

# **Optimal Design and Control of an Automated Bike Parking System**

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## Abstract

Large cities and metropolitan areas are facing parking space problems due to the increasing number of commuters who choose bicycles as the main mode of transportation. The bicycle parking should provide enough space for the bicycle, as well as corridors and isles to reach the space. Inspired by the automated storage and retrieving systems and by the cities' cycling encouraging plans and their problem of space and location for the bicycle parking, an automated bicycle parking system is introduced in this work.

First, the growth of cycling and the subsequent issues that the cities and cyclists confronting are investigated. Then the traditional and existing solutions and their deficiencies are explored. The automated parking system is studied as a solution which meets and improves the deficiencies of the existing solutions, it takes minimum space and encourages the use of bicycle by providing a more secure parking experience. To exhibit the superiority of the automated system, this thesis follows the design, model, and manufacture of such a system. However, to even improve the system further, a study in the optimization of some parts of the system to reduce energy consumption has been commenced.

The design, manufacturing, and installation of the system's exterior are not included in this work.

**Keywords:** Automated Bicycle Parking System; AS/RS; SolidWorks Model; Automation; Manufacturing; Security; Space efficiency; Optimization

# To my dear parents

Whose unconditional love, support, and  
encouragement has always been the shining beacon  
that illuminates my path through life.

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## List of Acronyms

ASRS	Automated Storage and Retrieval System
CCW	Counter ClockWise
CMA	Census Metropolitan Area
CSA	Canadian Standards Association
CW	ClockWise
EA	Evolutionary Algorithm
EoT	End-of-Trip
FEA	Finite Element Analysis
FSM	Finite State Machine
GA	Genetic Algorithm
HSS	Hollow Structural Section
NLPQL	Non-Linear Programming by Quadratic Lagrangian
PLC	Programmable Logic Controller
SF	Safety Factor
TIA	Totally Integrated Automation
VL-AS/RS	Vertical Lift Automated Storage/Retrieval System
VLSM	Vertical Lift Storage Modules
VPD	Vancouver Police Department



## List of Symbols

### Chap. 4

$E$	Module of Elasticity (Young Modulus)
$y_{max}$	Maximum Deflection of Column
$P$	Vertical load / Power
$e$	Eccentricity
$I$	Second moment of area
$P_{cr}$	Critical buckling Load
$\sigma$	Stress
$\tau$	Torque
$\omega$	Angular velocity
$\alpha$	Angular acceleration
$\eta$	Efficiency
$F$	Force
$f$	Coefficient of rolling friction
$W$	Load on wheel
$R$	Radius
$V$	Velocity

### Chap. 7

$J$	Rotational inertia
$M$	Mass
$r$	Radius
$\rho$	Density
$N_{Ed}$	Design value of the tension and compression force
$N_{Rd}$	Design capacity for normal force
$N_{pl,Rd}$	Plastic design capacity for normal force
$f_y$	Yield strength
$\gamma M_0$	Partial factor of resistance of cross section
$N_{c,Rd}$	Design compressive resistance
$u$	Deflection

# Chapter 1. Introduction

Over the past two decades, the number of Canadians who cycle or take transit to work has been rising while an inclination in growth of car commuters, in comparison to population growth, can be detected. More Canadians prefer an active and sustainable mode of transportation to what has been otherwise the main transportation mode of most people for decades, namely automobiles.

Most Canadians live and work in cities and surrounding areas with a population of 100,000 or more, known as census metropolitan areas (CMAs). According to Statistics Canada, in 2016 about 1 million Canadians used active transportation, of which more than 220,000 cycled to work. In other words, in general, 6.9% of all the commuters in 2016 used a mode of active transportation of which 1.6% used bicycle [1], [2], [3], [4].

The increases in the number of people living and working in CMAs and in the population density of CMAs are affecting how people get to work. There is an increase of 35.9% in the number of commuters to work who live in CMAs during the past two decades. The number of people living in CMAs who commuted to work increased from 8.6 million to 11.7 million from 1996 to 2016. However different modes of transportation have significantly different growth rates. Over the same 20 years period, the number of commuters who cycled to work increased by 87.9%. Figures 1.1 and 1.2 illustrate the portion of commuters as well as their growth respectively, by the main mode of the commute from 1996 to 2016 [4].

The bicycle share of work commuters, however, varies across Canadian metropolitans. According to Statistics Canada data although Victoria has the highest share of cyclers to work with 6.6% all across Canada, but for large CMAs, Vancouverites make for the highest share of cycling to work by 2.3% followed by Montreal (2.0%) and Toronto (1.4%) [2], [3], [4].

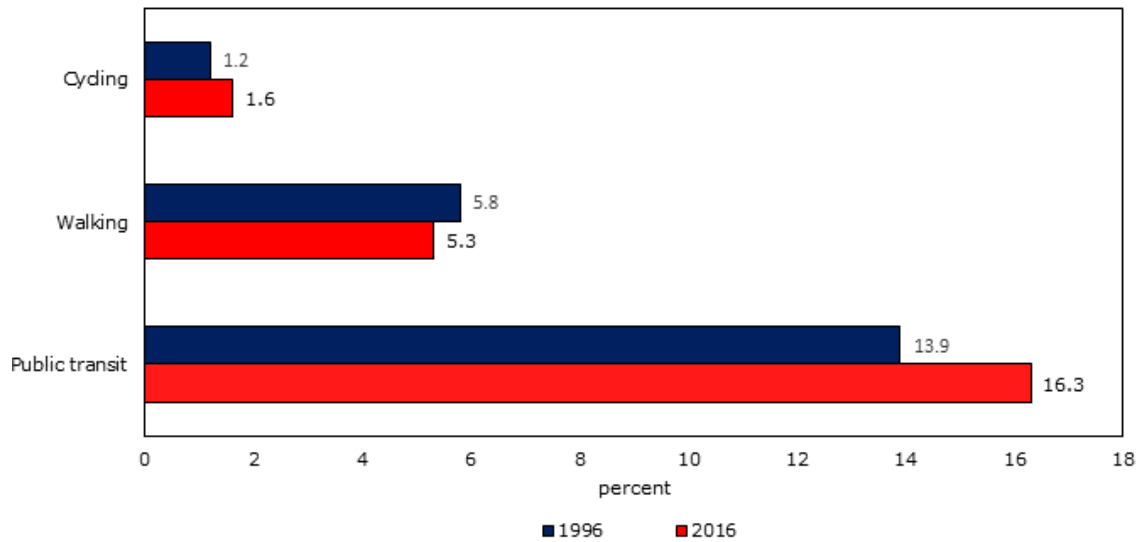


Figure 1.1 - Proportion of commuters, by selected main mode of commuting, all census metropolitan areas combined, 1996 to 2016

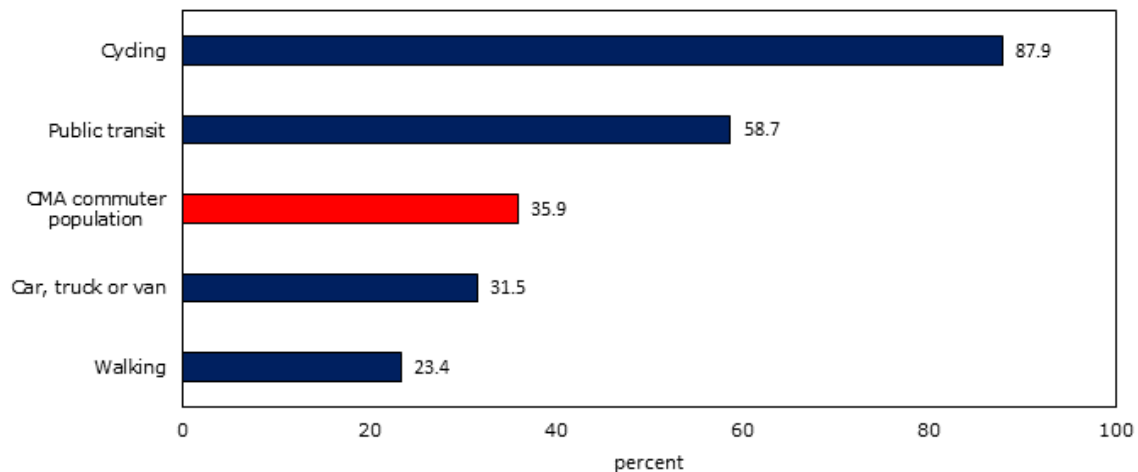


Figure 1.2 - Growth from 1996 to 2016 in the number of commuters, by main mode of commuting, all census metropolitan areas combined

Although Statistics Canada counts cost, availability, the environment, convenience, and personal health among the reasons for people to use active transportation, but there can be seen an underlying reason for the spike in cycling in Canada. The data elucidates a shift in the country's ways of how to get around.

Although active and healthy living is at the core of Canada's cycling renaissance, but it is also simply a result of Canadian cities getting bigger and more populated and

subsequently the traffic getting worse, impelling the country to re-evaluate and rethink the best ways to commute. This in turn, has prompted major cities in the country to encourage and promote active transportation in general, and cycling in particular by designing and including Active Transportation Plans and including them in their master plans. [1], [2], [3], [4], [7], [8], [9], [10].

The growing trend of using active transportation as the main mode of commute, however, is not affiliated just with Canada, this trend is now a North American prospective. The National Personal Transportation Surveys (NPTS) of 1977 to 1995 and National Households Travel Surveys (NHTS) of 2001 and 2009 indicate that the total number of bicycle trips in the USA has grown triple between 1977 and 2009, meaning that bicycles share of the total trips have been doubled, surging from 0.6% to 1% [5].

Although Canada commonly has a higher level of cycling compare to the USA, but spatial variations in cycling levels exist within each country. Table 1.1 and Figure 1.3 depict the trends in cycling and variation amongst states and provinces, respectively, in the US and Canada [5].

Table 1.1 Trends in cycling levels in Canada and the USA, 1977-2009

	United States				Canada	
	Annual Bike Trips (millions)	Bike Share of Trips (%)	Daily Bike Commuters (thousands)	Bike Share of Workers (%)	Daily Bike Commuters (thousands)	Bike Share of Workers (%)
1977	1,272	0.6	-	-	-	-
1980	-	-	468	0.5	-	-
1983	1,792	0.8	-	-	-	-
1990	1,750	0.7	467	0.4	-	-
1995	3,141	0.9	-	-	-	-
1996	-	-	-	-	137	1.1
2000	-	-	488	0.4	-	-
2001	3,314	0.9	-	-	163	1.2
2006	-	-	-	-	196	1.3
2008	-	-	786	0.5	-	-
2009	4,081	1.0	766	0.6	-	-

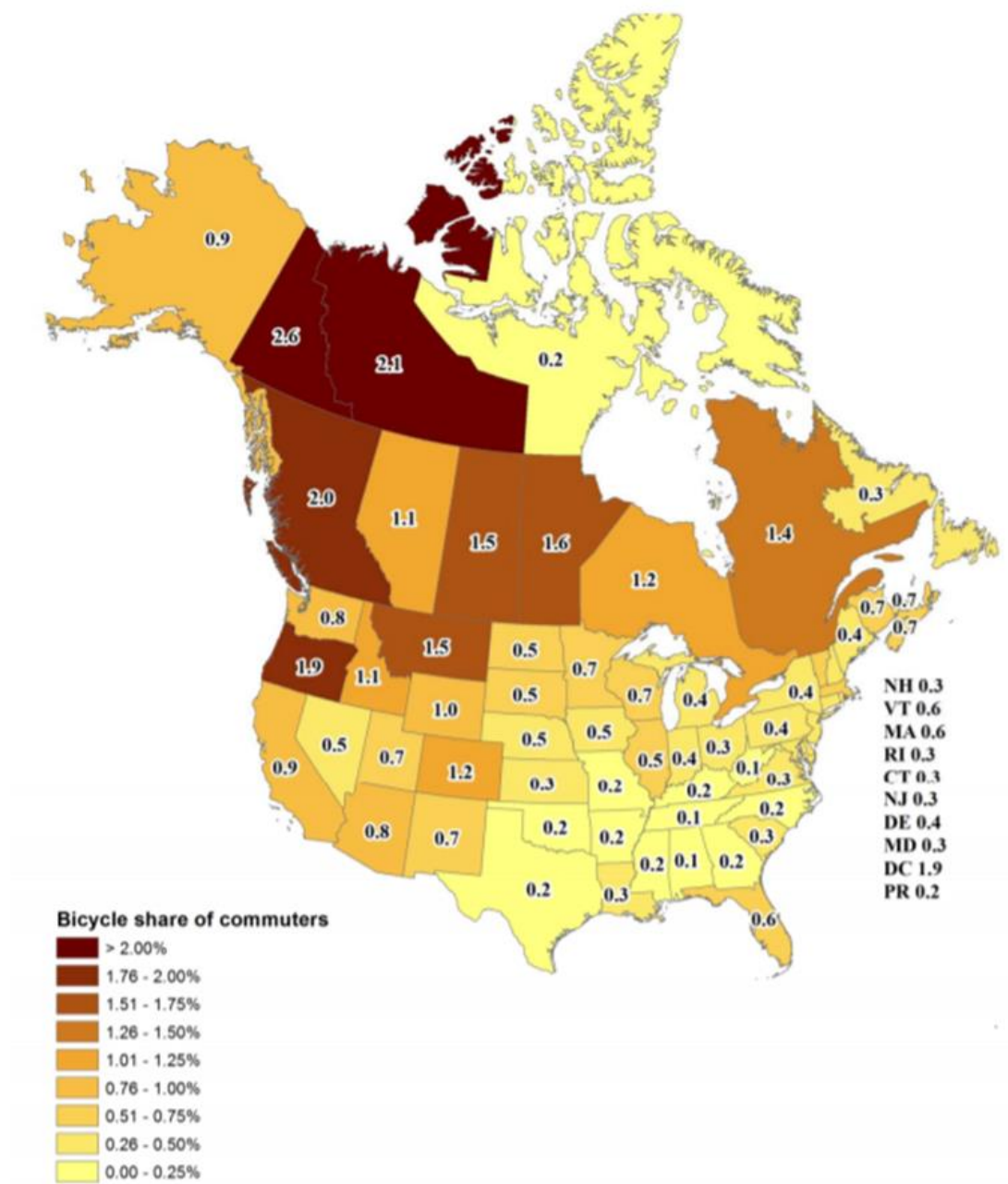


Figure 1.3 – Variation among states and provinces in bicycle share of work commuters in the USA (2005-2009) and Canada (2006)

## 1.1. Motivation

The growing trend of using active transportation as the main mode of commute, combined with municipalities' plans to encourage the use of bicycle have forced the transport authorities and planners to turn their attention to plan for more infrastructure for cycling. Providing parking space for bicycles is one of the important infrastructural incentives which greatly encourages the commuters to use their bicycles.

Knowing that there are available parking spaces at the destination or transit hubs, commuters will be more inclined to ride to their destination or to the transit hubs and catch the public transit. However, there are several discouraging factors that may alter the commuters' decision to use other modes of transportation.

Theft and vandalism are amongst the most important deterrents that cyclists usually facing. The security of their bicycle, which often costs a pretty price, is one of their top concerns, it is very disappointing and discouraging when a cyclist finds the bicycle, or its parts, is stolen or seriously damaged so that the cyclist must think of other ways to get to a destination.

The existing traditional parking facilities and solutions, such as Bike racks, cages or, even rooms, do not provide ample or sufficient protection against theft and vandalism. Bicycles are open and accessible to any mischievous person who can afflict damage to the bicycle. Besides inefficient security, these facilities also present another problem, to the cities and urban planners.

The traditional bicycle parking facilities are space inefficient and take up a large area for a relatively small number of parking spaces. A bike rack that can hold 20 bicycles would take up an area of about 18 to 20 m<sup>2</sup>, which makes it very difficult for the transportation planners to consider these parking facilities in every needed area.

Inspired by aforementioned deterrents and problems as well as by various Automated Storage and Retrieval Systems (AS/RS) which store goods, tools, and parts safely and securely and other existing solutions, this thesis proposes a design for a space-efficient, automated bicycle parking system that can store and retrieve bicycles safely and securely, through omitting common access.

A high level of security combined with space efficiency will work as great encouraging factors for both cyclists to use bicycles as their mode of commute, and the city planners to provide them with much less difficulty in small areas or confined spaces.

## 1.2. Background

As the cities and metropolitan areas getting larger and more populated, serious issues such as traffic and resultant carbon footprint become more and more palpable and intense. Traffic congestions and subsequent increased commute time combined by pollution problems urge the city planners to move towards designing and implementing more sustainable transit and transportation systems. Active transportation, especially cycling, is considered one of the effective answers to ever-increasing mobility and pollution problems of modern metropolitan cities.

Cycling as one of the modes of active transportation – besides Walking and public transit- is without a doubt one of the most sustainable modes with all the attribution of such transportation systems. Cycling promotes health and increases equity between generations (Social Sustainability) as well as being affordable and efficient and environmentally friendly (Economic and Environmental Sustainability) [1], [2], [6].

Vancouver 2040 transportation plan is set to achieve the goal of 12% of all trips be made by bicycle while the 2020 Action Plan targets to cut emissions by 33% from their 2007 level by 2020 [8], [18].

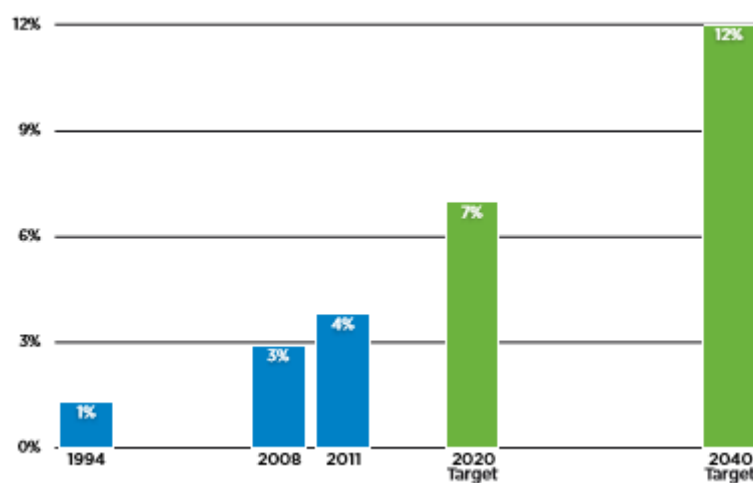


Figure 1.4 – City trips made by Cycling [8]

Cycling, according to a report by the City of Vancouver, has reached its target for 2020 by comprising 7% of all travels in 2017 showing a 4% increase from 2013. However, cycling share is still far behind the automobile mode share which comprised 52% of all travels in 2017 [17]. It is also a serious endeavor to achieve the goal of 12% of all city travels being made by cycling. Nevertheless, accomplishing these goals is imperative to fulfill the need for green cities in which people actively, and with the least carbon footprint, move around.

But how these targets and goals can be accomplished and realized? How can people be inspired to leave their cars at home and cycle to their destination? The answer might be simpler than it appears to be encouraging and motivating people by advocating cycling through providing cycling infrastructure and End-of-Trip (EoT) facilities.

The key reason for developing EoT facilities for bicycles is to encourage cycling as a mode of transportation and not just a recreational activity. EoT facilities make cycling more attractive and convenient for cyclers so that they will be used more often for functional purposes such as commute to work or shopping. Also including EoT facilities at transit hubs helps cultivating transit chaining, promoting, and encouraging both bicycle and transit use simultaneously, subsequently increase transportation sustainability [13].

Studies have identified the provision of secure and sufficient parking is one of the important and effective incentives. TransLink has conducted several studies on secure bicycle parking and EoT facilities. A 2008 regional survey identified the lack of secure bike parking at destinations as an obstacle to 8 to 15% of people, and bicycle theft was pointed out as a serious problem by 57% of people [19]. A study by the University of Leeds also shows that “Secure indoor/covered bicycle parking at destination”, is ranked 4 and 5 among the top ten wishes of frequent and non-frequent cyclists respectively [6].

Lack of proper and secure parking prompts cyclists to utilize whatever can be used as a substitute parking, namely trees, lamp or traffic signposts, etc. which leads to increase risk of theft as well as other risks and damages to public property and pedestrian and traffic safety. Thieves kick down young trees, unbolt or damage signposts to steal bicycles. Haphazardly parked bicycles can also be a nuisance to pedestrians and hinder the flow of foot traffic [20].



It is, therefore, evident that to realize their healthy, prosperous, and resilient future, cities should define an active plan of cycling infrastructure provision to achieve a sustainable, more environmentally friendly modes of transportation. Goal 4 of Vancouver's Greenest City Action Plan - Make walking, cycling, and public transit preferred transportation options – would not be materialized if the city's transportation plan does not include visions of making cycling “safe, convenient, comfortable and fun for people of all ages and abilities”. Therefore, to achieve Green city goals Vancouver Transportation 2040 has an explicit policy to “1 Provide abundant and convenient bicycle parking and end-of-trip facilities” [18], [8], [19].

As Gordon Price, a retired director of The City Program at Simon Fraser University who was a Vancouver councillor for 16 years and a Translink board member, said; “If you've built your city around the automobile, you will get drivers; if you build your city around transit, you will get riders” [2].

### **1.3 Bicycle parking facilities**

Transport Canada defines two broad and general temporal categories of bicycle parking facilities, Short-term and Long-term bicycle parking.

Short-term bicycle parking, also called *Class II* or *Class B* bicycle parking, consists of simple outdoor stands or racks. Two primary reasons for providing this category of parking is (1) To encourage cycling for utilitarian purposes and (2) To make bicycle parking more orderly and methodical.

Long-term bicycle parking, also called *Class I* or *Class A* bicycle parking, consists of bicycle stands or racks in an enclosure (partial or complete) or lockers that house individual bicycles. The main objective is to encourage the use of bicycles as the main mode of transportation or in combination with transit. However, since the cyclist must leave their bicycle for relatively long periods of time, theft and vandalism can be of disheartening factors [13].

However, from a design and operation point of view, bicycle parking can also be classified in another two broad categories: (1) Manual and (2) Automatic.

The manual class includes more simple and traditional systems such as bike rack and bike cages while the second category includes more sophisticated cover

parking which provides more security through different methods of automation and accessibility.

### **1.3.1. Bike stands and racks**

Bike stands and bike racks provide provisions for short term parking. A bicycle stand is a single vertical unit that can support one or two bicycles. Stands must be directly and properly anchored to the ground while bike rack is a unit with multiple vertical units to accommodate several bicycles, in other words, bike racks are composed of a group of bike stands [13].

Bicycle stands and racks come in many shapes and designs, amongst which the Inverted “U”, the Swerve, and the Post-and-Ring (or Ballard) can be considered as more common designs.



Figure 1.5 – Inverted “U” stand [23]



Figure 1.6 – Swerve stand [13]



Figure 1.7 – Post-and-Ring (Ballard) stand [23]

Bike racks, also come in different designs and shapes, including Grid (Ladder), Wave, and Campus racks, as common designs.



Figure 1.8 – Grid rack [22]



Figure 1.9 – Campus Rack [13]



Figure 1.10 – Wave rack [23]

Although bicycle stands and racks come in many shapes and designs, a good design provides areas to which the frame of the bicycle can be attached using a common lock such as “U” shape or cable locks.



