00;         %EURO/piece,
    COST8 = 10.00;           %EURO/PP,
    COST9 = 5.00;           %EURO/PP,
    COST10 = 10.00;          %EURO/m3,
%   COST11 = 431000,00;     %EURO/ piece,
    COST11=1500000;     %EURO/ piece,
    COST12 = 50.00;         %EURO/m,
%   COST13 = 240000,00;     %EURO/piece,
    COST13 = 50.00;         %EURO/m.


    %% ALTERNATIVE 1 - SUV CARS
%     %-------------------------------------------------------------
----------------
 %   Configuration
        CELLlength=5.500;       %cell length  % Storage cell
dimensions (L= 5.500 m, H=2.500 m, 3.000 m)
        CELLheight=2.100;       %cell height
        CELLwidth=3.000;        %cell width
        CELLweight=3200;        %kg - taken max value for the cars.
        tconcrete=0.100;        %clearance for steel structure
thickness + clearance for level.
  %   Clearance
```

```
        CLroof=CELLheight;      % Clearance area at the roof = size
of the car height
        CLbase=CELLheight;     % Clearance area at the bottom =
2*size of the car height
        CLrails=0.5;            %Clearance area between 2 cells for
S/R Rails = 0.5 m
        CLcrane=1.000;          %
        CLsafety=CELLlength;    %Clearance for outer of the ASRS for
safety
        CLext=0.500;            %S/R extension
   %  Dwell times
        Tdwellradial=15;         %waiting time for radial axis
        Tdwellvertical=25;      %due to acceleration and waiting
time of S/R
        Tdwellrotational=10;    %

%%  CALCULATIONS
%SYSTEM DIMENSIONS
%--------------------------------------------------------------------
----------
    Vangular=2*pi/x(2);                  %angular velocity of the
crane
% FOR LERHER,T.2012 DESIGN
%     CIRinner=113.12;
%     Htotal=21.16;

    CIRinner=x(2)*CELLwidth+2*CLrails;
    Rinner=CIRinner/(2*pi);
    Dinner=2*Rinner;
    Rtotal=Rinner+CELLlength+CLsafety;
    CIRtotal=2*pi*Rtotal;
    Dtotal=2*Rtotal;
%     Dtotal2=((x(2)*3+2*0.5)/(2*pi)+5.5+5.5)*2
    Htotal=x(1)*(CELLheight+tconcrete)+CLbase+CLroof;
% Htotal2=x(1)*(2.100+0.1)+2.100+2.100
%TRAVEL TIMES
%--------------------------------------------------------------------
----------
    Tvertical=x(1)*(CELLheight+tconcrete)/x(3)+Tdwellvertical;
    Trotational=CIRinner/(x(4)*0.0174533*Rinner)+Tdwellrotational;
    Tradial=(CLext+CLcrane+CELLlength)/x(5)+Tdwellradial;
    T=max(Tvertical,Trotational);
    Longesttrip=2*Tvertical+4*Tradial;
    STORAGEcapacity= x(1)*x(2)*Naisles*n;
%CONFIGURATION CALCULATION
%--------------------------------------------------------------------
----------
    b=min(Tvertical,Trotational)/max(Trotational,Tvertical);
    Nproducts=x(1)*x(2);
    Aland=pi*Rtotal^2;
    Aconstructed=pi*Rtotal^2-pi*Rinner^2;
    Vstorage=Aconstructed*(Htotal-CLroof);
    Vtotal=Aland*Htotal;

Utilization=CELLwidth*CELLheight*CELLlength*Nproducts/Vtotal*100;


%####################################################################
##
%    OBJECTIVE : EXPECTED TRAVEL TIME SC
```

```
%######################################################################
##
%CONTINOUS TRAVEL TIME
%---------------------------------------------------------------------
----------
    Esc=(1+b^2/3)*T+4*Tradial;
    Edc=(4/3+b^2/2-b^3/30)*T+6*Tradial;
    Fval=Esc;
%######################################################################
##

%THROUGHPUT CALCULATION
%---------------------------------------------------------------------
----------
    Throughputsc=floor(3600/Esc);
    Throughputdc=floor(3600/Edc);


 %DISCRETE EXPECTED TIME CALCULATION
%---------------------------------------------------------------------
----------
    Aa=zeros(1,100);Bb=Aa;Cc=Aa;

    for MoveNo=1:Nproducts

        Tx=randi([1,x(2)],[1,1,1,1]);
%Randomly assign x axis for storage location. used for calculation
of expected travel time for single command
        Tx1=randi([1,x(2)],[1,1,1,1]);
%randomly assigned x axis for retrieval location and used for
calculation of expected travel time for dual command.
        Ty=randi([1,x(1)],[1,1,1,1]);
%Randomly assign y axis for storage location.  used for calculation
of expected travel time for single command
        Ty1=randi([1,x(1)],[1,1,1,1]);
%randomly assigned y axis for retrieval location and used for
calculation of expected travel time for dual command.

Aa(MoveNo)=max(Tx*(360/x(2))/x(4),Ty*(CELLheight+tconcrete)/x(3));
%A is the time spent from I/O location to ith cell. A= max(i*w/Sh,
j*h/Sv)
        Bb(MoveNo)=max((abs(Tx1-Tx))*(360/x(2))/x(4),(abs(Ty1-
Ty))*(CELLheight+tconcrete)/x(3));    %B is the time spent between
storage location and retrieval location.

Cc(MoveNo)=max(Tx1*(360/x(2))/x(4),Ty1*(CELLheight+tconcrete)/x(3));
%C is the time spent for retrieval location to I/O location

    end

    S1=sum(Aa);
    S2=0;
    for i=1:Nproducts-1
        for j=i+1:Nproducts
                    S2=S2+(Aa(i)+Bb(j)+Cc(j));
        end %for j
    end %for i
```

```
    Escd=1/Nproducts*2*S1+4*Tradial;                % summation
equation continued.
    Edcd=2/(Nproducts*(Nproducts-1))*S2+6*Tradial;          %
summation equation continued.
%
%
%####################################################################
##
%    OBJECTIVE : ENERGY CONSUMPTION CO2 emission
%####################################################################
##
%%ENERGY CONSUMPTION CO2
%--------------------------------------------------------------------
----------
POWERtotal=POWERlifting+POWERrotational+POWERradial;   %kW
W=POWERtotal*Tshift*nwd*nweeks*E;           %kWh/year
CO2=W*p;                               %kWh/year

%####################################################################
##


%% COST FOR THE WAREHOUSE BUILDING
%--------------------------------------------------------------------
----------
% COST OF THE LAND
COSTland=Dtotal^2*100/Dz*COST_1;
COSTfloor=pi*(Rtotal-Rinner)^2*COST_2;


% COSTwall=2*Dtotal*(CELLheight*x(1)+CLroof+CLbase);
% COSTwall=2*Dtotal*Htotal*2*C3;
COSTwall=2*pi*(Htotal+(Rtotal)^2)*COST_3;   %cylinder surface area
COSTroof=Dtotal^2*COST_4;

% MATERIAL HANDLING EQUIPMENT
COSTupframe=(x(2)+1)*Ncrane*Htotal*COST_5;
% Lrb=2*pi*(Rtotal-Rinner)/x(2);      %length of the rack beam
Lrb=CELLlength;
% Lrb=2.65;% use it for lether,t.2012
COSTbeam=x(2)*x(1)*2*Ncrane*Lrb*COST_6;
COSTbuffer= 2*Naisles*COST_7;
COSTassembly=x(2)*x(1)*n*Ncrane*COST_8;
% COSTassembly=x(2)*x(1)*n*Ncrane*25;

% FIRE PROTECTION COST
COSTfireprot=x(2)*x(1)*n*Ncrane*COST_9;

% AIR VENTILATION COST
COSTairvent=pi*Rtotal^2*Htotal*COST_10;

%S/R MACHINE COST
COSTsr=S*COST_11+(CIRinner*COST_12)*Naisles;

%####################################################################
##
%    OBJECTIVE : TOTAL COST
```

```
%#####################################################################
##
%TOTAL COST
COSTwarehouse=COSTfloor+COSTwall+COSTroof;
COSTmh=COSTupframe+COSTbeam+COSTbuffer+COSTassembly;
TC=COSTland+COSTfloor+COSTwall+COSTroof+COSTupframe+COSTbeam+COSTass
embly+COSTfireprot+COSTairvent+COSTsr;
%#####################################################################
##