Figure 1.11 – U shape lock [22]















Figure 1.12 – Cable lock [22]

The fundamental advantage of the short-term bicycle parking (i.e. bike stands and racks) is convenience and ease of use. They are usually installed in high traffic and most central areas such as major transit hubs or downtown. There is also a level of security associated with this type of bicycle parking, however since they are located in

open areas and accessible by the public, the security level is low and there is no guarantee [22].

Nonetheless, bike racks allow cyclists to park their bicycles conveniently and in an orderly fashion. They are economic and easy to install and use, Figure 1.13 compares different types of bike racks.

	 ORGANIZED	 SECURE	 DENSITY	 BIKE FRIENDLY	 VALUE
 GRID	★	★	★★	★	★★
 WAVE	★	★★	★★	★★	★★
 ORNAMENTAL	★★	★★★	★★	★★★	★★
 INVERTED-U	★★	★★★★	★★	★★★	★★★
 BIKE DOCKS	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★
 VERTICAL	★★★★★	★★★★★	★★★★★ (OFFSET ONLY)	★★★★★	★★★★★
 TWO-TIER	★★★★★	★★★★★	★★★★★	★★★★★ (LIFT-ASSIST ONLY)	★★★★★

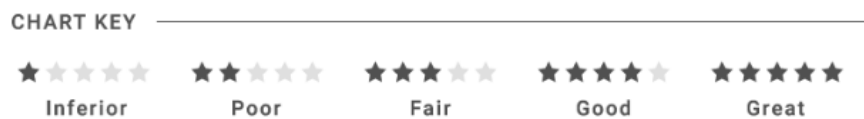


Figure 1.13 – Comparison of different bike rack designs [24]

### 1.3.2. Bike lockers, cages, and rooms

Meanwhile, long term parking facilities (i.e. bike lockers, cages, and rooms) provide more security and added protection by supplying sheltered and enclosure facilities. The main advantage of this type of parking is a relatively higher level of protection against theft and vandalism in addition to weather as they offer enclosed space and cyclists can also store cycling accessories attached to the bikes. Although the



unauthorized access is generally excluded, the common access is not completely eliminated since once one is inside the room, one will have access to all bicycles parked.



Figure 1.14 – Outdoor bicycle cage [13]



Figure 1.15 - Bicycle lockers at a SkyTrain station in Vancouver, BC [13]

Besides the low level of security and exposure to the public and therefore theft and vandalism, traditional parking facilities (i.e. bike racks, lockers, rooms, etc.) are hugely influenced by the area that they occupy or their “Land use”.

Land use is a key influencer for bicycle end-of-trip facilities. Levels of demand and availability of infrastructure vary significantly across land uses which in turn are reflected through cities and municipalities required bicycle parking facilities on private properties. Zoning bylaws normally disclose the requirements for bicycle parking with different amounts of short term (Class B) and long term (Class A) parking for each land use category.

The City of Vancouver Parking Bylaw specifies the following minimum dimensions for bicycle parking [19], [25]:

- Length of 1.8 m
- Width of 0.6 m
- Vertical clearance of 1.9 m
- Aisle width of 1.2 m (except with a special permit, for an absolute minimum of 0.9 m)

Which is similar to the recommended dimensions for most common bike racks.

The requirements for the amounts of Class B and Class A parking, as described earlier, varies however based on the category of the private property as it does for the metrics used to indicate the number of required bicycle parking spaces. For instance, for residential land uses, the number of parking spaces is directly related to the number of dwelling units, the greater the unit number of units the more parking spaces are required.

For commercial and industrial buildings, floor area is the metric with which the parking space is determined while for educational institutions the number of bicycle parking is proportional to the number of students and faculty members, table 1.2 illustrate an example of bicycle parking requirements for different land uses [19], [25].



Table 1.2 City of Vancouver bicycle parking requirements for different land uses

Building Classification	Class A	Class B
Dwelling Uses, including live-work use	No Requirements	No Requirements
Multiple Dwelling, Infill Multiple Dwelling, or three or more dwelling units in conjunction with another use, including live-work,	1.5 spaces for every dwelling unit under 65 m <sup>2</sup> . 2.5 per dwelling over 65 m <sup>2</sup> . 3 per dwelling over 105 m <sup>2</sup>	2 spaces for up to 20 dwellings. 1 space per every additional 20 dwellings
Office Uses	A minimum of one space for each 170 square meters of gross floor area.	A minimum of 6 spaces for any development containing a minimum of 2,000 square meters of gross floor area.
School - Elementary or Secondary; School – University, or College.	A minimum of 1 space for every 17 employees and for secondary schools, universities, or colleges, 0.4 space for every 10 students on a maximum attendance period.	A minimum of 0.6 space for every 10 students on a maximum attendance period except that elementary schools shall provide a minimum of 1 space for every 20 students.

Considering the required bicycle parking size combined with the amounts of mandatory spaces, the designated areas for bicycle parking, however, may introduce a potential problem with land efficiency and density along with other issues such as convenience, theft, and vandalism which will be discussed in more detail during the next section.

### 1.3. Outline

This dissertation has been divided into seven chapters.

Chapter one describes the motivation for the research by discussing the growing trend of cycling as well as active transportation plans and the required infrastructure and facilities. The chapter also portrays different types of traditional parking facilities and their use, while it delves deeper into bicycle parking requirements set by city bylaws.

Chapter 2 provides an overview of automated storage systems and discusses their working principals and applications as a foundation (or baseline) for the automated bicycle storage systems. The existing automated bicycle parking systems are introduced and discussed, further in this chapter.

Chapter 3 describes the design process and the steps which have been taken to generate concepts for the components of the system. The sequence of design is also discussed in this chapter.

Chapter 4 presents the process of the mechanical structural and static design of the system. The first section of the chapter explains the design objectives and how their development. Then the process of mechanical structure design for the structural and static sections of the system is explained. Chapter 4 concludes with actuators and mechanisms design of the system, which explains the calculation of required power and torque for various rotating and moving sections of the system as well as equipment and mechanism used to provide such motions.

Chapter 5 presents the approach for designing the control system and the automation of the parking system. This chapter depicts the development of tasks, logic, and the state machine model and concludes by explaining the programming of the controller.

Chapter 6 describes the manufacturing and assembly process of the parking system's various sections as well as the testing and results.

Chapter 7 is dedicated to the storage bin's weight optimization process. The chapter starts with providing a simple model of the rotating mass to explain the necessity of weight optimization. Next, it states the formulation of the problem, constraints, and the algorithm prior to concluding by presenting the results of the optimization process.

Chapter 8 finishes the thesis by presenting the conclusion and suggesting future work and research necessary to develop and improve the product furthermore.

## Chapter 2. Review of automated parking systems

Although conventional bicycle parking facilities – i.e. bike racks, cages, lockers, and rooms- provide facilities that make the parking experience more convenient and secure in an orderly fashion, they have inherent issues regarding the area they occupy and how secure they are.

Over two million bicycles are stolen each year in North America, almost one every thirty seconds [29]. In 2015, VPD received 3132 stolen bike reports, which makes for 52 per 10,000 residents [27]. U.S Department of Justice has considered removability and availability among the contributing factors of bicycle theft [26]. Since the short-term parking facilities are exposed to the public and mostly secured by some type of lock, the importance of these two factors become more evident.

Albeit conventional long-term bicycle parking provides a higher level of security than the short-term ones by offering enclosed facilities, however, they are not an efficient preventing and discouraging factor. Bicycle theft is among the top three complaints of the building residents in Vancouver [28].

Bike rooms and cages introducing another security issue which is the common space or common access. Once one is inside the bike room or cage, one has access to all the stored bikes which is encouraging for professional bike thieves considering that all they have to do is to get past a locked door, locks only keep honest people out.



Figure 2.1 – Common space and access in a bike room

Convenience is another influencing factor in bicycle parking usage. One of the key findings in a 2018 regional parking study by TransLink and Metro Vancouver is that “The design and capacity of bicycle parking facilities in apartment buildings appear to discourage use by many residents. The most frequently cited concerns were the risk of

damage to or loss of the bicycles, crowded facilities, and adverse perceptions of safety and convenience” [16].

Carrying the bicycle through multiple ramps, corridors, and gates to the bicycle storage area of the building not only introduces personal safety issues and risks – especially if those areas are not very well lit- but it becomes inconvenient at best if not nuisance.



Figure 2.2 (a) and (b) – Typical path to the bike storage room in a high-rise building

Furthermore, providing bicycle storage space in a building especially in high rises that enclose hundreds of dwelling units poses a serious problem for the developers. Vancouver’s parking bylaw requires bicycle space between 1.5 to 3 times the number of dwelling (see Table 1.2) located above or within the first level of automobile parking. Considering the required size of storage area, it will result in the utilization of vast prime real estate as a storage facility which could be otherwise used for other amenities and uses and generate more profit.

All the aforementioned issues and deficiencies of the conventional bicycle parking facilities have prompted the exigency of a more secure, reliable, and efficient parking solution. Valet bicycle parking has been considered and implemented as one of the solutions in various popular areas such as Granville Island in Vancouver. The City of

Vancouver has launched operation Rudy in 2015 which employed several strategies, including valet parking, to repress bike theft. The operation has reduced bike theft by 60% over the summer of 2015 [15]. However, the valet parking still provides traditional parking facilities that occupy a large area and space, with limited available hours within three months of summer. It also requires manpower to run and manage the valet parking which translates into an extra cost in form of personnel salary. Therefore, a more efficient solution is required to address the ever-increasing issues of bicycle parking.

## **2.1. Automated storage and retrieval systems**

Automated Storage and Retrieval Systems (AS/RS) has been in use for material handling since its introduction in the 1950s. In a broad sense, AS/RS can be defined as an integrated automated storage system that executes storing and retrieving operation with speed and accuracy. The AS/RS is principally used to store or retrieve loads in or out of the storage area. The control or automation system identifies the location where the load can be stored at or retrieved from and then plans the store or retrieval operation.

Although this definition of the automated storage system can be applied to a wide variety of systems with varying levels of complexity and flexibility, however, the term automated storage and retrieval system has come to mean a single type of system comprising one or multiple parallel aisles with multi-tiered racks; stacker crane (also referred to as storage/retrieval machine or S/R machine); input/output (I/O) stations (pickup/delivery stations, P/D stations or docks); accumulating conveyors and a central supervisory computer and communication system. Figures 2.3 and 2.4 exhibit examples of AS/RS machines.

AS/RS systems have numerous advantages; besides providing fast, accurate and efficient material handling on a 24/7 basis, they also provide savings in labour costs and space as well as increasing reliability and reducing human error. Noticeable disadvantage would be high investments costs [31], [32], [33], [34], [35], [36], [38].

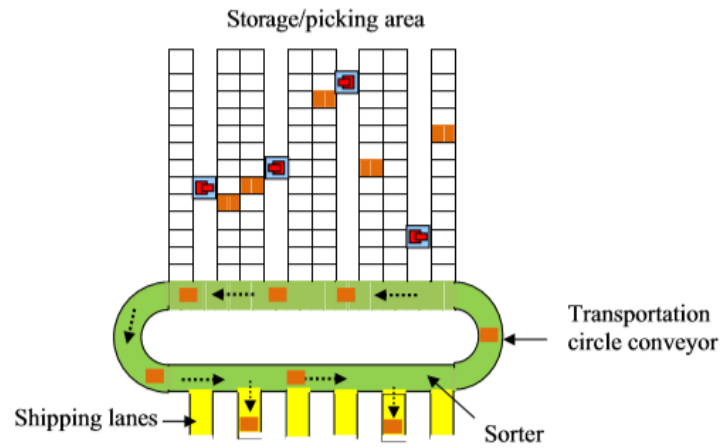


Figure 2.3 – Typical AS/RS [36]



Figure 2.4 – AS/RS Systems [31]

## 2.2. Types and application of AS/RS

Several types of AS/RS can be distinguished according to the size and volume of items to be handled, storage and retrieval methods, and interaction of a stacker crane and a human worker. The following are the principal types [66].



### 2.2.1. Unit-Load AS/RS

It is typically a large automated system with one crane in each aisle which cannot leave their designated isle (aisle-captive). It is designed to handle, and transport unit-loads stored on pallets or in other standard containers. The racks are stationary and single-deep which makes every load directly accessible by the crane. The unit-load system is the generic AS/RS. Other systems described below represent variations of the unit-load AS/RS.

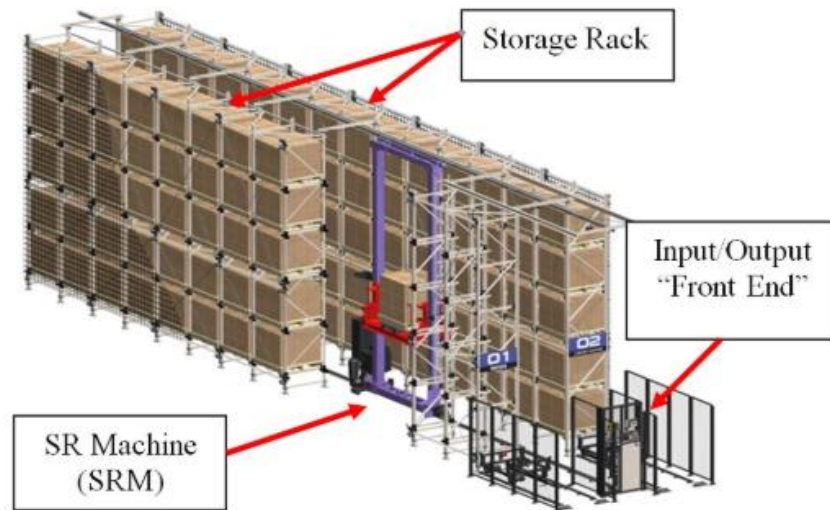


Figure 2.5 – Unit-Load AS/RS [61]

### 2.2.2. Deep-lane AS/RS

It is a unit load system that can accommodate more than one unit load by storing them to greater depths in the storage racks. The storage depth is greater than two loads deep on one or both sides of the aisle and one load is stored in front of another. Deep-lane AS/RS is suitable when large quantities of stock are stored, but the number of separate stock types is relatively small. In other words, it is beneficial when the variety of the load is low and the turnover rate of the load is high.

### 2.2.3. Miniload AS/RS

Miniload AS/RS is a unit load system that handles smaller loads that are contained by standard containers, bins, or drawers. The system performs like the unit



load system however the insertion/extraction device is designed to handle standard containers and bins which store components, parts, and tools instead of unitized load.

#### **2.2.4. End-of-aisle AS/RS**

Although AS/RS often store and retrieve unit-load, in many cases, however only part of the unit load is required. One approach to solve this issue and pick a part of the unit load is to integrate picking operation with AS/RS. To resolve the problem a picking area or workstation is designated to which AS/RS will deliver the load where picking operation is being carried out.

#### **2.2.5. Man-on-board AS/RS**

An alternative approach to the problem of retrieving individual items, from storage is the man-on-board system. In this system, a human operator rides on the stacker crane's carriage.

#### **2.2.6. Automated item-retrieval system**

These storage systems are also designed for retrieval of individual items or system product cartons; however, the items are stored in lanes rather than bins or drawers.

#### **2.2.7. Vertical lift storage modules (VLSM)**

Also called vertical lift automated storage/retrieval system (VL-AS/RS), VLSM systems are designed based on the principle of using a center aisle to access loads except that unlike the generic AS/RS, the aisle is vertical and not horizontal. Vertical lift modules are capable of holding large inventories while saving valuable floor space in the factory.

As it was mentioned, there are numerous variations from the generic AS/RS, an overview of which is provided in Figure 2.6 [31], [38],

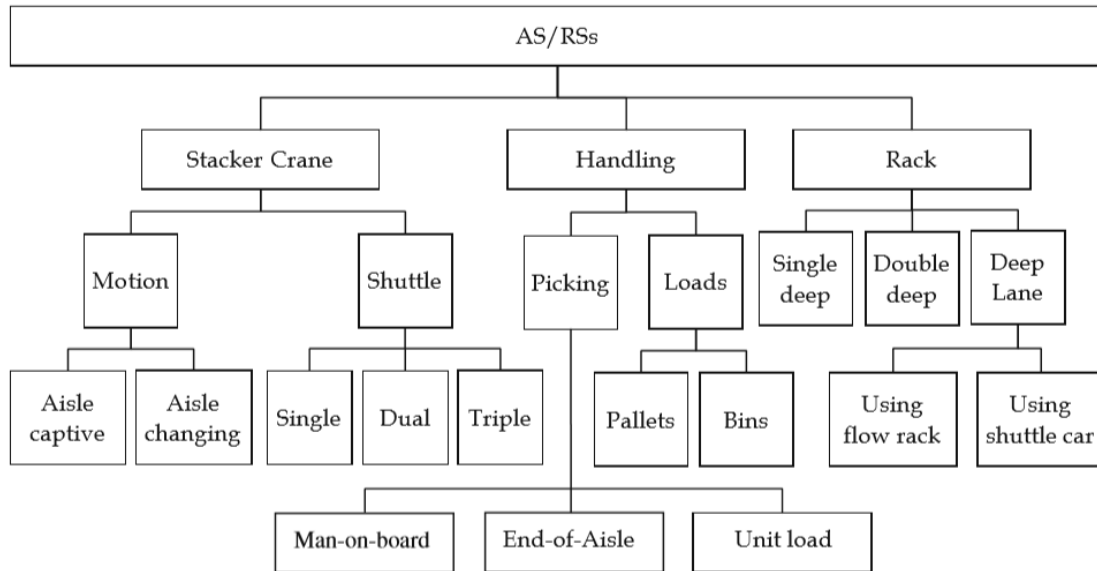


Figure 2.6 – Various concepts for AS/RSs

### 2.2.8. Carousel AS/RS

Carousel systems (vertical, horizontal) consist of a number of shelves or drawers, which are linked together and are rotating in a closed loop. It is operated by a picker (human or robotic) that has a fixed position in front of the carousel. Figure 2.7 shows a typical carousel system.

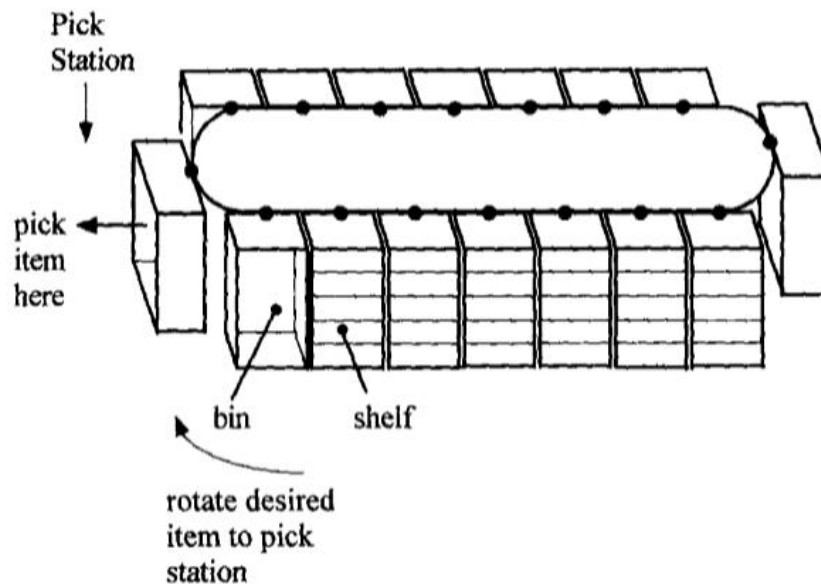


Figure 2.7 – A carousel storage and retrieval system.

Carousel systems are suitable for storing and retrieving small to medium-sized loads at different levels, they are substantially less expensive but more flexible than other highly productive alternatives such as miniload systems. In these systems, a crane provides vertical motion while the rotating carousel brings the load to the loading/unloading point where the crane can store or retrieve the load. In the case of two or more levels in one system, carousels can rotate independently. Most carousels are bi-directional, meaning that they can rotate in both a clockwise and counter-clockwise direction. In bi-directional carousels, the rotational direction is chosen by the controller to minimize the distance travelled by the next item to be picked.

Horizontal carousel storage systems are used in numerous environments. Table 2.1 provides the major businesses that employ carousels, the main function (in addition to storage) they serve.

Table 2.1 Carousel Applications

Sector	Function
Airlines	Maintenance
Book Publishing	Distribution
Distribution	Distribution
Entertainment	Distribution
Food: Manufacturing	Production
Groceries	Replenishment
Health Care: Manufacturing	Distribution
Health Care: Services	Replenishment
Mail-order Houses	Distribution
Manufacturing: Electronics	Distribution, Production
Manufacturing: Mechanical	Distribution, Production, Tooling Inventory
Military	Training
Space Industry	Production

An important practical problem in carousel management concerns the locations at which to stock the demanded items. Some facilities simply use a random storage strategy, wherein replenished items are put into any available bin. However, a more effective strategy is to use dedicated storage, with each separate item being assigned

permanently to its own bin. In this case, there arises the issue of how to assign individual items to bins so as to minimize the long-run average travel distance (or time) between successive picks [40], [41], [42], [43], [44].

## **2.3. Automated Bicycle Parking Systems**

### **2.3.1. Giken**

Giken Ltd, a listed company on the Tokyo Stock Exchange, is one of the world's leading developer of Press-In Construction technology and construction methodologies. Established as Kochi Giken Consultant and start civil engineering business in 1967, Giken was founded to extinguish construction pollution recognized as a major source of environmental contamination at that time. In 1975, GIKEN released the press-in machine, "Silent Piler", first in the world. Since then it has been developing machines and construction solutions based on the "Press-in Principle", having been accumulating results worldwide.

Giken has developed its design for underground automated bicycle parking systems during the 1990s and completed its first system, "ECO Cycle", in Kochi University of Technology, June 1998. Eco Cycle is an automated bicycle parking facility developed with the concept of "Culture Aboveground, Function Underground". With a compact entrance booth, it requires minimal space aboveground and provides more than 200 parking spaces underground. It consists of a circular static structure to keep the store bicycles and a rotating lift system at the center of the system, which transports the bicycles vertically, Figure 2.8 shows the system [45], [46].

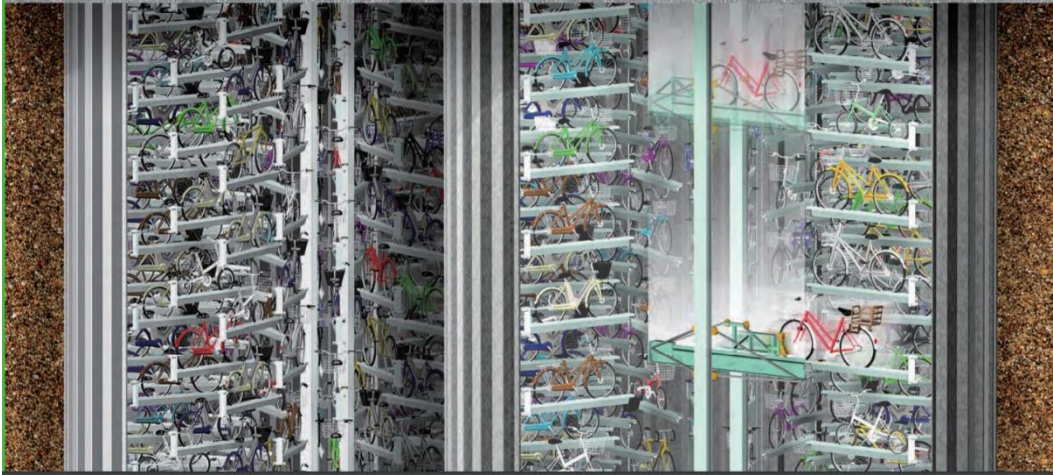


Figure 2.8 – Giken Eco System, Underground model with Bicycles

Giken has taken full advantage of its proprietary technology, the Press-In Method. This technology was originally developed for underground construction which became so useful in installing underground facilities such as bicycle parking. Figures 2.9 to 2.12 show the installation procedure [45].