    %%                              DISPLAY
    %----------------------------------------------------------------
-----------
%      Results = [x(1)  x(2)  Nproducts CELLlength CELLheight CELLwidth
CELLweight CLroof CLbase CLrails CLsafety CLcrane CLext tconcrete
x(3)  x(4)  x(5)  Tdwellvertical Tdwellrotational Tdwellradial
COST1  COST2 COST3 COST4 COST5 COST6 COST7 COST8 COST9 COST10 COST11 COST12 COST13 L
ongesttrip Fout   Edc double(Escd) double(Edcd) Tvertical
Trotational Tradial T Htotal Dtotal Dinner CIRtotal CIRinner   b
Nproducts  Aland Aconstructed Vtotal Vstorage Utilization
Throughputsc Throughputdc POWERlifting POWERradial POWERrotational
POWERtotal W CO2 COSTfloor COSTwall COSTroof COSTupframe COSTbeam
COSTbuffer COSTassembly COSTland COSTwarehouse COSTmh COSTfireprot
COSTairvent COSTsr TC ];
%                  dlmwrite('RESULTS.txt', Results,'-append',
'delimiter', '\t', 'precision', 14,'newline','pc');
%      disp ('             CALCULATIONS FOR Car parking C-AS/RS ');
%      disp ('----------------------------------------------------
-----------');
%      disp ('INPUTS');
%      disp ('-------CONFIGURATION--------');
%      disp ('--------------------------------------------- ');
%      disp (['NUMBER OF COLUMNS                          ='
num2str(x(1)) '  (amount)' ])
%      disp (['NUMBER OF ROWS                             ='
num2str(x(2)) '  (amount)' ])
%      disp (['NUMBER OF PRODUCTS                         ='
num2str(Nproducts) ' (amount)' ])
%      disp (['CELL LENGTH                                ='
num2str(CELLlength) '   (m)' ])
%      disp (['CELL HEIGHT                                ='
num2str(CELLheight) ' (m)' ])
%      disp (['CELL WIDTH                                 ='
num2str(CELLwidth) '   (m)' ])
%      disp (['CELL WEIGHT                                ='
num2str(CELLweight) '   (kg)' ])
%      disp (' ');
%      disp ('-------CLEARANCE--------');
%      disp ('--------------------------------------------- ');
%      disp (['CLEARANCE FOR ROOF                         ='
num2str(CLroof) ' (m)' ])
%      disp (['CLEARANCE FOR BASE                         ='
num2str(CLbase) ' (m)' ])
%      disp (['CLEARANCE FOR CRANE RAILS                  ='
num2str(CLrails) ' (m)' ])
%      disp (['CLEARANCE FOR OUTER OF ASRS (SAFETY)       ='
num2str(CLsafety) '   (m)' ])
%      disp (['CLEARANCE FOR CRANE                        ='
num2str(CLcrane) ' (m)' ])
%      disp (['CLEARANCE FOR EXTENSION                    ='
num2str(CLext) '   (m)' ])
```

```
%     disp (['CONCRETE THICKNESS                          ='
num2str(tconcrete) '   (m)' ])
%     disp (' ');
%     disp ('-------SPEED FEATURES--------');
%     disp ('--------------------------------------------- ');
%     disp (['VERTICAL SPEED                              ='
num2str(x(3)) ' (m/s)' ])
%     disp (['ROTATIONAL SPEED                            ='
num2str(x(4)) '   (degree/s)' ])
%     disp (['RADIAL SPEED                                ='
num2str(x(5)) '   (m/s)' ])
%     disp (' ');
%     disp ('-------DWELL TIMES--------');
%     disp ('--------------------------------------------- ');
%     disp (['DWELL FOR VERTICAL                          ='
num2str(Tdwellvertical) '   (m/s)' ])
%     disp (['DWELL FOR ROTATIONAL                        ='
num2str(Tdwellrotational) '   (m/s)' ])
%     disp (['DWELL FOR RADIAL                            ='
num2str(Tdwellradial) '   (m/s)' ])
%     disp (' ');
%     disp ('-------COST ANALYSIS INITIALS--------');
%     disp ('--------------------------------------------- ');
%     disp (['COST OF BUYING LAND                          ='
num2str(COST_1) '   (EURO/m2)' ])
%     disp (['COST OF LAYING FOUNDATION OF WAREHOUSE       ='
num2str(COST_2) '   (EURO/m2)' ])
%     disp (['COST OF BUILDING WALLS                       ='
num2str(COST_3) '   (EURO/m2)' ])
%     disp (['COST OF BUILDING ROOF                        ='
num2str(COST_4) '   (EURO/m2)' ])
%     disp (['COST OF UPRIGHT FRAMES                       ='
num2str(COST_5) '   (EURO/m)' ])
%     disp (['COST OF BUYING RACK BEAMS                    ='
num2str(COST_6) '   (EURO/m)' ])
%     disp (['COST OF BUYING BUFFERS                       ='
num2str(COST_7) '   (EURO/piece)' ])
%     disp (['COST OF ASSEMBLY PER PALLET POSITION         ='
num2str(COST_8) '   (EURO/PP)' ])
%     disp (['COST OF FIRE SAFETY PER PALLET POSITION      ='
num2str(COST_9) '   (EURO/PP)' ])
%     disp (['COST OF AIR CONDITIONING                     ='
num2str(COST_10) '   (EURO/m3)' ])
%     disp (['COST OF BUYING SINGLE AISLE S/R MACHINE      ='
num2str(COST_11) '   (EURO/piece)' ])
%     disp (['COST OF PICKING AISLE                        ='
num2str(COST_12) '   (EURO/m)' ])
%     disp (['COST OF CROSS AISLE                          ='
num2str(COST_13) '   (EURO/piece)' ])
%     disp ('-----------------------------------------------------------
------------------------------------------------');
%     disp ('-----------------------------------------------------------
------------------------------------------------');
%     disp ('OUTPUTS');
%     disp ('---------------');
%     disp (' ');
%     disp ('-------TRAVEL TIME--------');
%     disp ('--------------------------------------------- ');
%     disp (['LONGEST TRIP                                     ='
num2str(Longesttrip) '    (sec)' ])
```