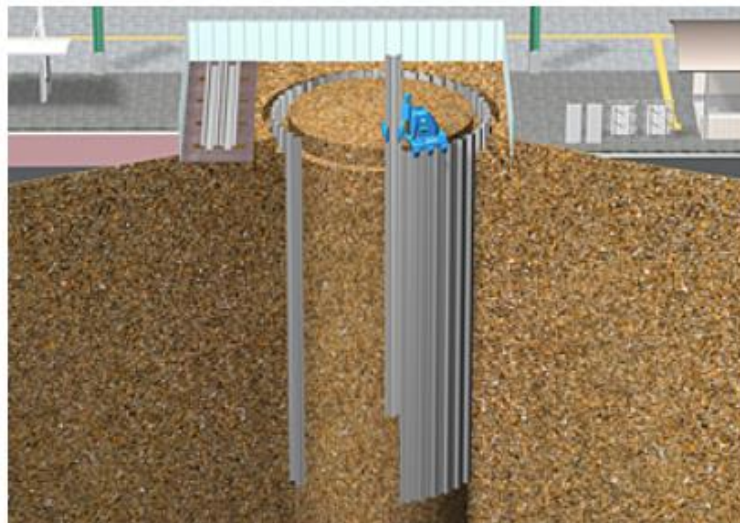


Figure 2.9 – Installing a specially designed piles to form a cylindrical wall using Silent Piler

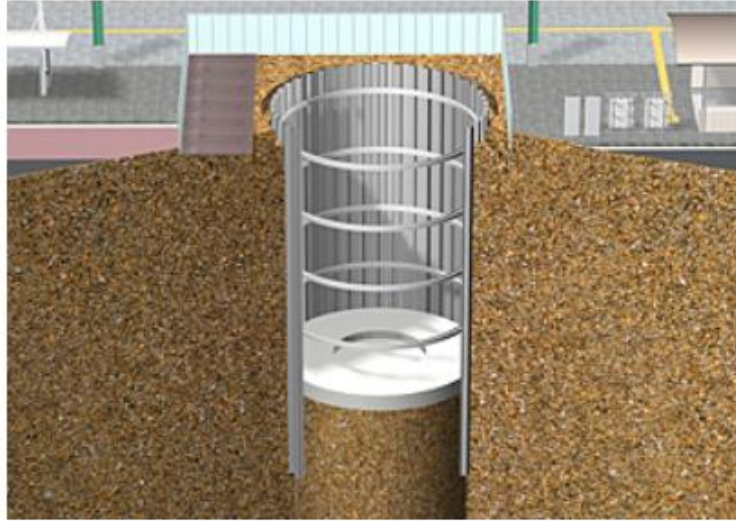


Figure 2.10 – Excavation of soil from the cylinder to create the underground space



Figure 2.11 – ECO Cycle is installed in the cylinder



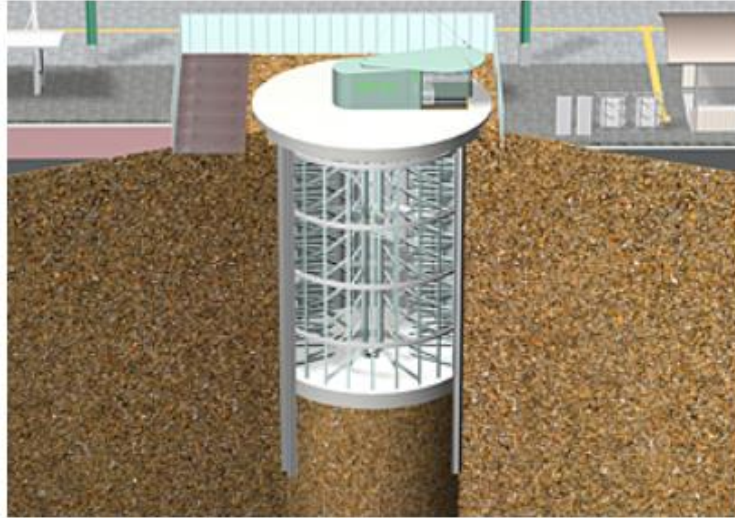
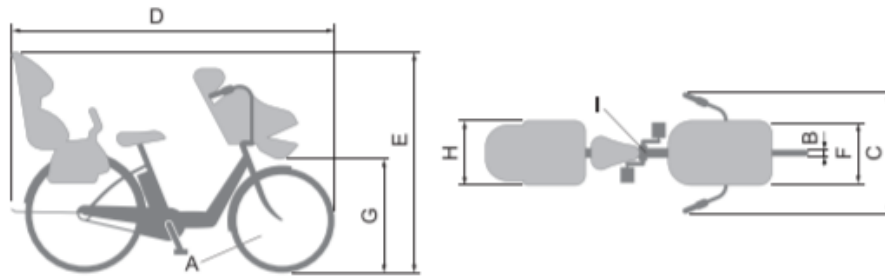


Figure 2.12 – Finally the entrance booth is fixed above ground

The system can accommodate a variety of bicycle models with different dimensions. Figure 2.13 provides the specifications of the bicycle.



A	Tire Size	18-28"
B	Tire Width	Max. 55mm
C	Total Width	Max. 650mm
D	Total Length	Min. 1400mm, Max. 1950mm
E	Total Height	Max. 1350mm
F	Front Basket Width	Max. 500mm
G	Front Basket Height From Ground	Max. 550mm
H	Rear Basket Width	Max. 500mm
I	Weight	Max. 40kg

Figure 2.13 Bicycle specifications 46]

### 2.3.2. Biceberg

Biceberg is another automated bicycle parking system developed by ma-SISTEMAS, s.l. The limited company ma-SISTEMAS, s.l. was created in 1994 in Spain to develop a safe system for the storage of bikes. The product, called biceberg, is an automatic underground bike parking which was patented on 2/12/94. Biceberg is an automatic underground bike park. It collects bikes from and returns them to street level. It can also be used to store accessories such as a helmet or backpack. The user carries out the operations using a microchip card with a secret personal code, in a process as straightforward as using cashpoints.

Biceberg is a modular system that can hold 23 bicycles at each level. The parking and retrieval of bicycles are done by means of biceberg park chip cards. The information about the user and the park is recorded in this chip. Figures 2.14 and 2.15 show the system and a user parking his bicycle [47].



Figure 2.14 – Biceberg model, showing underground installation





Figure 2.15 – Parking a Bicycle, Biceberg

### 2.3.3. Wohr

Established in 1902 as a metalworking shop, Wohr has been designing, innovating & installing various parking systems and solutions since 1959. Wohr is one of the leading manufacturers of car parking systems worldwide. For six decades now, since the number of cars on the roads began to increase, Wohr has been designing and installing parking systems.

Wohr's first electromechanical car parking system was installed as early as 1962, however, their bicycle parking systems were not developed until the 2010s. The first prototype of Wohr's fully automated bicycle parking, Wohr Bikesafe, was put to operation in BAU 2015 trade fair, in Munich.

The tower version of the WÖHR Bikesafe stores more than 120 bicycles on up to eight parking levels. The design of the Bikesafe requires a small footprint and is therefore space-efficient. Depending on preferences and requirements, the Bikesafe can be designed as a shaft version, tower version, or mixed version. Common bicycles, including pedelecs and e-bikes, with an overall weight up to 30 kg/66 lbs can be stored in the Bikesafe. Figures 2.16 and 2.17 show shaft and tower versions, respectively [48].

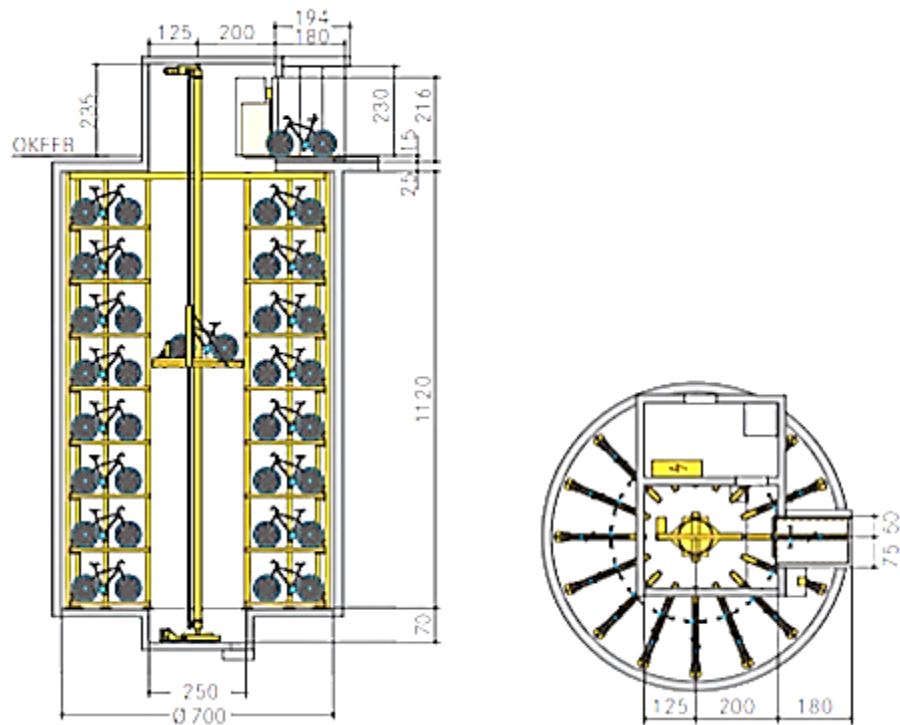


Figure 2.16 – Bikesafe, Shaft version

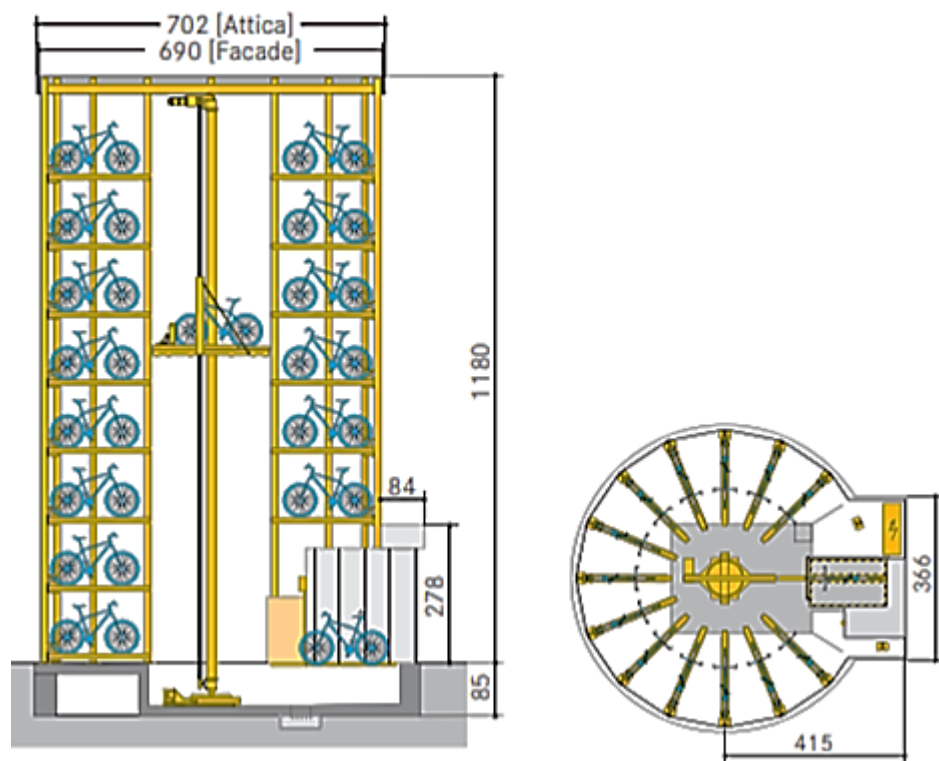


Figure 2.17 – Bikesafe, Tower version

Same as Giken's Ecocycle system, Bikesafe has a static metal structure with a rotating lifting system that transports bicycles vertically. The bicycles are stored inside the structure on similar equipment as a bike rack. The inside structure and storing equipment can be seen in Figures 2.18 and 2.19 [48].



Figure 2.18 – Storing and stored bicycles in Bikesafe



Figure 2.19 – Bikesafe, Inside structure

## **2.4. Summary / Conclusion**

In this chapter various AS/RS as well as existing automated bicycle storage systems are studied. It can be seen that in essence, an automated bicycle storage system is very similar to a carousel system and this type of storage system can be a good base for designing a bicycle storage system. Companies that are active in this field have products that to some extent mimic the basics of a carousel AS/RS.

## Chapter 3. Design process

In this chapter, the process of the mechanical design which had been followed in designing the automatic bicycle parking is described and discussed. The details of each step will be introduced, and examples provided to describe the design. The order in which elements of the system has been designed is reviewed at the end of the chapter. Some of the steps, such as defining the problem or product generation, are discussed in detail in chapters 2, 4, and 6.

Engineering design is a series of steps that designers follow to solve a problem, which many times includes designing a product that accomplishes a certain task in regard to certain criteria, Figure 3.1 depicts the general steps of design process.

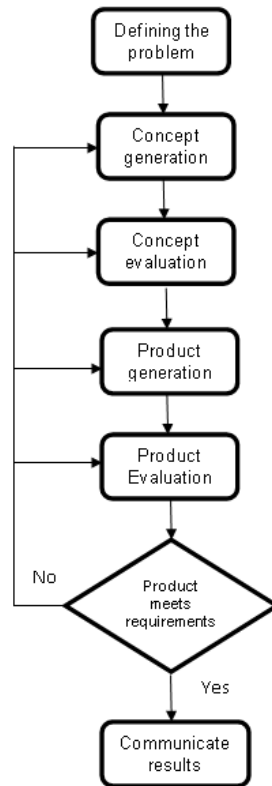


Figure 3.1 – Steps of the design process [60]

### 3.1. Defining the problem

Understanding the problem is the first step in designing a quality product. it means translating requirements into a technical description of what needs to be

designed. In order to comprehend the problem an organized plan to develop the major pieces of necessary information must be developed, an organized plan for:

- Hearing the voice of the customers
- Developing the specifications or goals for the product
- Finding out how the specifications measure the customers' desires
- Determining how well the competition meets the goals
- Developing numerical targets to work toward

To fulfill the problem, and consequently the product definition phase, following steps must be carried out:

1. Identifying customer
2. Customer requirements
3. The relative importance of the requirements
4. Competition evaluation
5. Engineering specification

These steps are discussed in chapters 2 and 4.

### **3.2. Concept generation**

The concept is an idea that is sufficiently developed to evaluate the physical principles that govern its behavior. Concepts are the means for providing the function. The function is the logical flow of energy (including static forces), material, or information between objects or the change of state of an object caused by one or more of the flows.

The goal of functional modeling is to decompose the problem in terms of the flow of energy, material, and information. This forces a detailed understanding at the beginning of the design project of what the product-to-be is to do.

Reverse Engineering, functional decomposition, or benchmarking is a method to understand how a product works. It is a good practice because many hundreds of engineering hours have been spent developing the features of existing products.

### 3.2.1. Overall function

By studying existing products and the requirements for the automated bicycle parking, and after deliberations the overall function of the product is defined as:

- To automatically position, locate, and store a bicycle in a secure enclosure by converting electrical signals and energy into mechanical motion.

This statement is brief, it tells that the goal is to alter the material and energy flow while processing the input information and that the boundaries of the system are the access door of the system and the storing location.

However, the overall function must be decomposed into subfunctions and arranged in the required order so they could be used in generating concepts. As it was mentioned previously, reverse engineering was the method used to understand the product's functions. Studying existing products helped to decompose the overall function into the following subfunctions:

- Lift
- Rotate
- Locate
- Translate
- Position

These are the major subfunctions that the product should accomplish.

- Locating a storage bin based on the input information,
- Moving the storage bin up and down,
- Position the storage bin by rotating
- Translating the storage bin to and from the door.

The function decomposition and the subsequent subfunctions will be discussed further in chapter 5.

### 3.2.2. Concept generation

Once the functions were identified and arranged in the required order, generating concepts for each function was the next step. Commonly used methods, such as brainstorming, analogies in design, reference books, and consulting experts were used to generate concepts for different functions.

Functions were first organized based on their type of motion, vertical translation, rotation, and horizontal translation, then for each function (or motion), concepts were generated. Table 3.1 shows the results for the vertical translation (or lift) as a sample to show how the process of concept generation has been utilized for the project.

Table 3.1. Vertical translation concepts

Function	Concept	Source
Vertical Translation	Scissor lift	Brainstorming
	Rack and Pinion	Brainstorming, Analogies, reference books, experts
	Rope and pulley	Brainstorming, Analogies, reference books, experts
	Pulley and belt	Analogies, reference books
	Hydraulic system	Brainstorming, analogies, experts
	Pneumatic system	Brainstorming, analogies, experts
	Linear motor	Brainstorming, reference books
	Chain and sprocket	Brainstorming, Analogies, reference books, experts



### 3.3. Concept evaluation

The goal is to expend the least amount of resources on deciding which concepts have the highest potential for becoming a quality product. The difficulty in concept evaluation and decision making is that we must choose which concepts to spend time developing when we still have very limited knowledge and data on which to base this selection.

Virtual and physical models of the concepts were prepared to evaluate the concepts. Because more cost was associated with physical modelling, virtual modelling was the dominant method to generate and evaluate concepts, however where physical modelling was necessary, they were produced. SolidWorks has been used as the modelling and simulation software to test and evaluate concepts. Appendix C provides some of the concepts and design iterations of some key elements of the system.

A good example of using both physical and virtual modelling can be shown in the concept of storage bin. One concept was to cut panels from sheet metal and connect them together to generate the storage bin, Figure 3.2 shows the SolidWorks generated model.

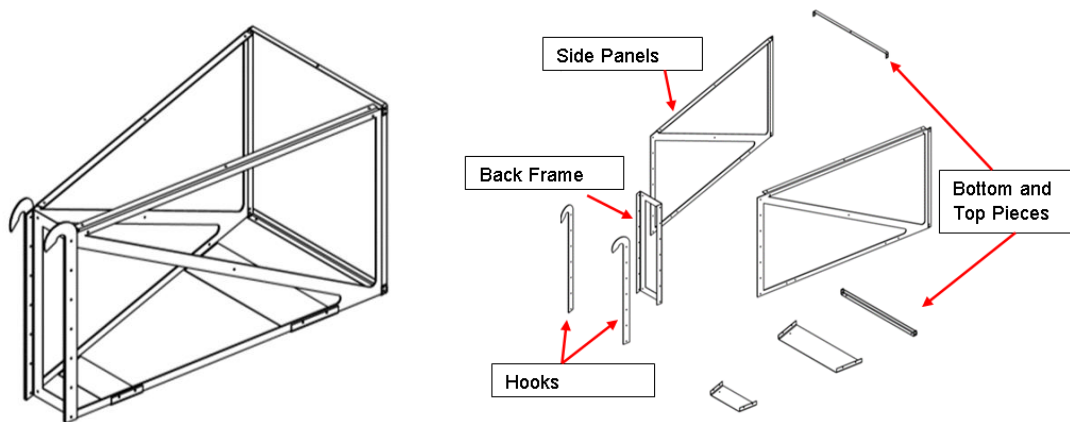


Figure 3.2 – SolidWorks model, storage bin frame

Another concept was to create the storage bin by using off the shelf metal profiles such as angle bars. Although this concept was eventually modelled by SolidWorks, however, to get a better understanding of how the final product will be and

how it will be arranged side by side on a circular path few scaled physical models were made using scrap parts, Figure 3.3 shows one of these physical models.

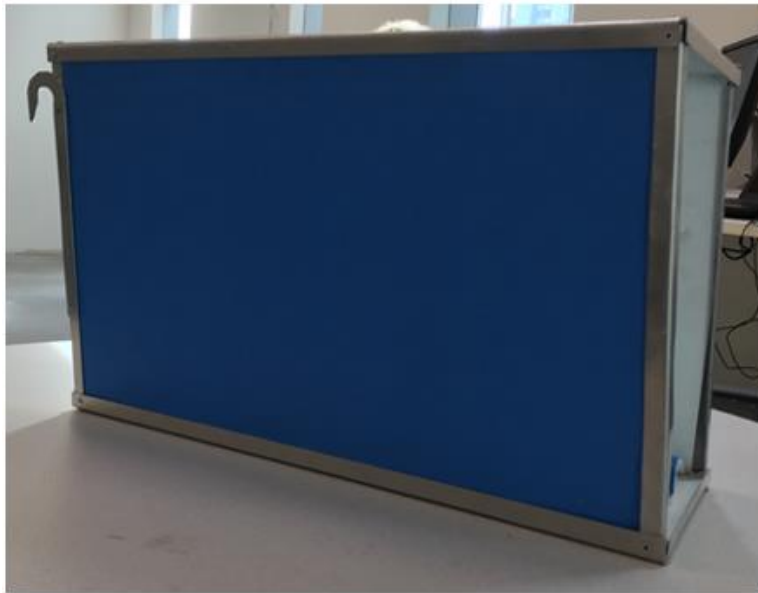


Figure 3.3 – Storage bin, scaled physical model

Manufacturing shops were contacted to obtain information about manufacturing considerations such as material, and manufacturing cost and methods. The final decision on these two concepts was that the first concept (Figure 3.2), due to cutting cost of sheet metal, is more costly than the one shown in Figure 3.3.

### **3.4. Product generation**

The goal of the product design phase is to refine the concepts into quality products. The knowledge gained making the transformation from concept to product can be used to iterate back to the concept phase and possibly generate new concepts. Product generation is discussed in sections one and two of chapter six which provides details of manufacturing and assembling of the automated bicycle parking system.

### **3.5. Product evaluation**

The goal of product evaluation is to compare the performance of the product to the engineering specifications developed earlier in the design project. Performance is the measure of behavior, and the behavior of the product results from the design effort to

meet the intended function. Thus, part of the goal is to track and ensure an understanding of the functional development of the product. Evaluation for performance provides an opportunity to be sure that a quality product is being developed, therefore design in quality is another goal of evaluation. Section three of chapter 6 addresses testing the final product.

### **3.6. System's elements design sequence**

One of the important considerations in this thesis is the sequence in which the automated bicycle parking system is designed. The design sequence affects the time spent on design as well as the accuracy of it. The parking system has many elements and components which affect each other directly. The size, shape, or weight of one component can change the design of others. To further explain the matter the effect of the storage bin on the design of other elements and components of the system is discussed.

The physical specifications of the storage bin, such as dimension, weight, etc., are considered as one of the inputs for designing the rotational structure that carries them. The combination of storage bins and the rotational structure, subsequently, affects the design of load-bearing structure that carries the combined weight of them. The storage bin also affects the design of the components which provide vertical and horizontal motion.

For instance, to design the rotational structure, the weight of the storage bins should be already obtained. If the design of the rotational structure is commenced before the storage bin by making assumptions about their weight, it is likely that the design of the rotational structure will not be accurate and therefore, must be redone. The same argument can be made for the load-bearing structure. The weight of storage bins is also an important factor in designing the drive system and the required power. Considering this cascade of design information from one component to the next, a design sequence was defined to prevent inaccurate design inputs for the components, Figure 3.4 shows the sequence of design.