```
%     disp (['EXPECTED TRAVEL TIME CONTINUOUS E(SC)        ='
num2str(Fout)     '    (sec)'])
%     disp (['EXPECTED TRAVEL TIME CONTINUOUS E(DC)        ='
num2str(Edc)     '    (sec)'])
%     disp (['EXPECTED TRAVEL TIME DISCRETE RACK E(SC)     ='
num2str(double(Escd))     '    (sec)'])
%     disp (['EXPECTED TRAVEL TIME DISCRETE RACK E(DC)     ='
num2str(double(Edcd))     '    (sec)'])
%     disp (['VERTICAL LONGEST TRIP                        ='
num2str(Tvertical) '    (sec)' ])
%     disp (['ROTATIONAL LONGEST TRIP                      ='
num2str(Trotational) '    (sec)' ])
%     disp (['RADIAL TRIP (LOADING/UNLOADING)              ='
num2str(Tradial) '    (sec)' ])
%     disp (['STORAGE TIME                                 ='
num2str(T) '       (sec)'])
%     disp (' ');
%     disp ('-------CONFIGURATION--------');
%     disp ('--------------------------------------------- ');
%     disp (['SYSTEM HEIGHT                                ='
num2str(Htotal) '       (m)' ])
%     disp (['SYSTEM DIAMETER                              ='
num2str(Dtotal) '    (m)' ])
%     disp (['SYSTEM INNER DIAMETER                        ='
num2str(Dinner) '    (m)' ])
%     disp (['TOTAL CIRCUMFERENCE                          ='
num2str(CIRtotal) '    (m)' ])
%     disp (['INNER CIRCUMFERENCE                          ='
num2str(CIRinner) '         (m)' ])
%     disp (['Shape factor(b)                              ='
num2str(b) ])
%     disp (['NUMBER OF STORAGE CELLS                      ='
num2str(Nproducts)     '        (Cells)'])
%     disp (['LAND  AREA                                   ='
num2str(Aland)     '   (m^2)'])
%     disp (['CONSTRUCTED  AREA                            ='
num2str(Aconstructed)     '   (m^2)'])
%     disp (['TOTAL VOLUME                                 ='
num2str(Vtotal)     ' (m^3)'])
%     disp (['STORAGE VOLUME                               ='
num2str(Vstorage)     '   (m^2)'])
%     disp (['UTILIZATION                                  ='
num2str(Utilization)     '    (%)'])
%     disp (' ');
%     disp ('-------THROUGHPUT--------');
%     disp ('--------------------------------------------- ');
%     disp (['THROUGHPUT FOR SINGLE COMMAND                ='
num2str(Throughputsc)     '    (Storage and Retrival per hour)'])
%     disp (['THROUGHPUT FOR DUAL COMMAND                  ='
num2str(Throughputdc)     '    (Storage and Retrival per hour)'])
%     disp (' ');
%     disp ('----------ENERGY CONSUMPTION-----------');
%     disp ('--------------------------------------------- ');
%     disp (['POWER REQUIRED FOR VERTICLE MOVEMENT         ='
num2str(POWERlifting)     '(kW)'])
%     disp (['POWER REQUIRED FOR RADIAL MOVEMENT           ='
num2str(POWERradial)     '(kW)'])
%     disp (['POWER REQUIRED FOR ROTATIONAL MOVEMENT       ='
num2str(POWERrotational)     '(kW)'])
%     disp (['TOTAL REQUIRED POWER                         ='
num2str(POWERtotal)     '(kW)'])
```

```
%     disp (['ENERGY CONSUMPTION                                  ='
num2str(W)      '(kW)'])
%     disp (['CO2 EMISSION                                        ='
num2str(CO2)      '(kW)'])
%     disp (' ');
%     disp ('--------COST ANALYSIS--------');
%     disp ('---------------------------------------------- ');
%     disp (['FLOOR COST
=' num2str(COSTfloor) '  (EURO)' ])
%     disp (['WALL COST
=' num2str(COSTwall) ' (EURO)' ])
%     disp (['ROOF COST
=' num2str(COSTroof) '   (EURO)' ])
%     disp (['UPFRAME COST
=' num2str(COSTupframe) ' (EURO)' ])
%     disp (['SUPPORTING BEAM COST
=' num2str(COSTbeam) '   (EURO)' ])
%     disp (['BUFFER COST
=' num2str(COSTbuffer) '   (EURO)' ])
%     disp (['ASSEMBLY COST
=' num2str(COSTassembly) ' (EURO)' ])
%     disp (' ');
%     disp ('----TOTAL COST CALCULATION----');
%     disp (['LAND COST
=' num2str(COSTland) '  (EURO)' ])
%     disp (['MATERIAL HANDLING COST
=' num2str(COSTwarehouse) ' (EURO)' ])
%     disp (['STORAGE CONSTRUCTION
=' num2str(COSTmh) ' (EURO)' ])
%     disp (['FIRE PROTECTION COST
=' num2str(COSTfireprot) '   (EURO)' ])
%     disp (['AIR VENTILATION
=' num2str(COSTairvent) '   (EURO)' ])
%     disp (['S/R MACHINE COST
=' num2str(COSTsr) ' (EURO)' ])
%     disp (['TOTAL COST
=' num2str(TC) '   (EURO)' ])
%     disp
('******************************************************************
********');