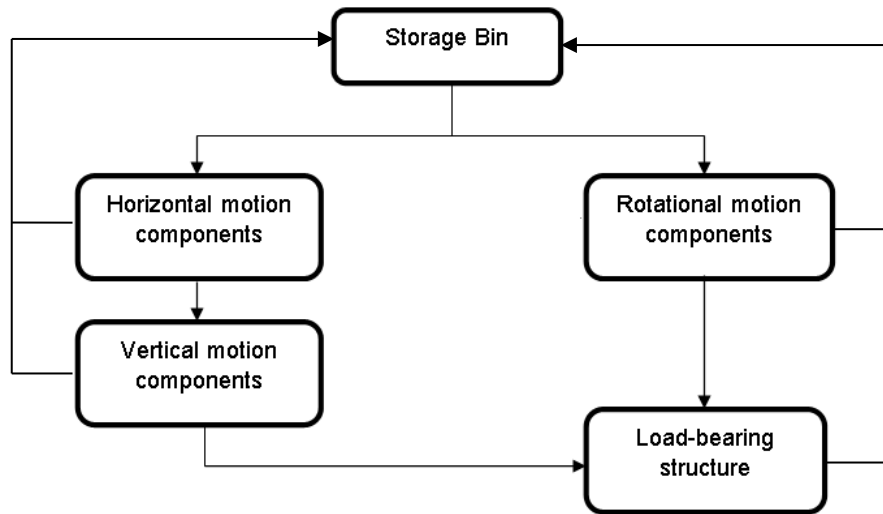


Figure 3.4 – Design sequence

## Chapter 4. System Design

This chapter introduces the mechanical design of the system which consists of structural design of the mechanical components, as well as actuators and mechanisms. It includes static and structural design of the main load-bearing components as well as drive system design for motion of the system.

Due to the complicated nature, complexity, and sophistication of applied loads, as well as components' geometry, shape, and position, the majority of the design and modelling have been done with the help of a CAD/CAM software -namely SolidWorks- however, high-level hand calculation has been applied when necessary to ensure that the result is consistent and sound.

### 4.1. Design Objectives

The design objectives for the automated bicycle parking system is based on two separate sources: Customer requirements and existing automated bicycle parking systems in the market.

#### 4.1.1. Customer Requirements

Two sectors have been identified as customers.

- External: End-users and Buyers, which comprises of Cyclists, high rise Developers, Municipalities and Architect firms
- Internal: the designer's management, manufacturing personnel, sales staff, and service personnel

Among which Bikehub, Bosa development, Westbank development, IBI group, Henriquez architects, City of Vancouver, City of Richmond, UBC campus and community planning, Burrard mechanical, and Open staircase can be mentioned.

Cyclists are the direct end-users of the system although they are not the buyers. However, they have a strong influence on purchasers and potential buyers. Municipalities and high-rise developers are the buyers of the system. They both are influenced by the cyclists' opinions and voices. What the public requires can have an immense impact on the decisions made by cities and municipalities. The demands of residents/buyers of the high-rise units can also affect developers' decisions.

To identify customers' requirements, different methods have been deployed for different segments. Surveys are used to collect cyclists' requirements and gathering information regarding bicycle parking problems and concerns that cyclists face. As for developers and architect firms, interviews were conducted in order to understand their pains and needs. Focus groups have also been considered to obtain concerns and requirements of Municipalities and cities. Committees and groups within the municipalities have an influential voice on what will be decided by the local governments.

Interviews and direct meetings as well as feedbacks on sales pitch, have been conducted to acquire internal customers' requirements. Meeting and interviewing manufacturers and manufacturing experts, as well as the feedback from the sales pitch has also provided valuable information about internal customers' needs and what their concerns are. Table 4.1 shows the results.

Table 4.1. Customer requirements

Segment	Customer	Requirements \ Concerns
<b>External</b>		
	Cyclist	Security, Theft and Vandalism, Convenience, Ease of use, Availability, ...
	Municipality	Aesthetic, Performance, Maintenance, Space ...
	Developer	Space, Performance, Maintenance, ...
<b>Internal</b>		
	Production	manufacturability, available resources, standard parts, ...
	Marketing\Sales	Easy and suitable to display, Aesthetic, Storage and Transportation, ...

#### **4.1.2. Existing automated systems**

Existing automated bicycle parking systems provide an invaluable source of information regarding design and product specifications. Considering and studying the technical brochures and specifications of the various automated bicycle manufacturers in the previous section, yielded a set of performance and functional specifications as well as an overview of customer requirements.

Since these companies have done market and customer requirement research, their specifications can be used as a base to define practical and acceptable engineering specifications for the product.

#### **4.1.3. Design objectives and specifications**

Design objectives for the automated bicycle parking system are defined based on customer requirements and existing automated parking systems for bicycles. Design objectives address various requirements, tabulated in Table 4.1, by both external and internal customers.

To address requirements of convenience, security, and ease of use for cyclists, the objectives include individual storage bins per stored bike, accessibility through individual ID and password, and a simple interactive interface. Additionally, the system accommodates a vast range of bicycle sizes and enables the cyclists to store their riding gear as well.

Space, as well as performance and maintenance, are other major concerns of customers, to satisfy these requirements, the maximum size of the system is 7m which is also within the range of what competitors offer. Also, equipment is procured from reliable manufacturers who provide sufficient aftermarket support. In addition, enough space for service and maintenance crew inside the system is considered so they can perform their tasks with relative ease. The parking system also has a modular design to provide easier and less costly manufacturing and installation.

Based on requirements and objectives a set of specifications for the parking system is defined. For instance, the dimensions of the storage bin are dictated by the maximum size of the regular bicycle available in the market. Using results from research that had been done to identify engineering specifications for the storage bins. As for the maintenance space inside the system based on personal experience in service and

maintenance, a minimum of 1m in diameter of space is considered. Table 4.2 provides specifications of the parking system.

Table 4.2. Design specifications

System's Specification		
<b>Type of system</b>		Overground
<b>Power</b>		220 V, AC
<b>Structure type</b>		Modular
<b>Capacity</b>		17 Bicycles per module
<b>Module height</b>		1350 mm
<b>Average waiting time</b>		~1 minute
<b>Diameter</b>		7000 mm
<b>Access point</b>		Ground level
<b># of access points</b>		1
<b>Bicycle specs.</b>	Length	2000 mm
	Maximum height	1200 mm
	Maximum width	800 mm
	Maximum weight (bicycle and riding gear)	35 Kg



## 4.2. Structure and static design

In this section, the structural and static design of the system components is introduced and discussed. Stationary design mainly consists of designing the load-bearing structure of the system which includes the Central columns, truss rings, lift towers and platforms, and the storage bin. Figure 4.1 shows the overall concept of the system.

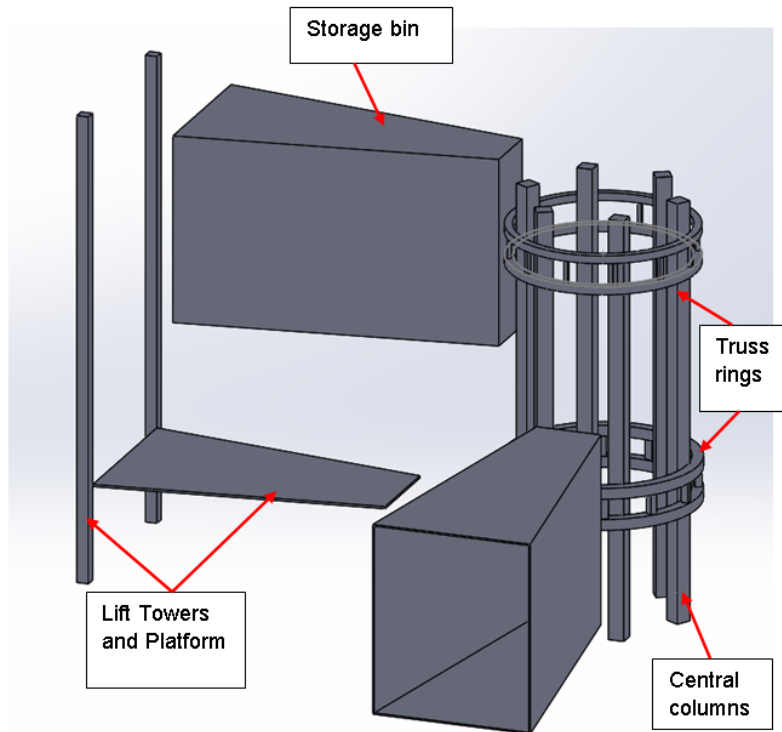


Figure 4.1 – Concept of structural and static design components

### 4.2.1. Storage Bin

The storage bin is a space in which a bicycle is stored. The storage bin, as can be seen in Figure 4.2, consists of a metal frame with plastic cladding. Structural steel is selected as the material for the metal frame because of its lower purchasing and welding costs compare to aluminum. Small size profiles, rectangular HSS tubing, and angle bar, make up the metal frame, these profiles provide sufficient mechanical strength, as well as enough space to install plastic cladding, and their weight per unit length is lower than solid bars. The back part of the bin (back frame), which includes the hanging apparatus as well as the resting area on the truss ring, is made of heavier gauges of metal to supply ample support and stiffness to carry the load of the storage bin.

The plastic cladding provides cover and privacy. The plastic cladding, however, is assumed to not support any of the acting loads and its weight is considered part of the acting load on the metal frame.

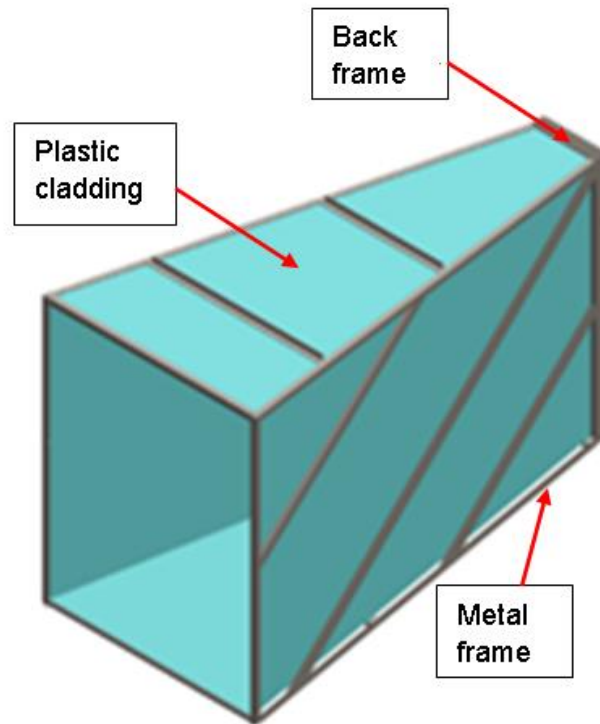


Figure 4.2 – Storage Bin, complete with plastic cladding

As it was mentioned, the back frame of the storage bin is the area that supports the storage bin weight when it is hung on the truss ring. It acts as a frame that the rest of the storage bin is connected to while it transfers and supports the horizontal and vertical load at its hanging point on the truss ring. Table 4.3 shows the forces and their calculation for the storage bin. The weight of the bin is obtained from the SolidWorks model of the designed Storage bin.

Table 4.3 Exerted Forces by the Storage bin

Base Calculations for Forces from the Storage Bin				
Distance from center of mass to back plating	40.125	in	1.019	m
Total lever arm distance	42.251	in	1.073	m
Mass of bin	220	lbm	100	kg
Weight of bin	220	lbf	981	N
Moment caused by bin	9295.22	lbf*in	1052.78	N*m
Force exerted on back plate	562.98	lbf	2510.4	N

Table 4.3 shows the forces that the storage bin exerts on its storing location on the truss ring; however, the storage bin itself will also support the forces due to its own weight and the weight of a bicycle. The SolidWorks model indicates that the total weight of the storage bin (metal frame and plastic cladding) is 100Kg and the bicycle weight at most is considered to be 35Kg (see Table 4.2). Therefore, the exerted load on the storage bin is 135Kgf. Table 4.4 and shows the result of the FEA analysis (also see appendix A).

Table 4.4 FEA results, Storage bin

FEA results_ Storage bin		
Max. Von Mises stress (Mpa)	Max. Displacement (mm)	Min. Safety factor
78.6	4.5	3.5

#### 4.2.2. Truss Ring

The function of the truss ring is to provide support for the storage bins as well as the ability to rotate and position them at the loading area, Figure 4.3.

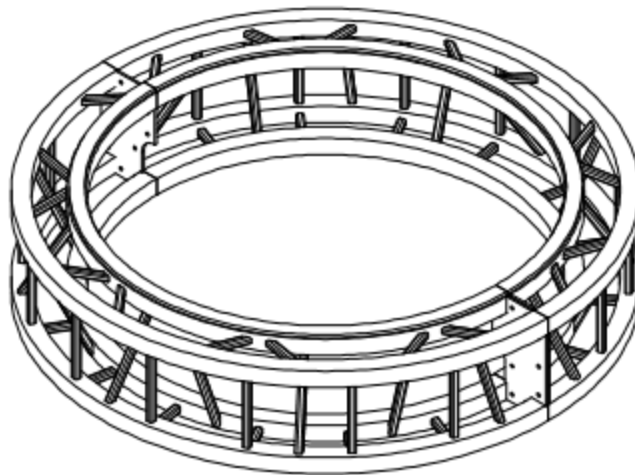


Figure 4.3 – Truss Ring

The storage bins are large and long storage elements (1000WX1200HX2000L mm), which are hanged on the truss ring via hooks, which are on the truss ring. The lower part of the storage bins is rested on the lower ring of the truss ring, which exerts a

horizontal force on the ring. Storage bins not only exert their weight on the ring, but they also apply a bending moment as well as contact stress on their support,

The truss ring should also be able to rotate around its central axis to move the desired storage bins to or away from the loading access. Therefore, there are wheels in this design to allow the ring to rotate freely. Figure 4.4 illustrates the support wheel assembly and the truss rings on their support wheels, respectively.

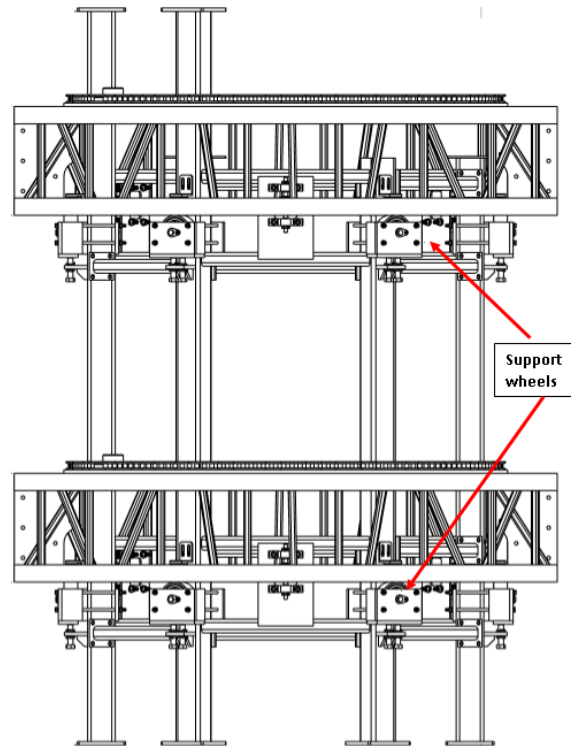


Figure 4.4 – Truss rings and their support wheels

Truss rings consist of 4 curved square tubes on the top and bottom of inner and outer rings combined with truss elements. The curved tubing can be modeled as horizontal curved beams. Complex equations govern the stress and displacement analysis for such beams [49], [50], [51]. However, truss rings are not just horizontally curved beams, they are horizontally curved trusses with members in a 3D space, nonetheless, the FEA results show that the designed structure is very well capable of handling the load, as it can be seen in table 4.5 (also see Appendix A).

Table 4.5 FEA results, Truss Ring

FEA results_ Truss Ring		
Max. Von Mises stress (Mpa)	Max. Displacement (mm)	Min. Safety factor
95	0.17	2.6

### 4.2.3. Lift frame and platform

The lift frame and platform are the subassembly of the lift upon which the storage bin rests while being moved to or from the access door. It is composed of two subsections: Lift frame and Lift platform. Figure 4.5 shows the components of this subassembly.

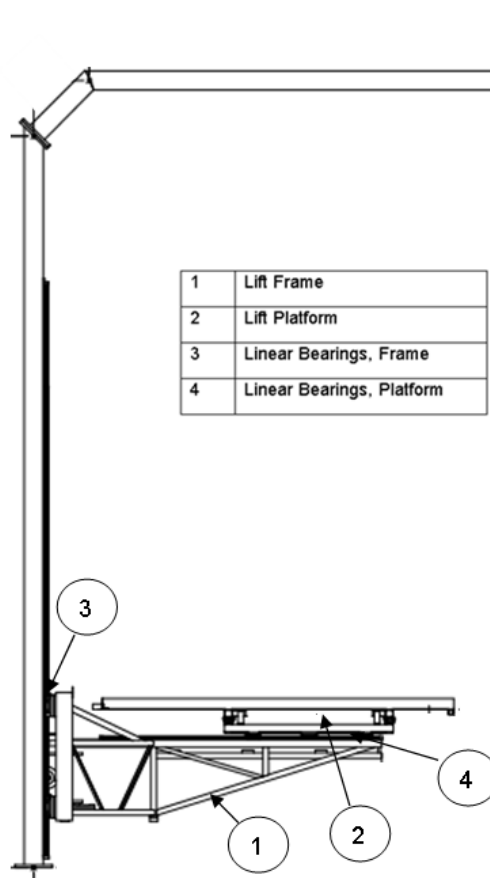


Figure 4.5 – Lift Frame and Platform

The lift frame provides the supporting structure for the motor and the platform. The frame is connected to the lift towers through linear bearings, Figure 4.6, which not only support the load but enable the whole lift platform and frame to move vertically. The sources of the loads are the weight of the cantilever structure of the frame and the storage bin loaded with bicycles.

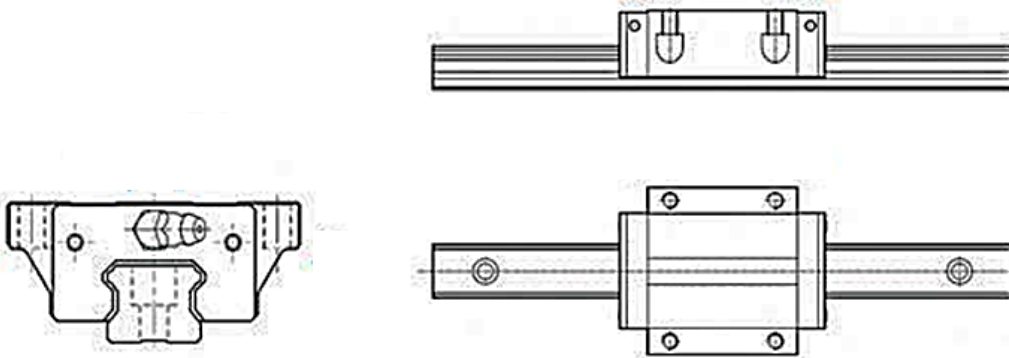


Figure 4.6 – Linear Bearing

The structure of the frame has two side trusses with crossing members, which creates the frame structure. At the front, it provides space and support for mounting motor and other drive equipment. Figure 4.7 shows the structure of the lift frame.

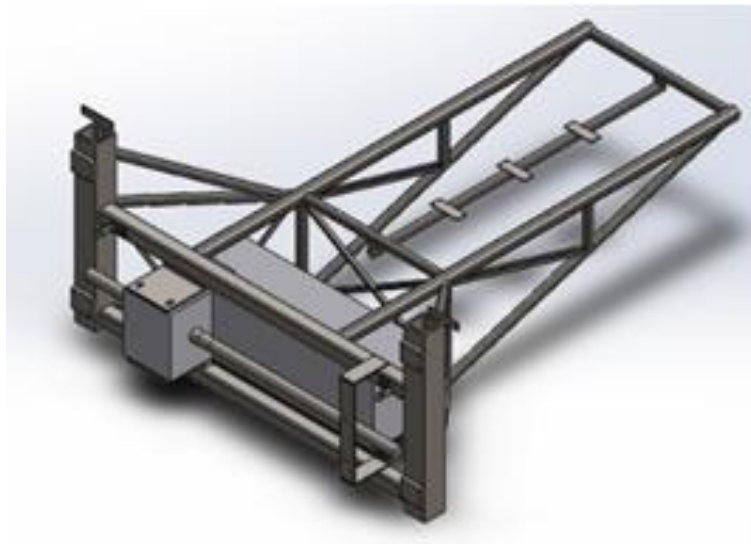


Figure 4.7 – Lift Frame

The lift platform, on the other hand, provides the seat for the storage bin as well as the horizontal motion to or from the access door. It consists of a simple frame on

which, during the loading or unloading cycles, the storage bin rests. Linear bearings provide load support as well as enabling the platform to move horizontally

#### **4.2.4. Lift Towers**

Lift towers are the support for the platform that moves vertically and brings the storage bin to the access door or back to its storing location on the truss ring. The lift towers support not only the weight of the platform, storage bin, and bicycle, but they also support the dynamic load from accelerating and decelerating of the vertical motion of the platform. The towers consist of two vertical columns which are framed by means of top and bottom lateral struts. Two cross members are added at the top of the columns for more stability and strength.

Although the lift tower assembly is installed by baseplates and anchor bolts, however, having it as a stand-alone structure without being secured is not desirable. Therefore, a connecting structure has been designed to secure the lift towers to the central column structure. Since the central column structure is hexagonal, which is anchor bolted to the ground, it provides stability and support for the lift towers. The connecting structure can be attached to the two taller columns of the central column assembly by the means of base plates and bolts. The resultant connected structure stabilizes the lift tower assembly and adds sturdiness and strength to the system to support heavy static and dynamic loads.

Although the lift tower assembly can be considered as a structural frame, however, since the forces, loads, and bending moments are not in the frame plane and are vertical to it; therefore each tower can be considered as a column with an eccentric load. The fact that forces are not in the frame plane also gives another reason (or justification) for the connecting structure. Figure 4.8 shows a schematic of the lift towers, the connecting structure, and the applied load (modeled as the grey box), which is the lift platform and a full storage bin combined. The resulting force and moment tend to bend the towers towards the center of the system, therefore the connecting piece provides support and restricts columns deflection.

The loads on the lift towers have resulted from the lift platform, storage bin (which seats on the lift platform), and the bicycle inside the bin. Table 4.6 shows the details of the lift tower loads.

Table 4.6 Static Load, Lift Towers					
Static Load Table (all values in Kg)					
Bins + Bikes	Lift Frame and Platform	Bins + Bikes + Lift Frame and Platform	Motor and accessories	Total Load	Load per Column
135	120	255	200	455	227.5

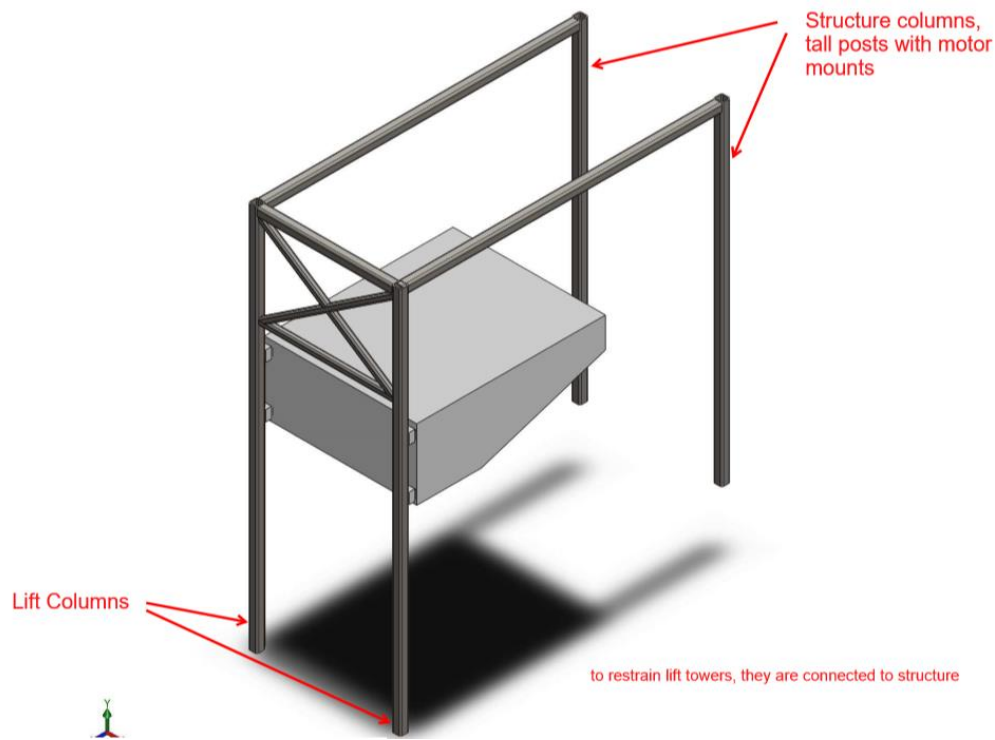


Figure 4.8 – Lift tower assembly schematic

The criteria for material selection is to possess proper mechanical and physical properties as well as purchasing and manufacturing cost, and availability. Although Aluminum may seem a better candidate because of its lighter weight but because of its lower tensile and yield strength (compare to steel), to achieve similar safety factor,



columns with a larger size would be needed. Furthermore, the cost of purchasing and welding aluminum is considerably higher than steel, therefore, the material of the columns is selected as structural steel CSA G40.21-13 50W. As for the profile of the columns, considerations are to have enough face width to install various parts such as load-supporting wheels as well as weight, therefore 3-1/2"x3-1/2"x3/8" Square HSS is selected as the column's profile. The 3-1/2" face width provides enough area to install linear railing and rack gear, and the hollowed tubing offers lighter weight than the solid square bar, Table 4.7 shows the material and section properties.

Table 4.7 Lift tower material and section properties

Columns' Material and section properties				
E (Gpa)	Yield (Mpa)	Tensile (Mpa)	I (mm <sup>4</sup> )	A (mm <sup>2</sup> )
205	429	491	2697179	2638

Table 4.8 shows the results of the FEA for stress and deflection analysis, for the lift tower assembly (also see Appendix A).

Table 4.8 FEA results, Lift Tower Assembly

FEA results_ Lift Tower Assembly		
Max. Von Mises stress (Mpa)	Max. Displacement (mm)	Min. Safety factor
59.81	0.36	4.1

#### 4.2.5. Central columns

The central columns are the main load-bearing component of the system that supports the load of the storage part of the system which is storage bins and truss rings as well as the weight of itself. Therefore, the strength of the components is of utmost importance. To provide a minimum diameter of 1m of open space inside the assembly for installation and maintenance purposes, a hexagonal shape column assembly has been chosen (see section 4.1.3 and Figure 4.9). Besides the fact that as the number of the sides increases the polygon approaches its base circle, the hexagonal arrangement (compare to a triangle or square arrangements) also offers less load per column which in

turn allows for smaller size columns, subsequently creating more space between the columns.

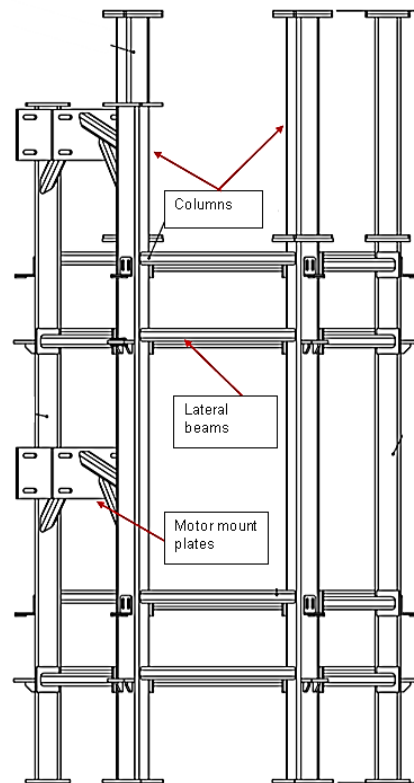


Figure 4.9 – Columns assembly

In essence, each column (see Figures 4.9, 4.10, and 4.11) can be modeled as one with eccentric loads. Each column takes a portion of the combined load of truss rings, storage bins, and the bicycles. Since this combined load rests on 6 supporting wheels, each attached to a column, therefore  $1/6$  of the load is supported by each column. The two columns with motor mount plates (see Figures 4.10 and 4.11) carry the additional load of the motors,

There are 2 modules (levels) each holding 17 storage bins. The weight of each bin is 100kg with a maximum bicycle weight of 35kg (see Figure 4.4 and Tables 4.2 and 4.3), in addition, the weight of truss rings, columns, and accessories such as motors and fasteners must be considered. The weight of the motors and their accessories are supported equally by two adjacent columns, Figure 4.10. Table 4.9 and Figure 4.11 show the load detail of each column.

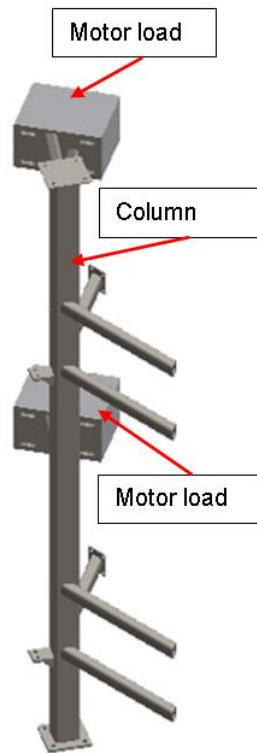


Figure 4.10 – Motor loads, modeled

Table 4.9 Static Load, Central Structural Column  
Static Load Table (all values in Kg)

Bins + Bikes	Truss	Bins + Bikes + Truss	Bins +Bikes+ Truss Load / column	Motor and accessories	Column weight	Total load per column
2295	270	2565	427.5	200	90	627.5

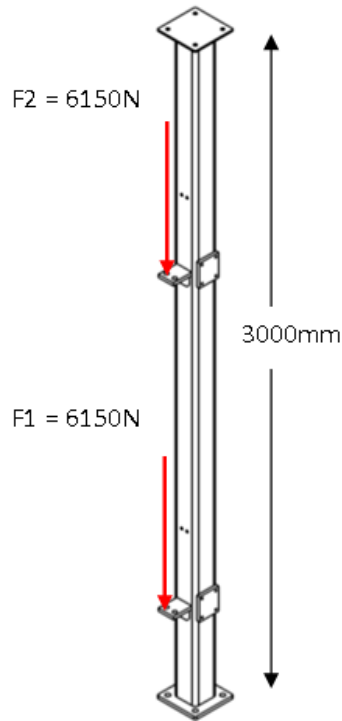


Figure 4.11 – Static loads, Column

The similar criteria for selecting the lift towers material (see section 4.2.4) can be considered for central columns. The material of the columns is structural steel CSA G40.21-13 50W and the profile of the columns is square tubing HSS 4X4X0.188", Table 4.10 shows the material and section properties.

Table 4.10 Columns, material, and Section properties

Columns' Material and section properties				
E (Gpa)	Yield (Mpa)	Tensile (Mpa)	I (mm <sup>4</sup> )	A (mm <sup>2</sup> )
205	429	491	2584797	1794

The governing equations for deflection and stress of a column with eccentric load, are:

$$y_{max} = e \left[ \sec \left( \sqrt{\frac{P}{EI}} \frac{L}{2} \right) - 1 \right] \quad (4.1)$$

$$\sigma_{max} = P \left[ \frac{1}{A} + \frac{ec}{I} \sec \left( \frac{\pi}{2} \sqrt{\frac{P}{P_{cr}}} \right) \right] \quad (4.2)$$

Where;

$$P_{cr} = \pi^2 EI / L \quad (4.3)$$

The critical buckling load for each column therefore is:

$$P_{cr} = 1743\text{KN} \gg 6.15\text{KN} \quad (4.4)$$

However, there are bending moments and shear forces that should be included in stress and displacement analysis, table 4.11 shows the summary of FEA analysis, (also see Appendix A).

Table 4.11 FEA Results, Column

FEA results_ Central Structural Column		
Max. Von Mises stress (Mpa)	Max. Displacement (mm)	Min. Safety factor
114	0.22	2.1

### 4.3. Actuators and Mechanisms Design

There are three drive systems to provide necessary motions of the machine, 1) to rotate the truss ring, 2) for lift's vertical movement, and 3) to translate the lift platform horizontally, Figure 4.12 shows these three motions.

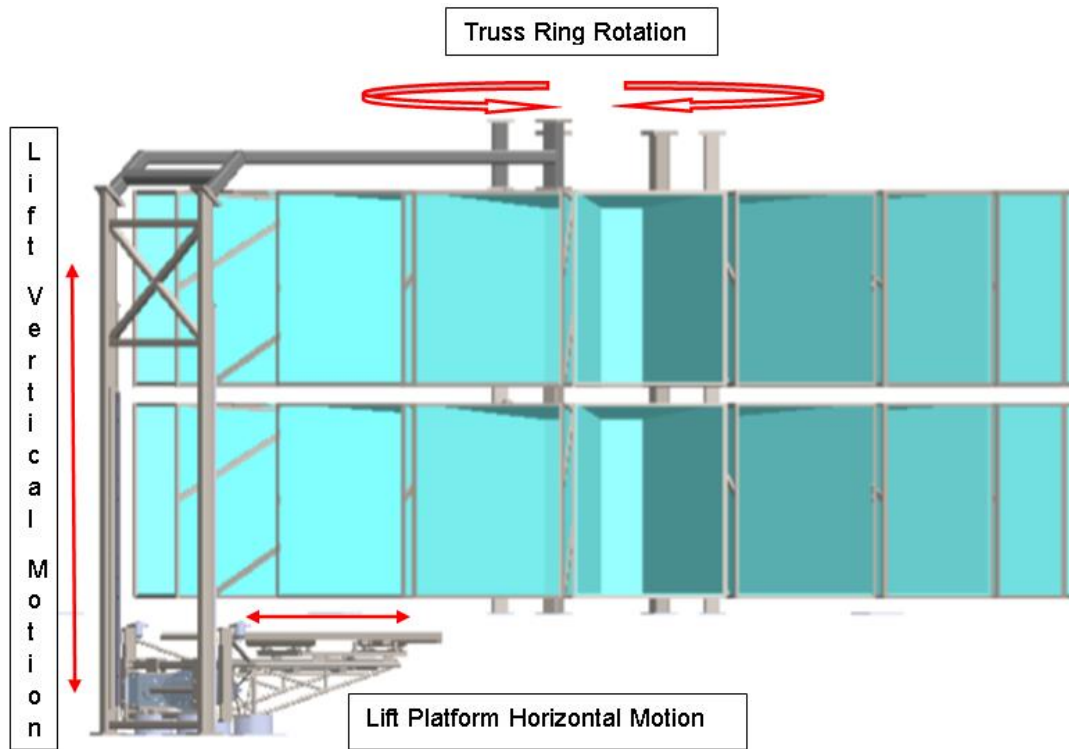


Figure 4.12 – Motions of the system

Electricity is considered as the main power source of the system, (see Table 4.2), therefore the options of actuators to generate motions of the system are electrical motors, AC and DC. Since AC power is available in urban areas therefore Ac motors seem like a good candidate. The motor selection will be discussed in the following sections of this chapter.

#### 4.3.1. Truss Ring Drive system

The truss ring is a large mass that rotates around the central axis of the machine in both directions, which reduces the operation time. When all the storage bins are hung on the truss ring, it looks like a pie with one missing slice. The opening is to provide a corridor for the lift's vertical motion without colliding with the adjacent storage bins.

#### 4.3.1.1. Power calculation and motor selection

To calculate the required power first the moment of inertia of the rotating mass must be calculated. The rotating mass consists of the truss ring and storage bins loaded with bicycles. As can be seen in Figures 4.13 and 4.14, the circular truss with the storage bins can be approximated as a hollow cylinder.

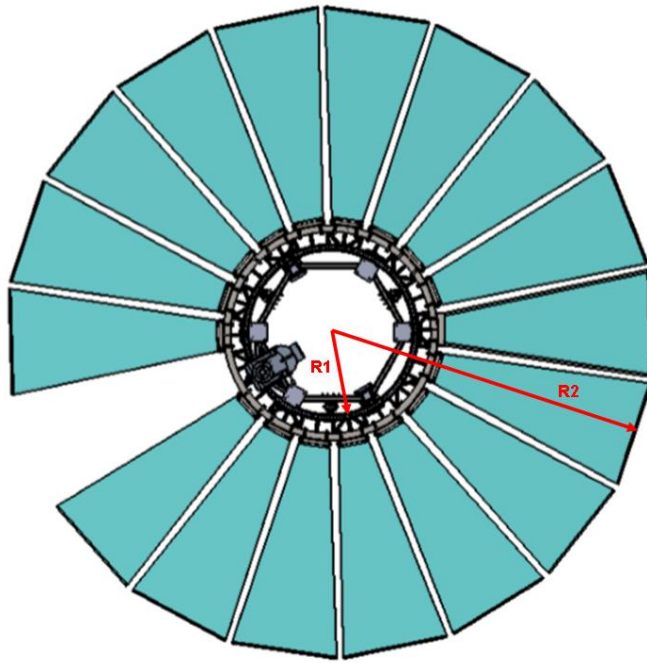


Figure 4.13 – Top view of the truss ring and the storage bins

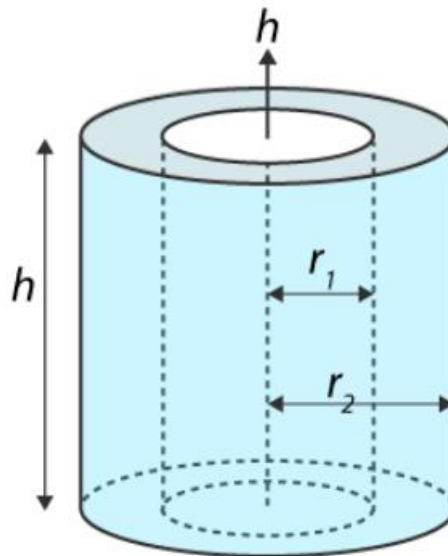


Figure 4.14 – Hollow cylinder

The mass moment of inertia of a hollow cylinder is calculated using equation 4.5.

$$I = \frac{1}{2} M(R_1^2 + R_2^2) \quad (4.5)$$

The weight of the storage bin and bicycle is 135 Kg (see Tables 4.2 and 4.3) and the weight of the truss ring, based on its SolidWorks model, is 270 Kg. Table 4.12 shows the result of the calculation.

Table 4.12 Moment of inertia, the truss ring, and the storage bins

Mass of the storage bin + bicycle (Kg)	Total mass of storage bins and bicycles (Kg)	Mass of the truss ring (Kg)	R1 (m)	R2 (m)	Mass moment of inertia (Kg-m <sup>2</sup> )
135	2606	270	0.82	3.1	12401

The rotational speed of the truss ring is chosen to be 6rpm with an acceleration of 0.63 rad/s<sup>2</sup> (1s acceleration time) to fulfill the design criteria. Table 4.13 shows the assumption for the truss ring drive system.

Table 4.13 Assumption for the truss ring drive system

Truss ring angular velocity	Motor rpm	Acceleration
6 rpm	1800	0.63 rad/s <sup>2</sup>

These assumptions enable us to calculate the required torque and power to rotate the system at the desired speed and subsequently select the suitable motor. The required torque can be calculated using equation 4.6.

$$\tau = I * \alpha \quad (4.6)$$

The required power can be calculated using equation 4.7.

$$P = \tau * \omega \quad (4.7)$$

Table 4.14 shows the result of the calculation.



Table 4.14 Required Torque and Power, Truss ring

Required Torque	Required Power
7813 N-m	4922 W

Based on this calculation, a 5KW motor should be sufficient for rotating the truss ring at 6rpm with an acceleration rate of  $0.63 \text{ rad/s}^2$ . However, to calculate required torque and power accurately, motor and reducer efficiency, as well as friction torque, should be considered.

As for the efficiency of the motor and reducer, they will be provided by the motor and reducer manufacturer after these components and their supplier are selected. Therefore, the calculation will be redone using equation 4.8.

$$P = \tau * \omega * \eta_1 * \eta_2 \quad (4.8)$$

Where  $\eta_1$  and  $\eta_2$  are motor and reducer efficiencies, respectively.

Friction torque can be calculated using the weight of the loaded truss ring and the coefficient of friction between the truss ring and the support wheels. The support wheels material is Polyurethane, and the truss ring is made of structural steel. The wheel supplier states that the rolling coefficient of friction of polyurethane on steel is between 0.030 and 0.057 inches [52]. Table 4.15 presents the coefficient of friction for different wheel materials on steel floor.

Table 4.15 Rolling coefficient of friction, Support wheel

Tread Material	Floor Material	Coefficient of Rolling Friction (inches @3mph)
Forged Steel	Steel	0.019
Cast Iron	Steel	0.021
Hard Rubber	Steel	0.303
Polyurethane	Steel	0.03 – 0.057
Cast Nylon	Steel	0.027
Phenolic	Steel	0.026

The friction force, therefore, can be calculated using equation 4.9.

$$F = f \times W/R \quad (4.9)$$

Where:

F = the force required to overcome the rolling friction

f = the coefficient of rolling friction (units must match the same units as R (radius))

W = Load on the Wheel

R = Radius of the Wheel

Consequently, the power loss due to friction (friction power) can be calculated using equation 4.10.

$$P_{fr} = F \times V \quad (4.10)$$

Where V is the linear speed of the support wheel. Table 4.16 shows the values and the result of the calculation.

Table 4.16 Variables and calculation result for friction power loss, support wheel

W	R	f	F	V	P <sub>fr</sub>
6156 N	63.5 mm	0.057"	140.36 N	0.524 m/s	73.49 W

Since there are six support wheels, therefore the total power loss due to friction is 6 times the calculated value, 440W, or less than a half a kW. Adding friction power loss to the required power which was calculated before (see table 4.16), the total required power is:

$$P_{Tot} = 4922 + 440 = 5362 \text{ W} = 5.46\text{kW} \quad (4.11)$$

As it was mentioned previously, because of the availability of AC power in urban areas AC motors are good candidates to rotate the truss rings. Servo and inductive motors are two types of AC motors which are commonly used in such application. Through consulting with different manufacturers and suppliers, it became clear that servo motors and drives are more expensive than inductive ones of similar power and speed ratings. Another concern is the ability of closed-loop control of positioning and speed, something which is inherent in servo drives. However, modern Variable

Frequency Drives (VFD) can perform closed loop-control. Therefore, considering lower cost and the capability of open looped control, AC inductive motor is selected to rotate the truss rings.

Using the result of the calculation, a 6.3 Kw, 1800rpm, 3phase AC geared motor is selected. The geared motor option provides a gear ratio of 1:22.08, which delivers an output velocity of 79.94rpm.

#### 4.3.1.2. Drive mechanism

Although the motor has been selected, however, a mechanism to transfer the motion and power from the motor's output shaft to the truss ring is needed to be designed. Since the truss ring is a circular structure that is to be rotated around its center, a mechanism such as an internal gear, friction wheel, or chain and sprocket system seems suitable for the task. However, considering that slipping of the truss ring against the drive system is a critical issue due to the positioning of the storage bin at the load/unload location, the friction wheel was not considered as an option. Furthermore, as it was mentioned at the beginning of this chapter, having off-the-shelf equipment not only helps to lower the cost of the system, it also helps with better and lower cost maintenance. Consequently, an internal gear system, due to being custom design, was omitted from the considered mechanisms. Therefore, a special type of chain drive is selected for rotating the truss ring, a Pin Wheel inner drive. Figure 4.15 shows a typical inner drive pinwheel drive, it acts as an internal gear system, but instead of gear and pinion, it consists of a special circular chain and a sprocket.

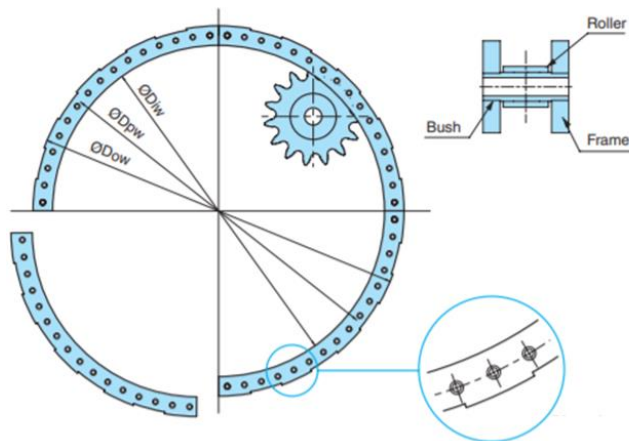


Figure 4.15 – Inner drive pinwheel

The advantage of this system over a regular roller chain and sprocket is that a pinwheel mechanism can be used where there is a large ratio between the sprocket and circular chain diameters. In other words, even when the angle of wrap is much less than  $90^\circ$ , the pinwheel mechanism performs adequately.

As can be seen in Figure 4.16, the pinwheel lays on top of the inner circular member of the truss ring. The sprocket, which is installed at the motor output shaft, engages with the pinwheel, and rotates the wheel and the truss ring. Table 4.17 shows the specifications of the selected pinwheel mechanism.

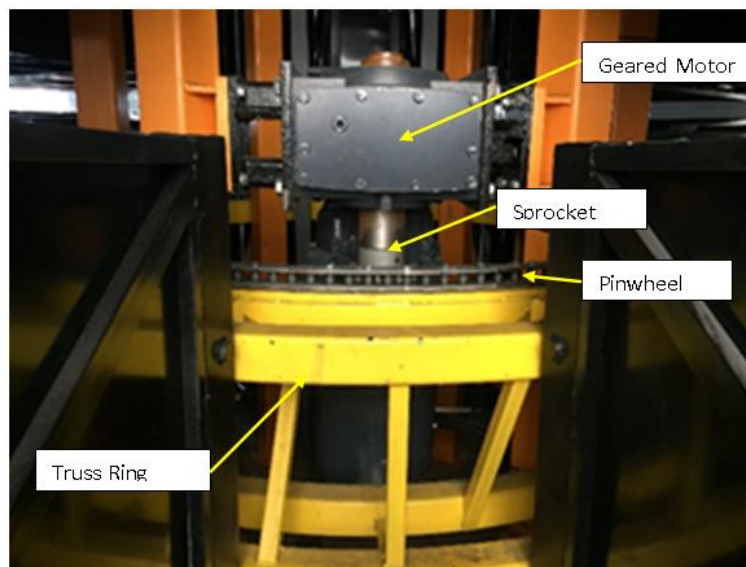


Figure 4.16 – Drive System, Truss Ring

Table 4.17 Pinwheel and sprocket specifications

# Of Pins\Teeth			
Pinwheel	Sprocket	Ratio	Pitch
166	12	1:13.83	30 mm

### 4.3.2. Lift system; Vertical and Horizontal motion

There are two separate motions with the lift system, the vertical motion of the lift assembly and the horizontal motion of the lift platform.