%###############################################################
% SAVING RESULTS
%###############################################################
%     Results = [x(1) x(2) Nproducts CELLlength CELLheight CELLwidth
CELLweight CLroof CLbase CLrails CLsafety CLcrane CLext tconcrete
x(3) x(4) x(5) Tdwellvertical Tdwellrotational Tdwellradial
```
$COST_1$ $COST_2$ $COST_3$ $COST_4$ $COST_5$ $COST_6$ $COST_7$ $COST_8$ $COST_9$ $COST_{10}$ $COST_{11}$ $COST_{12}$ $COST_{13}$
```
Longesttrip Fval   Edc Tvertical Trotational Tradial T Htotal Dtotal
Dinner CIRtotal CIRinner   b Nproducts  Aland Aconstructed Vtotal
Vstorage Utilization Throughputsc Throughputdc POWERlifting
POWERradial POWERrotational POWERtotal W CO2 COSTfloor COSTwall
COSTroof COSTupframe COSTbeam COSTbuffer COSTassembly COSTland
COSTwarehouse COSTmh COSTfireprot COSTairvent COSTsr TC ];
%   Results = [Fval x(1) x(2) x(3) x(4) x(5) Nproducts c(1) c(2)
c(3) c(4) c(5) c(6) CELLlength CELLheight CELLwidth CELLweight
CLroof CLbase CLrails CLsafety CLcrane CLext tconcrete
Tdwellvertical Tdwellrotational Tdwellradial
```
$COST_1$ $COST_2$ $COST_3$ $COST_4$ $COST_5$ $COST_6$ $COST_7$ $COST_8$ $COST_9$ $COST_{10}$ $COST_{11}$ $COST_{12}$ $COST_{13}$
```
Longesttrip    Edc Tvertical Trotational Tradial T Htotal Dtotal
Dinner CIRtotal CIRinner   b Nproducts  Aland Aconstructed Vtotal
```

```
Vstorage Utilization Throughputsc Throughputdc POWERlifting
POWERradial POWERrotational POWERtotal W CO2 COSTfloor COSTwall
COSTroof COSTupframe COSTbeam COSTbuffer COSTassembly COSTland
Cwarehouse COSTmh COSTfireprot COSTairvent COSTsr TC ];
%   Results = [Fval Esc TC CO2 x(1) x(2) x(3) x(4) x(5)
STORAGEcapacity Dinner Htotal Htotal Dtotal Dtotal Nproducts
CELLlength CELLheight CELLwidth CELLweight CLroof CLbase CLrails
CLsafety CLcrane CLext tconcrete  Tdwellvertical Tdwellrotational
Tdwellradial
COST1 COST2 COST3 COST4 COST5 COST6 COST7 COST8 COST9 COST10 COST11 COST12 COST13
Longesttrip    Edc Tvertical Trotational Tradial T Htotal Dtotal
Dinner CIRtotal CIRinner   b Nproducts  Aland Aconstructed Vtotal
Vstorage Utilization Throughputsc Throughputdc POWERlifting
POWERradial POWERrotational POWERtotal W CO2 COSTfloor COSTwall
COSTroof COSTupframe COSTbeam COSTbuffer COSTassembly COSTland
COSTwarehouse COSTmh COSTfireprot COSTairvent COSTsr TC ];
Results = [Fval Esc Edc Throughputsc Throughputdc TC x(1) x(2) x(3)
x(4) x(5) CLroof CLbase CLrails CLsafety CLcrane CLext tconcrete
COST1 COST2 COST3 COST4 COST5 COST6 COST7 COST8 COST9 COST10 COST11 COST12 COST13
Longesttrip Tvertical Trotational Tradial T Htotal Dtotal Dinner
CIRtotal CIRinner   b Nproducts  Aland Aconstructed Vtotal Vstorage
COSTfloor COSTwall COSTroof COSTupframe COSTbeam COSTbuffer
Cassembly COSTland COSTwarehouse COSTmh COSTfireprot COSTairvent
COSTsr];

     dlmwrite('RESULTS.txt', Results,'-append', 'delimiter', '\t',
'precision', 14,'newline','pc');

end
```

### Main Function

```
%% CAR PARKING C-AS/RS
%---------------------------------Specifications Based on C-AS/RS in
Wolfsburg, GERMANY (VW Car Tower----------------------------
% Number of columns = 20
% Number of rows = 20
% Number of crane = 1
% Number of aisle = 1
% Storage cell dimensions (L= 5.500 m, H=2.500 m, 3.000 m)
% Height = 48 meter+
% Number of cars = 400
% Crane speed = 2 m/s
% Clearance area at the roof = size of the car height
% Clearance area at the bottom = 2*size of the car height
% Clearance area between 2 cells for S/R Rails = 0.5 m
% Clearance area between S/R extension and inner diameter of ASRS =
3.5* lenght of the car
% Building is made by galvanised steel frame
% From I/O to the the farthest cell takes 1 min 44 sec.
%Suburban Utility Vehicle (SUV) dimensions (Lenght=5.7 meter,
Height= 2.5m, width= 2.4 meter)
%%                        SUV CAR MODELS FOR C-AS/RS
% Model                              Price         L(m)        H(m)
W(m)     Weight(kg)
% Tesla Model X P85D-                $110000     5.0038     2.3622
2.58445     2390
% Porsche Cayenne Turbo S-           $146995     4.855       1.705
1.938       2375
```

```
% Porsche Cayenne Turbo -         $111395     4.855       1.705
1.939       2184
% BMW X6 M-                       $94825      4.876       1.684
2.195       2350
% Mercedes Benz ML63 AMG-         $98175      4.820       1.860
1.950       2880
% Jeep Grand Cherokee SRT8-       $64990      4.8707      1.807
1.9659      2315
% BMW C5 xDrive50i-               $69125      4.908       1.762
1.938       2336
% Range Rover Sport Supercharged- $79100      4.871       1.780
1.9837      2335
% Audi SQ5-                       $52795      4.6710      1.6586
2.141       1994
% GMC Typhoon-                    $47606      4.326       1.524
1.732       1734
% Mercedes Benz G63 AMG-          $136625     4.762       1.938
1.938       3201
% Porsche Catenne GTS-            $84295      4.855       1.6891
2.164       2105
%---------------------------------------------------------------------
-------------------------------------

clc; clear all; close all;
% global x;
% global Fval ;
global CELLlength ;
global CELLheight;
global CLroof;
global CLbase ;
global tconcrete  ;

%%%%%%
% Parameters:
CLroof=2.100;
CELLlength= 5.500;
CELLheight=3.000;
CLbase=2.100;
tconcrete=0.100;
%%                                  LB AND UB  (FOR C-AS/RS)
nvars = 5;
ncon = 6;
nrun = 1;
intcon=[1 2];
% A=[-1 0;-1.0017 1.5;-0.21 -4.2;0.21 4.2;-0.954 -13.32;0.954
13.32];
% b=[-10;-5.5;-10;60;-20;60];

% Generations_Data=5
% Generations_Data=101;
%---------------------------------------------------------------------
-------
% #of levels NOL   #of columns (NOC)    Vvertical(m/s)
Vrotational(m/s)   Vradial(m/s)
lb=  [ 1                  1                   0.1                 0.1
0.1                ];  %UB AND LB ARE DEFINED BY ME.
ub=  [ 100                100                 1                   18
3               ];
x0 = [10    10  1   18   1];
% x1=[1    100  1   18   1];
% x2=[100    1  1   18   1];
```

```
% xstar=[10    10 0.995874943   17.7175606  2.993962029];
xSTAR=[8    7   0.995321159 17.9889576  2.987152869];
% ObjectiveFunction_CarParking_CASRS_VERIFICATION(x)
FitnessFunctionQZ(xSTAR);
% ObjectiveFunction_CarParking_CASRS_Travel_Time(xstar);
% ObjectiveFunction_CarParking_CASRS_Travel_Time(x2);
%
x=ga(@ObjectiveFunction_CarParking_CASRS,nvars,A,b,[],[],lb,ub,@CASR
S_const_ga,IntCon);


%WORKING -------------------------------------------
% rng(0, 'twister');
% [xbest, fbest, exitflag] = ga(@ObjectiveFunction_CarParking_CASRS,
nvars, [], [], [], [], ...
%     lb, ub, @CASRS_const_ga, [1 2]);
%END ---------------------------------------------