#### 4.3.2.1. Vertical motion

The lift frame moves vertically against the lift columns, which in turn ascends and descends the lift platform with the storage bin on top of it and the bike inside the bin. The motion is a linear translation, however since the motor output is rotary, a mechanism to convert the rotational motion to a linear one has been designed.

##### 4.3.2.1.1. Torque and power calculation

The load which is needed to be carried up and down by the lift consists of the lift frame and platform, storage bin, and the bicycle. The total load at its maximum, according to table 4.6, is 455kg with traveling speed chosen to be 1.2 m/s. like the case of power calculation for truss rings, the speed assumption enables the calculation of the required power. Using equation 4.12, the required power for the lift motor is 5.4kw.

$$P = F * V \quad (4.12)$$

The assumption and variables for the lift's vertical motion can be found in table 4.18

Table 4.18 Required power, Lift

Load, F	Velocity	Power
4464 N	1.2 m/s	5340 W

Although the required power is calculated, before calculating the required torque, the drive mechanism to convert linear to rotational motion should be designed. There were several mechanisms that were considered during the concept generation phase (see Table 3.1). Since the main power source is electricity, therefore pneumatic and hydraulic systems failed to be considered as acceptable mechanisms. Scissor lifts pose special and installation problems while linear motors are costly. Considering the travel length of the lift (1.7 m) and the high efficiency of rack and pinion systems which is up to %97 [62], it seems like a suitable candidate as the drive mechanism for the lift.

The selected mechanism comprises a 64mm in diameter pinion with a 2m long rack. The racks are installed on the lift towers, one rack per tower, table 4.19 provides the specifications of the rack and pinion.

Table 4.19 Specification, Pinion

Module	# Of Teeth	Diameter
2	32	64 mm

Two pinions move simultaneously by a single drive shaft that passes through the geared motor. The single drive shaft moves both pinions at the same time. Since it is essential to have both pinions on one shaft, the hollow shaft geared motor is selected. Figure 4.17 shows the geared motor.

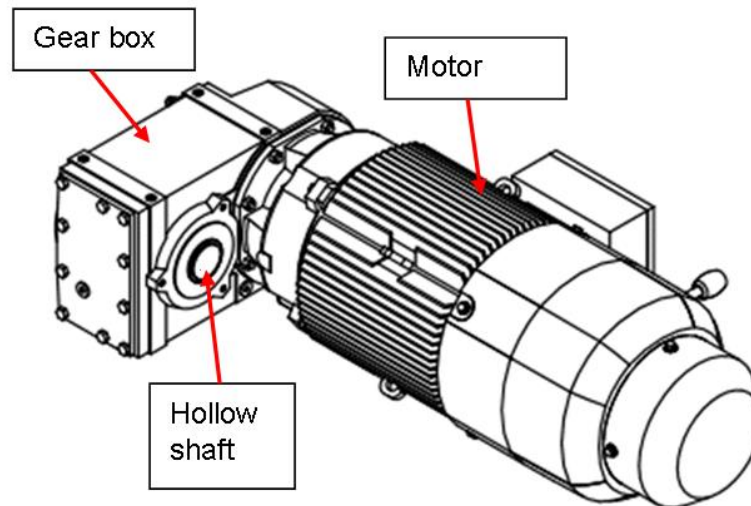


Figure 4.17 – Hollow shaft geared motor

Using equations 4.7 and 4.13, the required torque and angular speed, and therefore the required gear ratio can be calculated.

$$\omega_{\text{pinion}} = V / R_{\text{pinion}} \quad (4.13)$$

Table 4.20 shows the result of the calculations.

Table 4.20 Torque calculation results, Lift

V	$\omega_{\text{pinion}}$	P	T	Ratio
1.2 m/s	358 rpm	5340 W	142.4 N-m	1:5.02

The specification of the selected motor can be found in table 4.21.

Table 4.21 Specification of the motor, Lift

Type	Power	rpm	ratio
Parallel shaft, geared	6.3 Kw	1765	1: 6.39

#### 4.3.2.2. Horizontal motion

The horizontal motion enables the lift platform to move to and from the storage bin hanging point during the loading/unloading cycle. To grab a bin, after the truss ring rotates and positions the desired bin at lifting location, the lift platform travels towards the storage bin. Then the lift picks up the storage bin and brings it down to the access door. Finally, the lift platform travels towards the access door and brings the storage bin with it.

The moving load is the weight of the platform, the storage bin, and the parked bicycle. However, the lift platform is supported by four linear bearings that support the total load on the lift platform (see Figures 4.5 and 4.6). Therefore, the required torque and power is just to overcome the friction force. Since the linear bearing and rail system has a very small coefficient of friction, thus the required torque and power are not very large. Figure 4.18 shows the coefficient of friction for linear bearing.

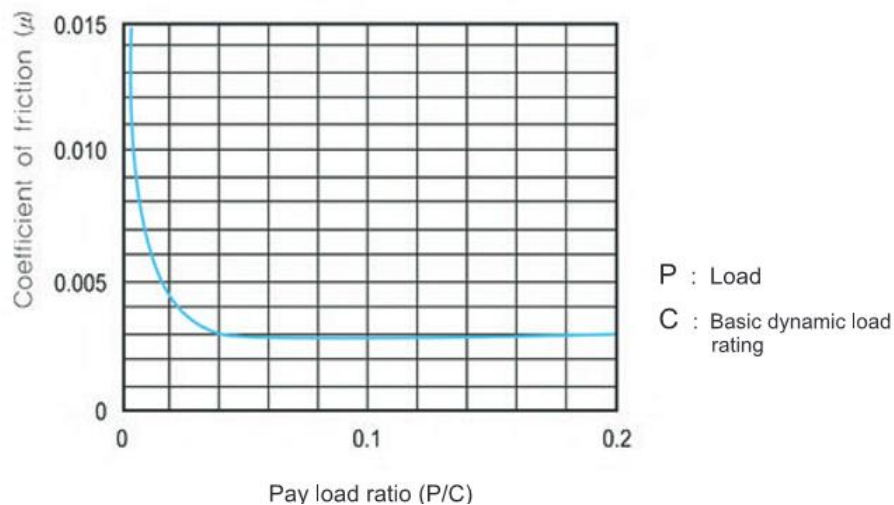


Figure 4.18– Coefficient of friction, linear bearing [63].

The working load is the sum of the weights of storage bin and bike weights, which is 135 kg or 1324N. By selecting a linear bearing with basic dynamic load rating (C) of at least ten times the working load, the coefficient of friction will be 0.0025, therefore, the friction force is 3.31N.

Considering that the resistance forces and torques for the horizontal motion are not very significant, a linear actuator powered by a DC stepper motor is selected as the drive system. Table 4.22 and Figure 4.19 provide information about the components of the selected drive system.

Table 4.22 Linear actuator, specifications [64].

Design	Stroke	Max. Force	Max. Rotational Speed	Repetition accuracy
Ball screw	600 mm	200 N	4000 rpm	$\pm 0.01$ mm

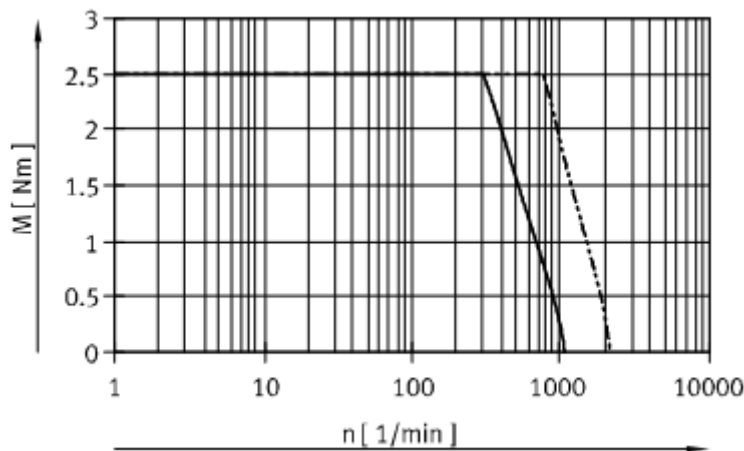


Figure 4.19 – Stepper Motor's Torque as a function of rotational speed [65].

The actuator and motor are installed under the bin seat on the lift platform, and the installation location is shown in Figure 4.20



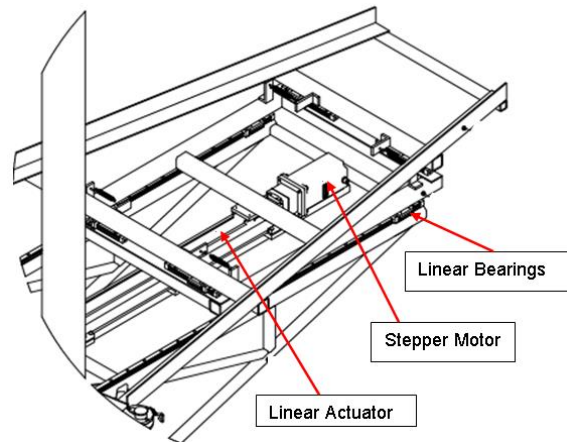


Figure 4.20 – Installation location of the linear actuator, bearing, and stepper motor

## Chapter 5. Automation and Control

### 5.1. Overview

A control system consists of interconnected components to achieve the required function. It is used to define and ensure the performance of a system over time [53], [54]. The control system of the automatic bicycle parking controls all the motions, tasks, performance, and the safety of the bicycle parking. It communicates with various components of the system, such as motor drives and safety equipment to ensure required performance based on the system logics.

The components of the system are all industrial rated equipment that can be operated under severe conditions. This is because the automated bicycle parking system can be installed at any suitable space under different environmental conditions, therefore the control system and its component should also be compatible with the majority of the possible working conditions. To include such considerations for the controller, a Programmable logic controller (PLC) system was selected to be the brain of the system.

PLC is an industrial solid-state computer that monitors inputs and outputs and makes logic-based decisions for automated processes or machines. PLCs are robust and can survive harsh conditions, including severe heat, cold, dust, and extreme moisture. Their programming language is easily understood, and they can be programmed without much difficulty. PLCs are modular and can be plugged into various setups. Figure 5.1 shows the typical components of a PLC system.

Since the positioning of different systems and mechanisms of the machine - such as positioning the storage bin or lift platform at pick up location is of utmost importance, to avoid inaccuracy and increase the cycle time, the control system is considered to be a close loop system.

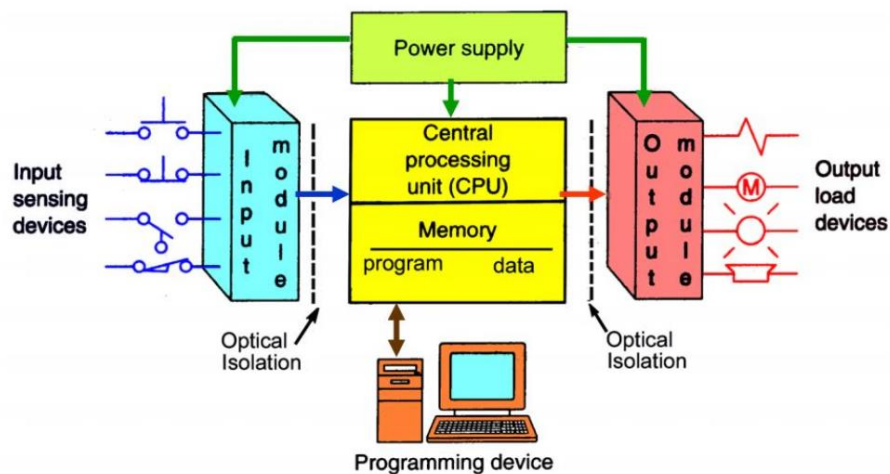


Figure 5.1 – PLC System

## 5.2. Developing motions and tasks

Before developing the control logic, motions, and tasks of the system should be identified and defined. These tasks and motions define the overall function of the system, which is automatically storing and retrieving bicycles. These motions and tasks can be defined as subfunctions and followed in a logical sequence to fulfill the overall function of the system.

By following the logical actions of parking a bicycle as well as studying existing products, the overall subfunction of the system are:

- Lift
- Rotate
- Locate
- Translate
- Position

However, these subfunctions are very general and must be defined further to suit the designed mechanical system. By studying the mechanical system (central columns, truss ring, storage bin, and lift) more clear definition of these subfunctions can be obtained as follows:

- Locate desired storage bin based on the input information

- Move the storage bin up and down
- Position the storage bin by rotating the truss ring CW or CCW
- Translate the storage bin to and from the door
- Open and close the access door

These are still high-level subfunctions and must be refined further to obtain the detailed tasks and motions of the system. For instance, the second subfunction is to move the storage bin up and down, but it is not clear that which systems, mechanisms, or parts of the machine should come to motion to fulfill this subfunction. Furthermore, the order and sequence of these tasks should be clearly defined to achieve the overall function of the system optimally.

### **5.3. Developing logic and sequence**

Developing the motion sequence is a critical stage in developing the control system. Task flow and motion sequence define the system's behavior as well as its performance.

Motion and task sequence should be defined and developed so that no interference between tasks and motions exists. The sequence must anticipate and prevent physical collision between different moving parts and mechanisms of the machine. For instance, if while the lift is ascending to the pick-up position where it grabs the storage bin, the lift platform moves toward the storage bin, there will be a potential collision between the lift platform and the adjacent storage bins.

Moreover, the overall motion and task sequence should be as simple as possible, to avoid complex and unpredictable situations. Simplifying motions and tasks not only helps with cost efficiency through avoiding complex control systems, but it also allows for better implementation of safety features. Having multiple axis motion necessitates a more expensive controller and sensory devices to ensure the required condition at each step of the sequence is achievable. However, since the cycle time is another important design criterion, a trade-off between cost, complexity, and cycle time should be considered.

Considering all the concerns, the sequence of the principal functions of the system are defined as follows:

- Receive input information from a user
- Locate storage bin by processing input information (information flow)
- Rotate the storage bin to the pickup location
- Ascend the lift to the pickup location
- Move the lift platform to the pickup location
- Hold the storage bin and lift it down to access door
- Translate the storage bin to the door
- Move up the access door
- Move down the access door
- Move the storage bin to the storage location
- Translate the storage bin to the storage location
- Descend the lift platform
- Rotate truss ring to initial (Home) position
- Output information to the user

Figure 5.2 shows the flowchart of the systems' functions.

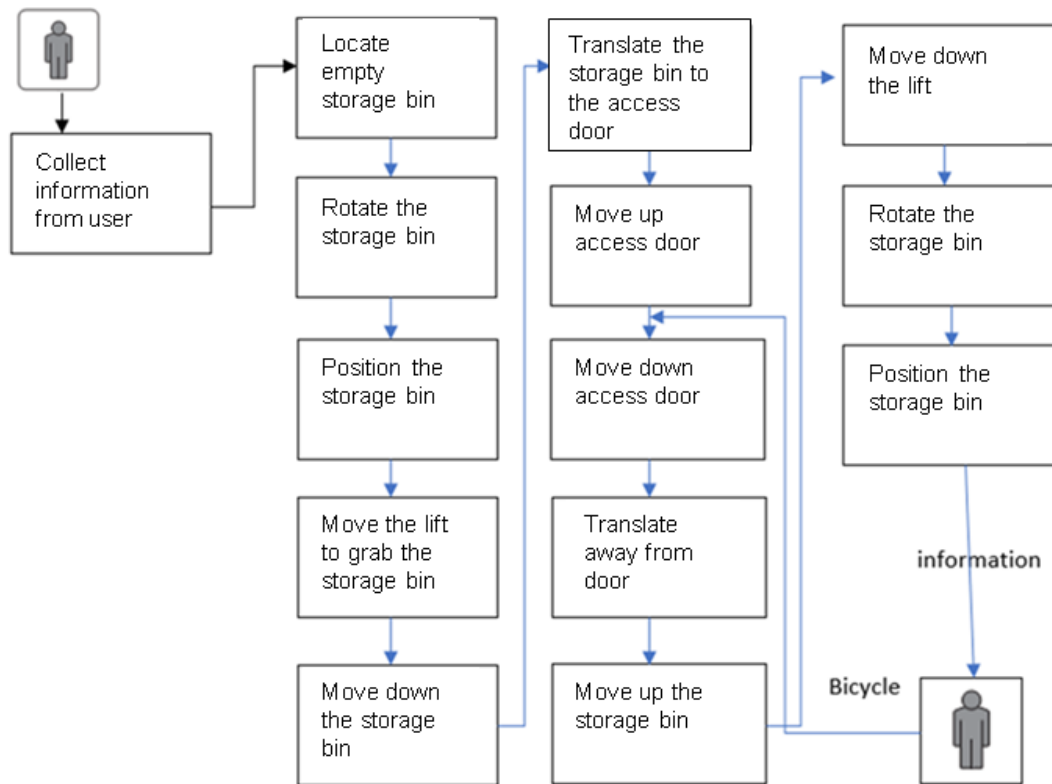


Figure 5.2 – Flowchart, tasks, and functions

## 5.4. Developing a state machine model

State machine modelling is used to develop the algorithm of the control system. A Finite State Machine (FSM) is a mathematical abstraction used to design algorithms. In simple terms, a state machine will read a series of inputs, and will switch to a different state.

To develop the state machine, all the sequences are redefined, and the input and output of the state have been established. However, due to the complexity of the system and to better model the behavior of the system, the state machine has been developed into two stages; one models the overall function of the machine, while others model each subfunction. The overall function state machine comprises of subfunctions as states at a very high level, Figure 5.3 shows the overall function state machine.

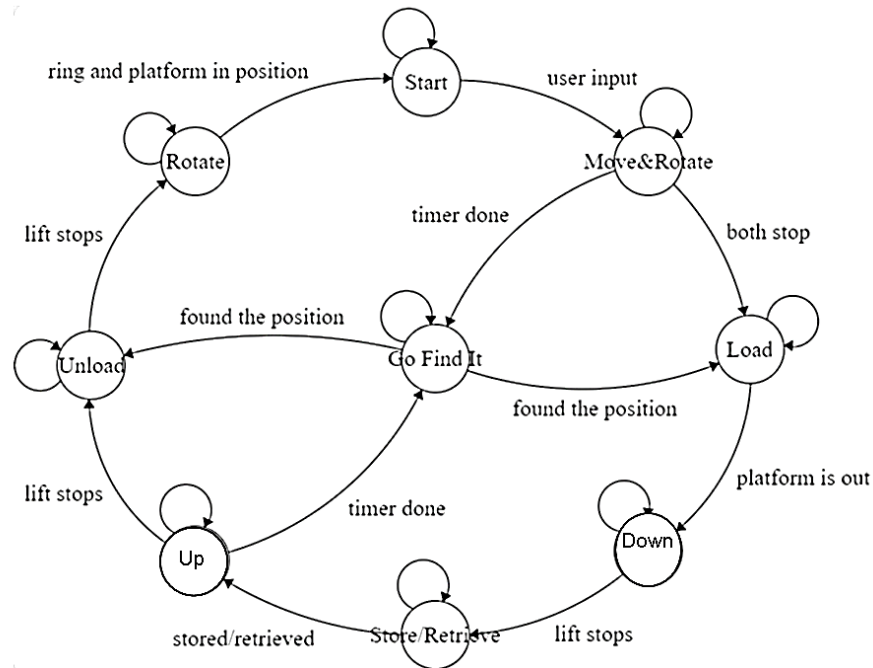


Figure 5.3 – Overall function state machine

The FSM in Figure 5.3 is high-level modelling of the overall function of the system. In FSM, each state has defined conditions with identified inputs, outputs, activities, and tasks to reach to the next state. However, since there are many tasks and activities and inputs and outputs for each state, they are listed outside the FSM diagram. For instance, here are the activities and input/output for the state “Down”, Figure 5.3:

1. Platform moves to “middle” position
2. Door closes
3. Lift moves up
4. Lift stops at a pre-determined distance above the target ring
5. Check if the ring is at position

Input: Signal from the state “Store/Retrieve”

Output:

The signal that the lift has stopped at and the truss ring is at position

In this state, the bicycle has already been either stored or retrieved by the user, so the signal from Store/Retrieve state sets the system into action to reach the next state which is “Up” (Figure 5.3). Here, the system executes predefined activities to reach the next state, which is “Unload.” Once the system reaches the next state it generates the output signal, which indicated that the lift and truss ring are in the desired position, so that the system commences reaching state “unload.” However, as it can be seen, each of the states of the overall function state machine has many activities and tasks and can be broken into subtasks. This further decomposition of the overall function FSM helps with the development of the control system algorithm. By breaking the overall function FSM into simpler and detailed FSMs, or substate machines, each high-level function can be broken down into detailed tasks. The detailed tasks provide more insight into each state, its inputs and outputs, and the conditions, as well as the failure scenarios. Figure 5.4 shows the substate machine for this state.

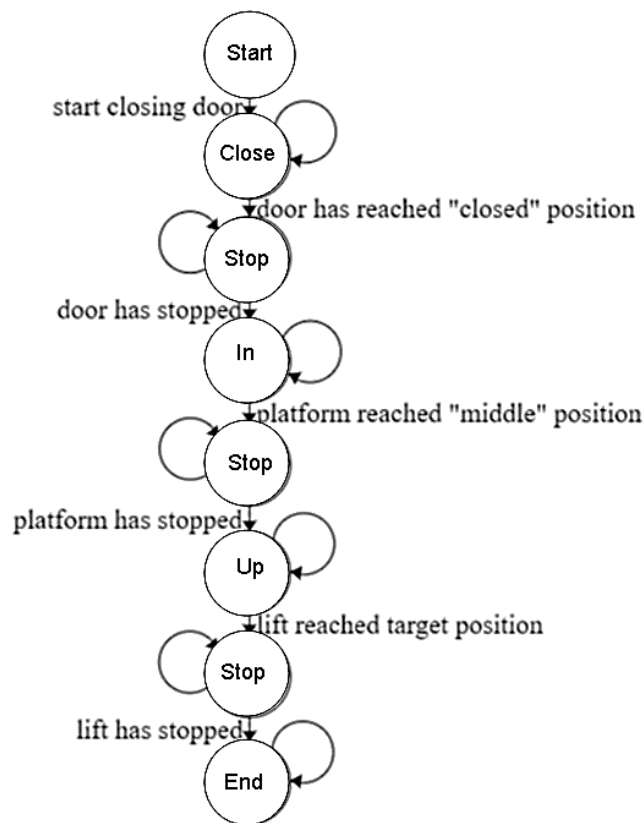


Figure 5.4 – Substate Machine for the state “Up”

As can be seen, the activities which are defined at the high-level FSM have been broken down and refined to a completely defined state. Each state of this decomposed



substate machine has a more detailed definition of activities, condition, and input/output to fulfill the high-level state. This makes it easier to define and determine failure scenarios for each substate and therefore preventing the future failure of the machine with more refined and detailed predictions and anticipation.