%% Start with the default options
options = gaoptimset;
%% Modify options setting
% options = gaoptimset(options,'EliteCount', EliteCount_Data);
% options = gaoptimset(options,'CrossoverFraction',
CrossoverFraction_Data);
% options = gaoptimset(options,'MigrationInterval',
MigrationInterval_Data);
% options = gaoptimset(options,'MigrationFraction',
MigrationFraction_Data);
% options = gaoptimset(options,'Generations', Generations_Data);
% options = gaoptimset(options,'SelectionFcn', {
@selectiontournament [] });
% options = gaoptimset(options,'CrossoverFcn', @crossovertwopoint);
% options = gaoptimset(options,'MutationFcn', {  @mutationgaussian
[] [] });
% options = gaoptimset(options,'HybridFcn', {  @fmincon [] });
% options = gaoptimset(options,'Display', 'final');
% options = gaoptimset(options,'PlotFcns', {  @gaplotbestf
@gaplotbestindiv @gaplotdistance @gaplotexpectation @gaplotgenealogy
@gaplotrange @gaplotscorediversity @gaplotscores @gaplotselection
@gaplotstopping @gaplotmaxconstr });
% [x,fval,exitflag,output,population,score] =
ga(@ObjectiveFunction_CarParking_CASRS,nvars,[],[],[],[],lb,ub,@CASR
S_const_ga,[],options);
% [xbest, fbest, exitflag] = ga(@ObjectiveFunction_CarParking_CASRS,
nvars, [], [], [], [], lb, ub, @CASRS_const_ga, [1 2]);



%%%%
%% Modify options setting
options = gaoptimset(options,'PopulationSize', 40);
options = gaoptimset(options,'EliteCount', 2);
% options = gaoptimset(options,'CrossoverFraction', 0.8);
options = gaoptimset(options,'CrossoverFraction', 0.8);
options = gaoptimset(options,'MigrationDirection', 'both');
options = gaoptimset(options,'MigrationInterval', 10);
options = gaoptimset(options,'MigrationFraction', 0.3);
options = gaoptimset(options,'Generations', 200);
% options = gaoptimset(options,'InitialPenalty',
InitialPenalty_Data);
% options = gaoptimset(options,'PenaltyFactor', PenaltyFactor_Data);
```

```
options = gaoptimset(options,'SelectionFcn', {  @selectiontournament
5  });
options = gaoptimset(options,'CrossoverFcn', @crossovertwopoint);
options = gaoptimset(options,'MutationFcn', {  @mutationuniform
0.2623 });

% options = gaoptimset(options,'PopInitRange' ,[LB;UB]);
% options = gaoptimset(options,'PopulationSize' ,100);
% options = gaoptimset(options,'Generations' ,500);
options = gaoptimset(options,'TolFun' ,1e-29);
options = gaoptimset(options,'TolCon' ,1e-29);
% options = gaoptimset(options,'TolFun' ,1e-5);
% options = gaoptimset(options,'TolCon' ,1e-5);
% options = gaoptimset(options,'StallGenLimit' ,100);
options = gaoptimset(options,'StallTimeLimit' ,20000000);
% options = gaoptimset(options,'CrossoverFcn' ,@crossovertwopoint);
% options = gaoptimset(options,'MutationFcn' ,{ @mutationuniform
0.25 });
% options = gaoptimset(options,'Display' ,'iter');
% options = gaoptimset(options,'OutputFcns' ,{ { @gaoutputgen 1  }
});
%
% options = optimoptions(options,'ParetoFraction',0.5);
options = gaoptimset(options,'Display', 'iter');
% options = gaoptimset(options,'PlotFcns', {  @gaplotbestf
@gaplotbestindiv @gaplotdistance @gaplotexpectation @gaplotgenealogy
@gaplotrange @gaplotscorediversity @gaplotscores @gaplotselection
@gaplotstopping @gaplotmaxconstr });
options = gaoptimset(options,'PlotFcns', {  @gaplotbestf
@gaplotbestindiv  });
% [x,fval,exitflag,output,population,score] = ...
%%%%
% [x,Fval,exitflag,output,population,score] =
ga(@ObjectiveFunction_CarParking_CASRS, nvars, [], [], [], [], lb,
ub, @CASRS_const_ga, intcon, options);

%####################################################################
% FOR TRAVEL TIME
%####################################################################
% Options =
optimset('LargeScale','on','Display','iter','MaxIter',1000000,'TolFu
n',1e-20,'Tolcon',1e-20,'TolX',1e-5,'MaxFunEval',5000000);
% % %
[x,fval,exitflag,output]=fmincon(@ObjectiveFunction_CarParking_CASRS
_Travel_Time, x0,[],[],[],[],lb,ub,@CASRS_const_ga, Options);
%
% [x,Fval,exitflag,output,population,score] =
ga(@ObjectiveFunction_CarParking_CASRS_Travel_Time, nvars, [], [],
[], [], lb, ub, @CASRS_const_ga, intcon, options);


%####################################################################
% FOR THROUGHPUT MAXIMIZATION
%####################################################################

% [x,Fval,exitflag,output,population,score] =
ga(@ObjectiveFunction_CarParking_CASRS_Throughput, nvars, [], [],
[], [], lb, ub, @CASRS_const_ga, intcon, options);
```