## 5.5. Failure scenarios

Failure scenarios represent the conditions under which the system fails to fulfill its overall function. Studying failure scenarios is the process of proactively identifying the cause of failure and defining needed actions to prevent or mitigate the risk of failure. The result of studying failure scenarios is valuable in developing a more reliable control system.

Continuing with the example of the state “Up,” different failure scenarios can be determined at high and low levels. Studying overall function FSM (see Figure 5.3), the following failures are identified:

- Lift platform does not reach the middle position

Reason: platform motor failed to move the platform to the position for either mechanical or electrical failure

Action: Output a message to the users to take their bike back and wait for maintenance.

- The door does not close

Reason: sensor failed to see the door

Action: Output a maintenance request

The lift does not stop above the target ring

Reason: lift positioning sensor failure or misreading, or mechanical/electrical failure

Remedy: Must have extra sensors at every level to double-check the position

Action: stop the operation, output maintenance request

However, by studying the substate machine of the same state (see Figure 5.4), more detailed failure sources and actions can be determined. For instance, considering state “Up.” The definition of this state is:

1. Lift motor on
2. Lift ascends until a predetermined distance above target position has been reached

Input: Signal from “Stop”

Output: Signal that predetermined distance has been reached

The failure scenarios are:

- The lift does not move

Reason 1: electrical/input power failure

Remedy: chose a motor drive that can detect the input power. Use the encoder reading.

Action: stop the operation, output maintenance request

Reason 2: lift does not move because of mechanical failure

Remedy: Drive can sense motor overload. Also, add proper overload equipment and motor starters.

Action: Output a maintenance request.

- The Lift fails to find the target position

Reason: Motor Encoder fails to sense the position.

Remedy: Install a max travel sensor at a pre-set position, so when the lift reaches the sensor, it stops without any damage.

Action: stop the operation, output maintenance request

Developing the state machines for each subfunction provides insight as to what should be measured or sensed and where should the sensing station be. A maximum travel sensor is needed to prevent the collision of the lift in case of encoder failure or

overload situation must be checked by overload equipment and communicated with the controller.

## 5.6. Programming

PLC has been selected as the controller for the control system. Although state machines have been developed as a base for programming the controller, however the program logic and all the function modes, activities, and checkpoints must be identified, defined, and developed in detail.

Based on the developed FSMs, a narrative of the system is generated, in which machine function modes – i.e. Manual/Maintenance, Idle, and Automatic – are defined, and all the motion, tasks, and activities within each mode is sequentially defined and described. The followings are excerpts from the generated system narrative which describes two modes of the system:

### **Manual**

Technicians will use this mode for easy recovery of bikes (depending on the failure), and maintenance. In this mode, a button will appear on the screen that will allow a technician to perform troubleshooting and maintenance activities.

#### Entry

- Set screen to maintenance (out of order with access button)
  - This access button will require a level 1 login
    - Can access automated tasks
  - Level 2 login will allow manual motor jogging and safety bypass

#### State

- Jog motors (depending on input)
  - This would ignore all inputs
  - Would need indicators for certain I/O points
  - Login level 2

- Automated tasks
  - Select to retrieve or deposit bin
    - Select bin and the system run through the sequence to retrieve or deposit the bin
- Allows access to set points
  - Commissioning and configuration
- Allows access to Fault screen
  - Show a list of faults
  - Allow clearing of fault logs here
- I/O feedback to see failures
  - List of I/O with indicators so that the tech can see the state of each I/O point
  - Used for debugging

#### Exit

- Set all motors to off
- All brakes are set on
- Set screen to out of order
  - No tech access button
- Set state to Disabled

#### Idle

This is the state the system will spend the most time. This state waits for input from a user and could do time checks on bins for data collection

#### Entry

- Set the welcome screen to either:

- Welcome: no issues
- Out of Order: faulted (no help)
  - Display a help number, identifying information, fault code
- Out of Order: faulted (recovery only)
  - Perhaps safety has been compromised but the machine still works
  - The techs want to do maintenance and need the machine empty, so this state allows people to retrieve only
  - Grey out any storage buttons
- Full: displayed if all active bins are storing something

#### State

- Poll HMI for input from the user.
- Once moved from the welcome screen move to the next state
  - Get started button

#### Exit

- none

Next, based on the system narrative, an overall flow chart that summarises all of the machine's high-level but detailed tasks and activities is generated. The flow chart is shown in Figure 5.5

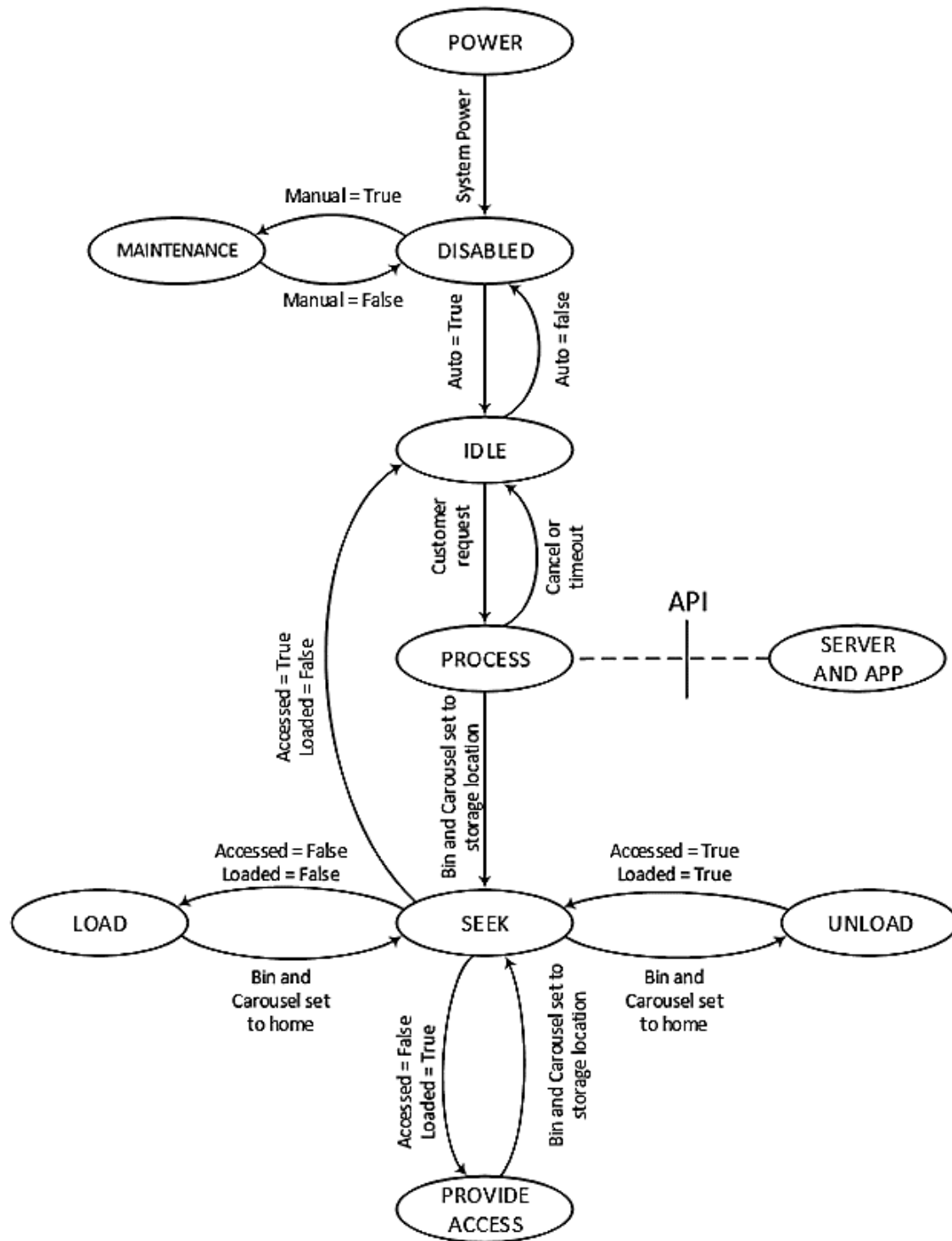
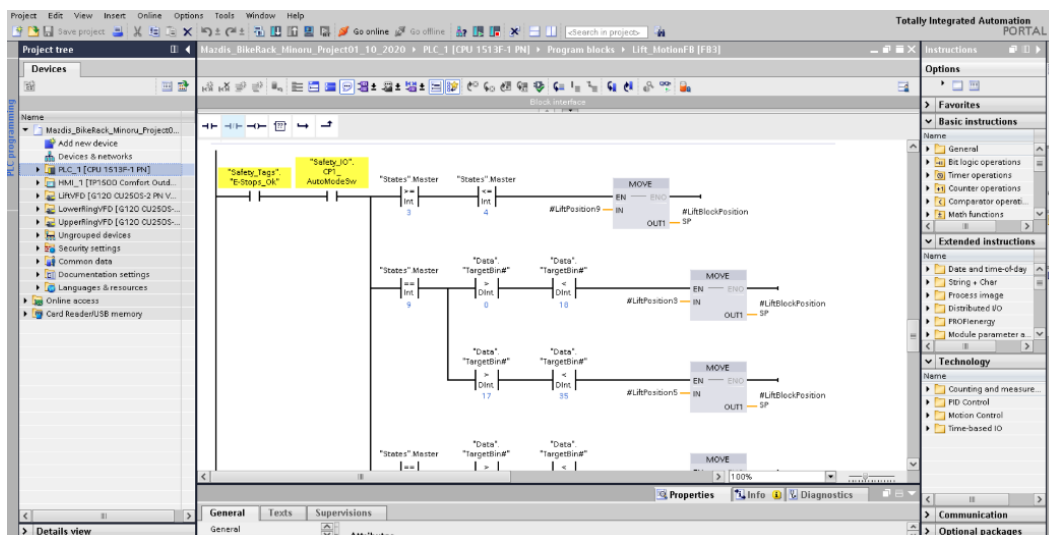


Figure 5.5 – System Flow Chart

The system narrative and the flow chart are the basis for developing the PLC program. Based on the described modes, their activities and tasks, and their sequence, a logic program is generated for the PLC. The programming language is selected to be Ladder logic, and since Siemens is the manufacturer of the PLC, its programming platform, Totally Integrated Automation Portal (TIA Portal), is used to program the PLC. The TIA Portal is a powerful programming and automation tool which enables users to develop automation systems quickly and intuitively. It provides unrestricted access to a complete range of digitalized automation services, from digital planning and integrated engineering to transparent operation.



## Chapter 6. Fabrication, Assembly, and Test

This chapter introduces the fabrication, assembly, and testing of the bicycle parking system. The structural parts of the system are fabricated through cutting, forming, machining, and joining processes. The fabricated parts then assembled to create the structure of the system. Afterward, other components of the system, such as drive systems, guide rails, and support wheels, were installed on the structure. Finally, a series of tests were carried out to ensure the required performance of the system has been achieved.

### 6.1. Structural parts fabrication

Once the detailed design of the machine was completed, drawings were generated and sent to a fabrication shop, however, parts that needed machining were sent to a machine shop. For instance, the guide rails for the linear bearings of the lift should mount on a machined surface since they are vastly affected by the smoothness of the surface they are mounted on. Therefore, the surface of the lift towers needed to be machined (Figure 6.1).

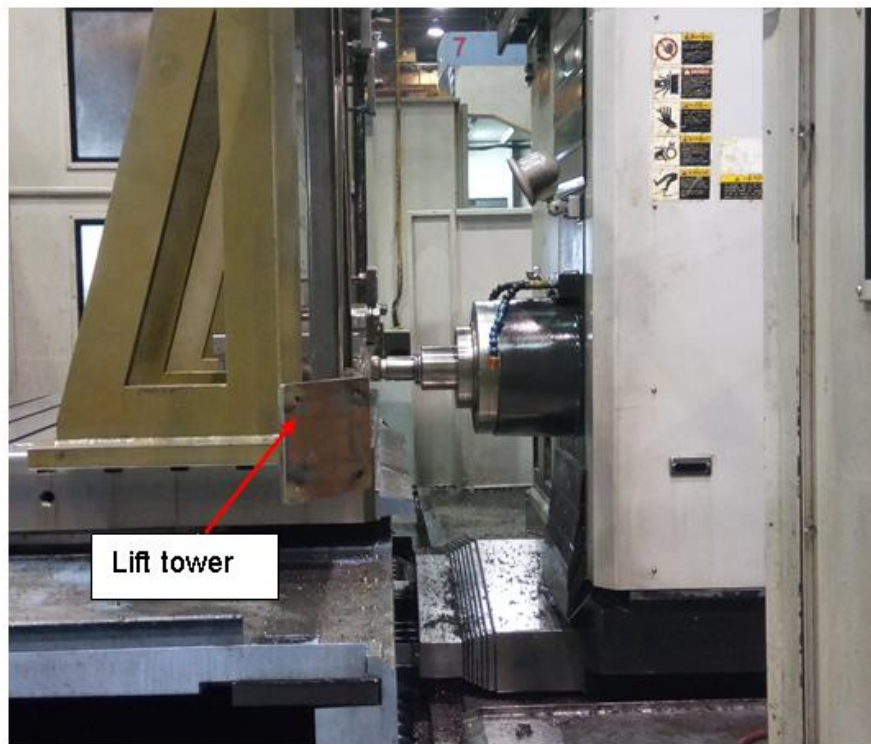


Figure 6.1 – Machining of the linear railing mounting surface, Lift Towers



Truss ring, as was mentioned before, is a circular structure which its manufacturing includes profile rolling. Since the diameter of the ring is relatively large (2m), to achieve optimal accuracy in shape and size, it was decided to manufacture the truss rings in two separate pieces and connect those with proper fasteners.

A special jig was also made by the manufacturer to space out the hooks, which are welded on the outer ring of the truss ring, to ensure that the direction of the hooks, as well as their spacing, is in accordance with the drawings. Figure 6.2 shows the truss ring and the hooks.



Figure 6.2 – Two halves of Truss Ring

Once the manufacturing of the metal parts of the system was done, all were coated by epoxy paint to prevent rusting and environmental effects. The coating was done in house.

## **6.2. Assembly**

### **6.2.1. Structural and stationary parts**

After fabrication was completed, different sections of the bicycle parking system were assembled to ensure that there is no problem, and they fit together correctly. To begin with, truss rings were assembled on the central columns. Few storage bins were also installed on the ring to ensure the overall dimension of the system.

Other parts such as support and side wheels were also installed on the central columns using their mounting plates. The height adjustment of the support wheels was also checked to make sure that the two truss rings can be adjusted to the desired heights independently. Figure 6.3 shows the assembly of truss rings on the central columns.

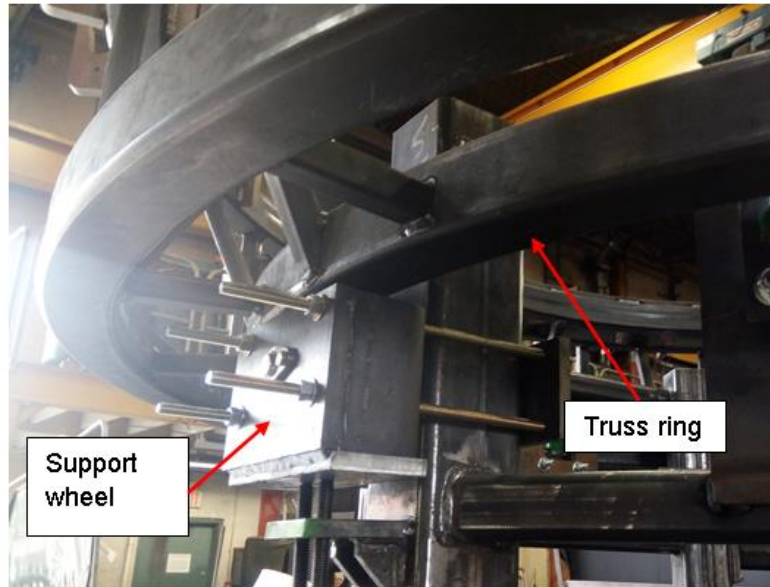


Figure 6.3 – Truss rings resting on support wheels

### 6.2.2. Equipment and drive systems

After completing the assembly and installation of the metal and static structure, drive mechanisms and equipment were installed. The pinwheel mechanism, which rotates the truss ring, is in sections that are installed on top of the truss ring, Figure 4.16. Tapped holes were drilled on the outer ring to install the pinwheel.

To install the motors, as can be seen in Figure 6.4, a special motor mount was designed and manufactured to ensure relatively easy installation and adjustment.

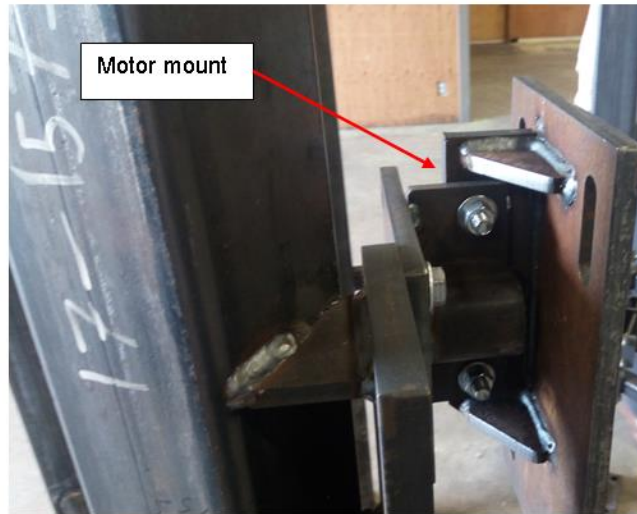


Figure 6.4 – Motor Mount

The linear railing and the rack for rack and pinion drive system of the lift were also bolted on the surface of the lift towers, Figure 6.5. The linear railing, as it was mentioned before, was installed on the machined surface of the tubing, while the original finished surface of the column was sufficient to install the rack on. The lift motor was also installed on its mounting plate.

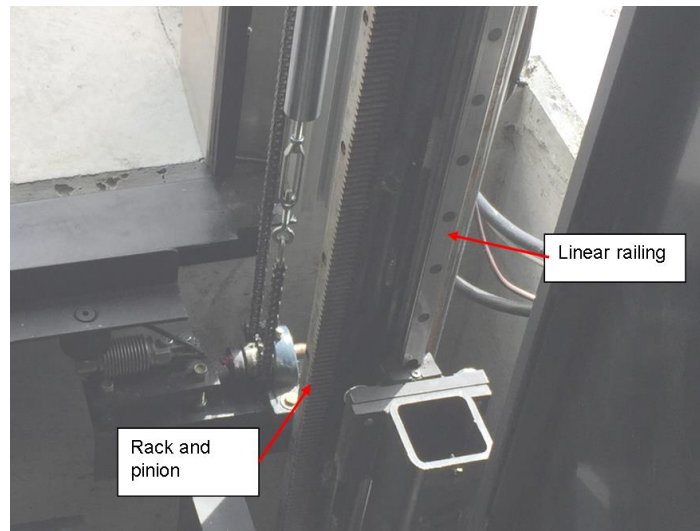


Figure 6.5 – Linear railing and rack gear, Lift

The next step was to assemble the whole system. In the final assembly, all the parts of the system must match correctly without any mechanical or manufacturing flaws or problems.

## **6.3. Test and Results**

To confirm the proper performance of the system and to ensure that it complies with the design objectives, a series of tests has been performed.

### **6.3.1. Comparison with design requirements and specs**

As it is discussed in section 4.1.1 (also see Table 4.1), there are different requirements and expectations depending on who is the customer/user of the system. Cyclists' concerns are protection against theft and vandalism (or security) and convenience. Several bicycles were stored and attempts have been made to retrieve them through random and fake credentials, however, the control system security set up performed admirably in checking the inputs against legitimate stored credentials and preventing unauthorized access to the stored bicycles. The storage bin, furthermore, provides the user with ample space to store cycling gear and gadgets as well as some cyclists' items such as a small backpack, which makes the parking experience more convenient. Moreover, the exterior of the system, made of metal columns covered by sheets of high impact-resistance material, prevents possible vandals and stops thieves from breaking into the system quickly or quietly.

Another concern of the cyclists is waiting time during storing or retrieving. Based on the design specification, the average storing and retrieving waiting time should be about 1 minute. The measured waiting time to retrieve or store from different storage bins on different levels of the system is about 1 minute.

### **6.3.2. Functionality and reliability test and results**

Previous tests verified the desired performance is achieved; however, the reliability and repeatability are other concerns that should be tested and proved. A reliable system is much less prone to breakdowns and downtimes which subsequently reduces maintenance time and cost. For instance, the storage bin should be positioned at the access door within the defined tolerance, which defines the accuracy of the storage bin positioning, and it has to be placed within the same positioning boundaries in every cycle of the system. In other words, the system must repeatedly complete its cycle without any operational error. Therefore, the system must go through cycles of operation and the results confirm its reliability. The system has been put through 2000 cycles and no error or warning message has been reported.



Figure 6.6 – First operational bicycle parking system

## Chapter 7. Storage Bin Mass Optimization

Although design iterations were made to improve the design of the bicycle parking system, studying the manufactured bicycle system showed that further improvement of the system in areas of manufacturing cost and energy consumption is possible. Manufacturing costs can be reduced by using less raw material or smaller parts. Lighter moving parts also result in lower consumption of energy.

As it was mentioned previously (see section 4.3), there are three movements in the system: rotation of truss rings, vertical translation of the lift, and horizontal translation of the lift platform. The reduction of the weight of these moving parts will result in less material, smaller drive systems, and less energy consumption. Considering these moving parts, it seems that they have one thing in common, they provide motion for storage bins. The storage bins are located on the truss rings and rotate with it. The lift and the lift platform move the storage bin vertically and horizontally. So, it seems that reducing the weight of the storage bins will reduce the total rotational and translational mass. Furthermore, there are seventeen storage bins on each level of the system (34 in total), which are the farthest located masses from the center of rotation. Therefore, reduction in the storage bin's mass will result in a relatively considerable reduction in raw material and required power. The reduced power requirements may as well result in smaller size motors and gear reductions.

Figure 7.1 shows a very simple configuration, in which a storage bin can be modeled as a point mass  $M$  being located at distance  $r$  from the center of rotation,

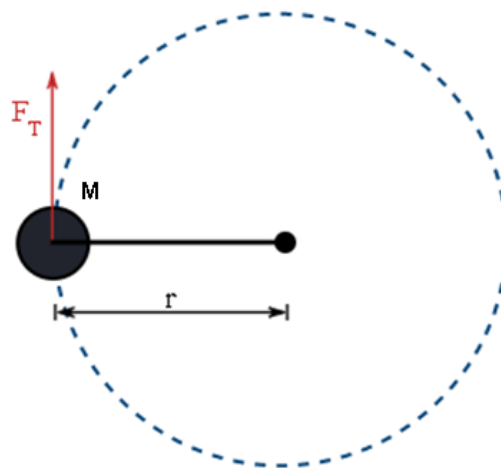


Figure 7.1 – Point load model, Storage bin

The rotational inertia is calculated using equation 7.1

$$J = M \cdot r^2 \quad (7.1)$$

From equation 7.1 it can be concluded that to reduce the rotational inertia, either  $M$  or  $R$  or both must be decreased. However, in lowering, spatial restrictions and constraints as well as design specifications must be considered. The distance from the center of rotation comprises of the open area inside the center column assembly and the length of the storage bin are examples of spatial and design restrictions (see section 4.1.3, Figure 4.1, and Table 4.2). The minimum space requirements for the maintenance personnel to be able to perform their duties is a restriction that imposes a minimum distance, which cannot be reduced. The length of the storage bin is also defined in accordance with the length of the largest standard bicycle size available. Since these two variables have already been set, therefore there is not much room to improve.