```
%
%################################################################
% % FOR TOTAL COST
%
%################################################################
%
% [x,Fval,exitflag,output,population,score] =
ga(@ObjectiveFunction_CarParking_CASRS_Total_Cost, nvars, [], [],
[], [], lb, ub, @CASRS_const_ga, intcon, options);
%
%
%################################################################
% % FOR CO2 EMISSION
%
%################################################################
%
% [x,Fval,exitflag,output,population,score] =
ga(@ObjectiveFunction_CarParking_CASRS_CO2_EMISSION, nvars, [], [],
[], [], lb, ub, @CASRS_const_ga, intcon, options);
%
% %##############################################################
% FOR MULTIBOJECTIVE
%################################################################


% fitnessfcn = @(x)[ObjectiveFunction_CarParking_CASRS_Travel_Time
(x),ObjectiveFunction_CarParking_CASRS_Total_Cost(x)];
% rng default % for reproducibility
% [x,Fval,exitflag,output,population,score] = gamultiobj(fitnessfcn,
nvars, [], [], [], [], lb, ub, @CASRS_const_ga, options);

%% ///////////1ST WAY///////////////
% [x,fval,exitflag,output, population, score] =
gamultiobj(@FitnessFunction,nvars,[],[],[],[],lb,ub,@CASRS_const_ga,
options);
%
% f1=(1+b^2/3)*T+4*Tradial;
% f2= COSTfloor COSTwall COSTroof COSTupframe COSTbeam COSTbuffer
COSTassembly COSTland COSTwarehouse COSTmh COSTfireprot COSTairvent
COSTsr;
% figure;hold on
% plot(x0,f1);
% plot(x0,f2);
% % plot(Fval(1),Fval(2),'r*')
% grid;
% xlabel('Travel Time')
% ylabel('Total Cost')
% title('Pareto Front')
% legend('Pareto front')

%%///////////////////////////////////////////////use this
%%/////////////2ND WAY////////////////////
% %
% FitnessFunction1 = @(x) FitnessFunction(x);
% % options = gaoptimset(options,'PlotFcns', {  @gaplotbestf
@gaplotbestindiv @gaplotscorediversity @gaplotselection });
% options =
gaoptimset('PlotFcns',{@gaplotpareto,@gaplotscorediversity});
% [x,fval,exitflag,output, population, score] =
gamultiobj(FitnessFunction1,nvars,[],[],[],[],lb,ub,@CASRS_const_ga,
options);
```

```
% [x,fval,exitflag,output, population, score] = ga(@FitnessFunction,
nvars, [], [], [], [], lb,ub, @CASRS_const_ga,intcon, options);

%//////////////////////////////////////////////////
%%////////////3RD WAY///////////////////
% plot(x(:,1),x(:,2),'ko')
% t = linspace(-1/2,2);
% y = 1/2 - t;
% hold on
% plot(t,y,'b--')
% hold off
% rng default;
% fitnessfnc= @(x)[ObjectiveFunction_CarParking_CASRS_Travel_Time,
ObjectiveFunction_CarParking_CASRS_Total_Cost];

% [x,Fval,exitflag,output,population,score] =
gamultiobj(@FitnessFunction, nvars, [], [], [], [], lb, ub,
@CASRS_const_ga, options);
[x,Fval,exitflag,output,population,score] = ga(@FitnessFunctionQZ,
nvars, [], [], [], [], lb, ub, @CASRS_const_ga, intcon, options);
% [x,Fval,exitflag,output,population,score] =
gamultiobj(@FitnessFunction, nvars, [], [], [], [], lb, ub,
@CASRS_const_ga, options);

% ------------------------------------------------------------------
----------------------------------------------------------
%******************************************************************
**********************************************************
%UNCOMMENT BOTTOM SECTION FOR R-AS/RS
%******************************************************************
**********************************************************
% ------------------------------------------------------------------
----------------------------------------------------------



% %                   LB AND UB  (FOR R-AS/RS)
% %-----------------------------------------------------------------
---------
% #of levels NOL   #of columns (NOC)    Vvertical(m/s)
Vhorizontal(m/s)   Vradial(m/s)
% lb=  [ 10                 10                  0               0
0                ];  %UB AND LB ARE DEFINED BY ME.
% ub=  [ 500                100                 1               3
3                ];
% x1 = [10    10  1   1   1];

% ObjectiveFunction_CarParking_RASRS(x0);
%
% options = gaoptimset;
% % options = gaoptimset(options,'EliteCount', EliteCount_Data);
% % options = gaoptimset(options,'MigrationDirection', 'both');
% % options = gaoptimset(options,'Generations', Generations_Data);
% % options = gaoptimset(options,'Display', 'off');
% [x,fval,exitflag,output,population,score] = ...
%
ga(@ObjectiveFunction_CarParking_RASRS,nvar,[],[],[],[],lb,ub,@RASRS
_const_ga,[],options);
```