The other factor in inertia reduction is the mass of the storage bin itself. The reduction of the storage bin's mass will reduce the power consumption proportionally which reduces the energy cost over the years of use of the system. The reduced mass of the storage bin will also decrease the manufacturing cost of the storage bin since less material is required.

The storage bins have been designed by connecting frames using HSS profiles with angle profiles. Hollow Structural Sections (HSS) have high bending and torsional rigidity compare to their weight which makes it is possible to reduce material, shipping, handling, and erection costs, as well as fireproofing/painting costs [56], [58].

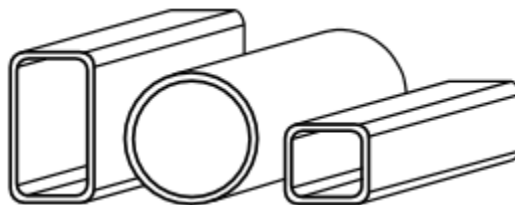


Figure 7.2 – Rectangular, Tubular, and Square hollow section

Although HSS and angle profiles are the main profiles used in storage bins' structure, each storage bin, on average, weighs about 100 Kg, and when it is multiplied by their quantity, it becomes a large rotational mass. Therefore, conducting mass optimization for the storage bin is highly critical.

## 7.1 General formulation of the problem

A structure can be optimal in different aspects. These different aspects are called objectives and may include cost, weight, or stiffness. An objective function,  $f$ , provides a numerical evaluation of a certain objective within some constraints and determines the goodness of the structure in terms of cost, weight, or stiffness. There are, in general, two types of constraints for the structural optimization problems, i.e. design and behavioral. Limited profile sizes and lack of availability of some structural parts are examples of the design constraints, while material, stress, and deformation are behavioral constraints [57].

The optimization problem finds an optimal solution for an objective function, which can be the total mass or cost of the structure. The total mass of the storage bin structure,  $M_{\text{tot}}$ , can be calculated using equation 7.2 [56]

$$M_{\text{tot}} = \sum_1^n \rho_i l_i A_i \quad (7.2)$$

Where:

$\rho_i$  is the material density

$l_i$  is the length of every element of the structure

$A_i$  is the section of the element

$n$  is the number of the elements

however, since the material is set be structural steel (see section 3.2.5) for the storage bins, therefore, the objective function for optimizing total mass/weight can be formulated as equation 7.3 [59].

$$\text{Optimum total mass, } M_{\text{opt}} = \sum_{i=1}^n l_i A_i \quad (7.3)$$

As it was mentioned before, the total length of the storage bin, which determines the length of most of the other parts of the system, is determined by the largest regular bicycle size in the market and cannot be manipulated much. Consequently, the objective function can be simplified further as equation 7.4.

$$\text{Optimum total mass, } M_{\text{opt}} = \sum_{i=1}^n A_i \quad (7.4)$$



The objective function in equation 7.4 determines the optimum mass of the storage bin by optimizing the cross-section of the elements. Therefore, the expected results will be optimum values for width, height, and thickness of the elements' cross-sections.

However, since deflection is inversely proportional to the second moment of inertia, Equation 7.5, reducing cross-section dimensions may increase the deflection of the structural element because of lower moment of inertia.

$$\delta \propto 1/I \quad (7.5)$$

## 7.2 constraints

Constraints are defined to guarantee that the optimized solution remains practical. The following constraints are applied in the optimization to ensure that the generated solution is in accordance with the design objectives.

### 7.2.1 Tension / Tensile Strength

The basic criterion for a steel bar subjected to tensile stress is that it at each cross-section must satisfy the following relationship:

$$\frac{N_{Ed}}{N_{t,Rd}} \leq 1.0 \quad (7.6)$$

Where

$N_{Ed}$  is the design value of the tension force;  $N_{Rd} = N_{pl,Rd}$  if no holes are present.

If any holes are present,  $N_{pl,Rd}$  is calculated using equation 7.7 [56], [57], [58], [59]:

$$N_{pl,Rd} = \frac{A f_y}{\gamma M_0} \quad (7.7)$$

Where:

$A$  is the area of the gross cross-section,  $f_y$  is the yield strength of steel

$\gamma M_0$  is the partial factor of resistance of the cross-section

### 7.2.2 Compression

The primary criterion for a steel bar subjected to compressive stress is that at each cross-section it has to satisfy the following relationship [56], [57], [58], [59]:

$$\frac{N_{Ed}}{N_{c,Rd}} \leq 1.0 \quad (7.8)$$

Where;

$N_{Ed}$  is the design value of the compression force,

$N_{c,Rd}$  is the design compressive resistance of the section. It can be calculated as  $N_{pl,Rd}$  using equation 7.7.

### 7.2.3 Deflection

The limit for the maximum deflection for the structure is determined through the accepted tolerance of the positioning of the storage bin at the loading location where the lift system picks up the bin of the circular truss. The maximum deflection should not exceed the limits which ensure the proper gap between the bin platform and the bottom of the storage bin. A small gap makes the bin platform hit the bottom of the storage bin and reversely a large gap prevents the bin platform from locking onto the storage bin properly. Nonetheless, the primary criterion for the structure is to satisfy the following relationship [56]:

$$u_i \leq u_i^{\max} \quad (7.9)$$

### 7.3 Problem Statement

According to the above definitions, the optimum design of a storage bin structure is defined as:

Find the best vector  $\mathbf{x} \in \Omega$  to minimize  $f(\mathbf{x}) = M(\mathbf{x})$  satisfying the following constraints:

$$\left\{ \begin{array}{l} \frac{N_{Ed}}{N_{t,Rd}} \leq 1.0 \\ \frac{N_{Ed}}{N_{c,Rd}} \leq 1.0 \\ u_i \leq u_i^{\max} \end{array} \right. \quad (7.10)$$

### 7.4 Algorithm

Optimization techniques are categorized into classical and modern methods of optimization. Classical methods are analytical and make use of Differential calculus for locating optimum solutions e.g. Linear and nonlinear programming etc. In contrast, modern methods adapt their operation from nature and natural evolution.

The Evolutionary Algorithms (EAs) are population-based methods that result in a group of solutions instead of a single one, which is the characteristic of the local search algorithms. The idea is that a group can offer some extra benefits compare to an individual. Evolutionary Algorithms (EAs) are stochastic search methods that mimic the metaphor of natural biological evolution and/or the social behavior of species. One of the most popular EAs is the Genetic Algorithm (GA).

Genetic Algorithms have three characteristic operators, namely, selection, crossover, and mutation. In each iteration or generation, these operators are applied to a population of possible solutions, or individuals to improve their fitness. Each individual is represented by a string, which has a very close resemblance to the natural chromosomes, hence the name genetic algorithms.

There are several advantages in using the GA technique, primarily its simplicity and vast field of application. The GA can be easily modified to solve various and different range problems, as opposed to the classical methods which are specified on a specific type of problem. The algorithm is relatively robust and does not tend to get stuck in local optimums. Furthermore, like other population-based techniques, GA does not need to choose an initial guess because the first group of solutions is selected randomly. Therefore, the efficiency of GA, unlike local search algorithms, is not dependent on the initial guess, and since it is sometimes very difficult to provide a feasible initial solution, the randomly selected initial solution makes the starting easier. However, on the downside, the GA may require many function evaluations and sometimes may suffer from premature convergence, which is the high similarity of the individuals in the early process [55], [56], [57], [58].

## **7.5 Results**

The optimization has been performed using ANSYS software as the optimization tool. ANSYS is a powerful tool that enables the user to not only analyze the structure but to optimize variable parameters using classic or modern optimization methods. Before commencing the optimization, it is necessary to establish the optimum mesh size for analyzing and optimizing the model. Mesh size defines the number of mesh elements applied to the model. However, due to technical and process time limitation, a decent number of mesh elements must be applied to the model to ensure obtainable results in a time-efficient manner. It is worth mentioning that in setting up the optimization problem with ANSYS, instead of the tensile force ratio, the more tangible parameter of Safety Factor (S.F), which is a representative of the stress( which is a representation of the force ratio), is chosen.

### **7.5.1. Mesh study**

As was mentioned, it is imperative to select the proper number of mesh elements applied to the model. To achieve that, a mesh study has been performed, and the results compared. Since SF is the primary constraint of the optimization problem (deflection has been considered as an objective) therefore, the number of mesh elements has been weighed against the resultant SF. Figure 7.3 shows the result.

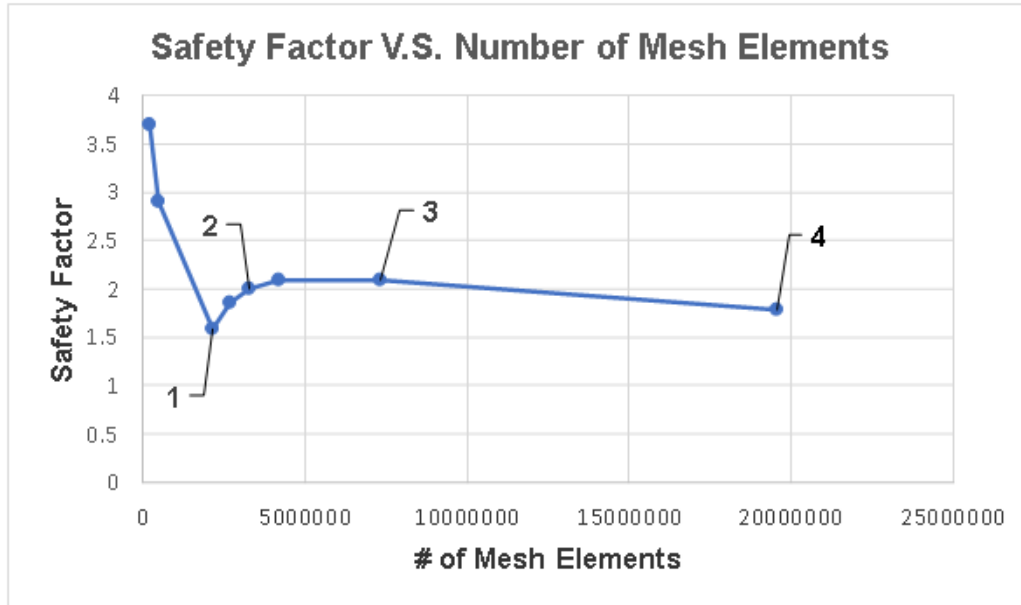


Figure 7.3 – Mesh study results

At first glance, it might be concluded that the portion of the curve, which is between points 2 and 4, represents the best solution neighbourhood. In that area, the curve is almost flat, and the changes of the SF are not substantial even though the number of the mesh elements is increasing. However, by investigating the associated number of mesh elements to these data points, it can be observed that the mesh element quantity of these points is relatively large, which may cause problems with optimization. Table 7.1 provides data points' information.

Table 7.1 Mesh study, result comparison

Data Point #	# of Mesh elements	Safety Factor (SF)
1	2,120,935	1.59
2	3,264,310	1.99
3	7,319,318	2.09
4	19,583,755	1.77

Table 7.1 confirms our first selection and affirms that the area between data points 2 and 4 must be the choice. However, looking at the number of the mesh elements, data point 1 could be a better candidate, it has a lower number of mesh elements, and the associated SF is relatively close to the other data points.

Data points 3 and 4 have a high number of mesh elements, which increases the optimization time exponentially. Datapoint 2 has a relatively lower number of mesh elements – it still has about %55 more mesh elements than point 1- but due to technical limitations such as processing power and memory capacity of the available computer, it will still be a very costly optimization process (it took about 2 days to generate data point 4). Therefore, considering the technical and equipment limitations and that SF deviation is relatively low, data point 1 is selected as a suitable number of mesh elements to perform optimization.

### **7.5.2. Optimization results**

Optimization has been carried out using two different algorithms, Genetic Algorithm (GA) and Non-Linear Programming by Quadratic Lagrangian (NLPQL). The result of GA optimization was then used as a feasible initial solution for the NLPQL to obtain reliable results and be able to compare the outcome of both algorithms.

To further investigate the optimization results, GA was applied both with non-constrained and constrained objectives. With non-constrained objectives, both storage bin mass and the final deflection of the structure were minimized without constraints. The constrained GA, however, applies a maximum limit on final deflection while minimizes the total mass of the storage bin unconstrained.

Due to hardware and computer memory constraints and because the storage bin is symmetrical along its longitudinal axis, the optimization process has been applied to half of the structure of the storage bin to save optimization time and cost.

#### **7.5.2.1 GA results**

Figures 7.4 and 7.5 show the convergence criteria as well as the candidate solutions for unconstrained and constrained GA, respectively, where P115 is the total mass, P116 is the final deflection, and P118 is the Safety Factor.

Optimization Study			
Minimize P115	Goal, Minimize P115 (Default importance)		
Minimize P116	Goal, Minimize P116 (Default importance)		
P118 >= 1.5	Strict Constraint, P118 values greater than or equals to 1.5 (Default importance)		
Optimization Method			
MOGA	The MOGA method (Multi-Objective Genetic Algorithm) is a variant of the popular NSGA-II (Non-dominated Sorted Genetic Algorithm-II) based on controlled elitism concepts. It supports multiple objectives and constraints and aims at finding the global optimum.		
Configuration	Generate 100 samples initially, 50 samples per iteration and find 3 candidates in a maximum of 20 iterations.		
Status	Not Converged.		
Candidate Points			
	Candidate Point 1	Candidate Point 2	Candidate Point 3
P1 - T1_L1 (in)	2.4788	2.7413	2.3288
P2 - T_1_250 (in)	0.24672	0.2516	0.22719
P5 - T1_L2 (in)	1.8142	2.1167	1.9377
P13 - T_2_1875 (in)	0.13163	0.14263	0.13563
P18 - T2_L2 (in)	0.93617	0.91722	0.97699
P24 - T2_L1 (in)	1.1244	1.2277	1.207
P67 - T_3_065 (in)	0.062719	0.05895	0.068565
P68 - T3_L1 (in)	1.6366	1.6695	1.5466
P71 - T3_L2 (in)	0.79336	0.71718	0.76566
P115 - SYS\Solid Mass (lbm)	★★★ 59.557	★ 62.449	★★★ 59.993
P116 - Total Deformation Maximum (in)	— 0.047287	— 0.042191	— 0.052532
P118 - Safety Factor Minimum	★★★ 2.4002	★★★ 3.2522	★★★ 2.4152

Figure 7.4 – Unconstrained GA, convergence criteria and candidate solutions

Optimization Study			
Minimize P115	Goal, Minimize P115 (Default importance)		
P116 <= 0.2 in	Strict Constraint, P116 values less than or equals to 0.2 in (Default importance)		
P118 >= 1.5	Strict Constraint, P118 values greater than or equals to 1.5 (Default importance)		
Optimization Method			
MOGA	The MOGA method (Multi-Objective Genetic Algorithm) is a variant of the popular NSGA-II (Non-dominated Sorted Genetic Algorithm-II) based on controlled elitism concepts. It supports multiple objectives and constraints and aims at finding the global optimum.		
Configuration	Generate 100 samples initially, 50 samples per iteration and find 3 candidates in a maximum of 20 iterations.		
Status	Not Converged.		
Candidate Points			
	Candidate Point 1	Candidate Point 2	Candidate Point 3
P1 - T1_L1 (in)	2.4788	2.3288	2.3063
P2 - T_1_250 (in)	0.24672	0.22719	0.2975
P5 - T1_L2 (in)	1.8142	1.9377	2.0303
P13 - T_2_1875 (in)	0.13163	0.13563	0.18063
P18 - T2_L2 (in)	0.93617	0.97699	0.7627
P24 - T2_L1 (in)	1.1244	1.207	1.0707
P67 - T_3_065 (in)	0.062719	0.068565	0.065565
P68 - T3_L1 (in)	1.6366	1.5466	1.4584
P71 - T3_L2 (in)	0.79336	0.76566	0.68671
P115 - SYS\Solid Mass (lbm)	★★★ 59.557	★★★ 59.993	★★★ 61.024
P116 - Total Deformation Maximum (in)	★★★ 0.047287	★★★ 0.052532	★★★ 0.056007
P118 - Safety Factor Minimum	★★★ 2.4002	★★★ 2.4152	★★★ 2.8006

Figure 7.5 – Constrained GA, convergence criteria and candidate solutions

Since GA can solve unconstrained objectives and does not need an initial solution, both unconstrained and constrained GA resulted in very similar candidates. In fact, candidates 1 and 3 in Figure 7.4 are similar to candidates 1 and 2 in Figure 7.5, respectively. The difference between the other candidates stems from the fact that in one of them, the final deformation of the structured had an upper limit and not being necessarily just minimized without a bound. Figures 7.6 to 7.9 illustrate the trade-offs between optimization parameters for both conditions.



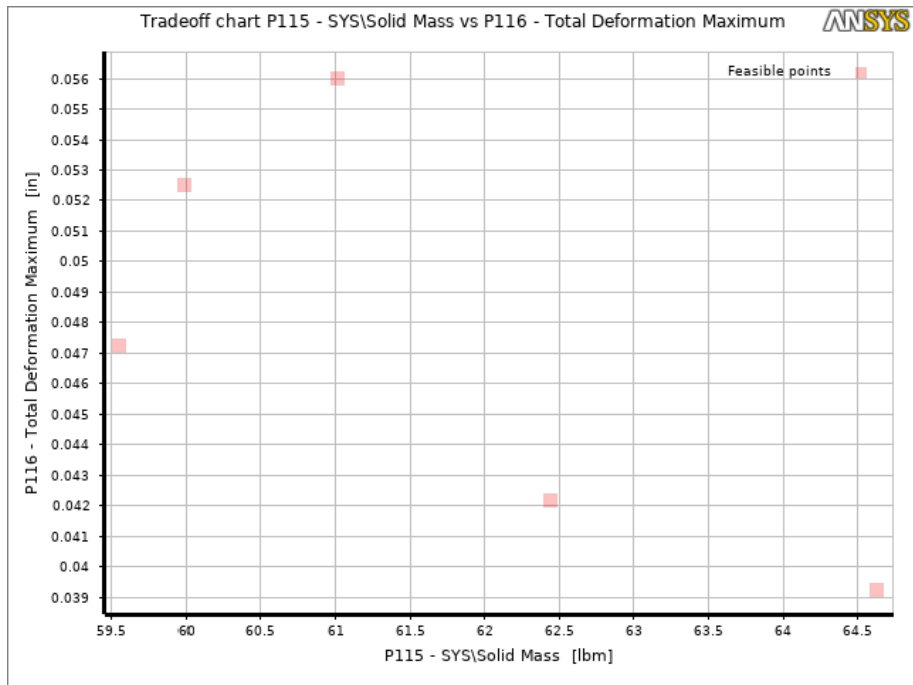


Figure 7.6 – Unconstrained GA, Total mass VS Total Deformation

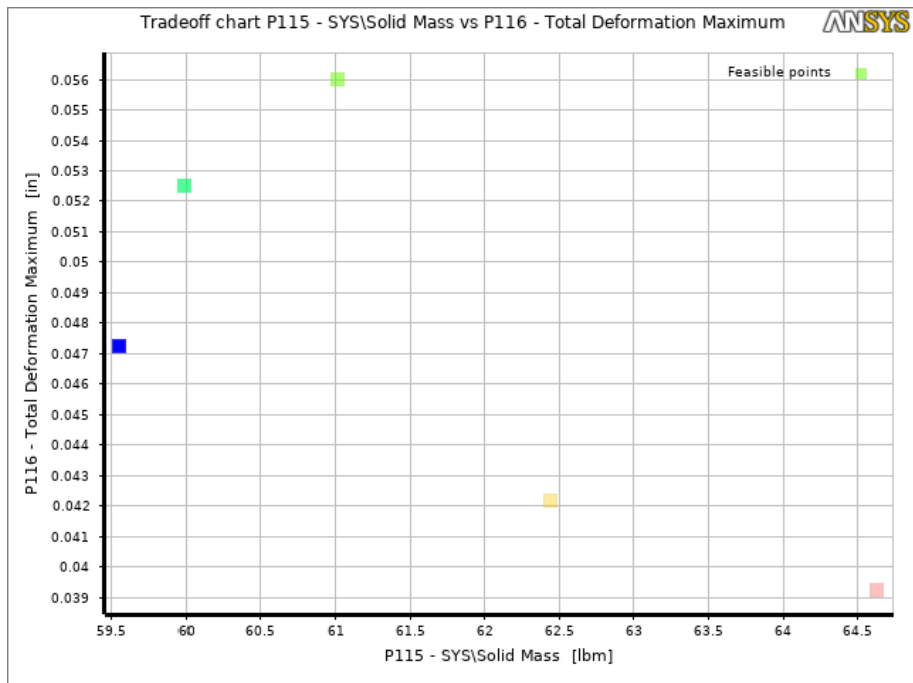


Figure 7.7 – Constrained GA, Total mass VS Total Deformation

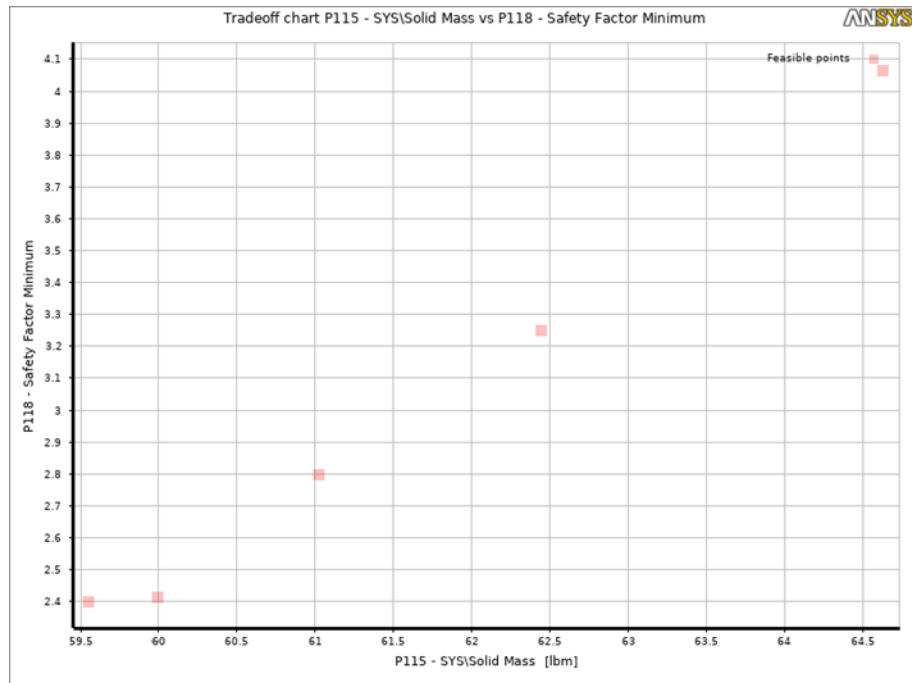


Figure 7.8 – Unconstrained GA, Total mass VS Safety Factor

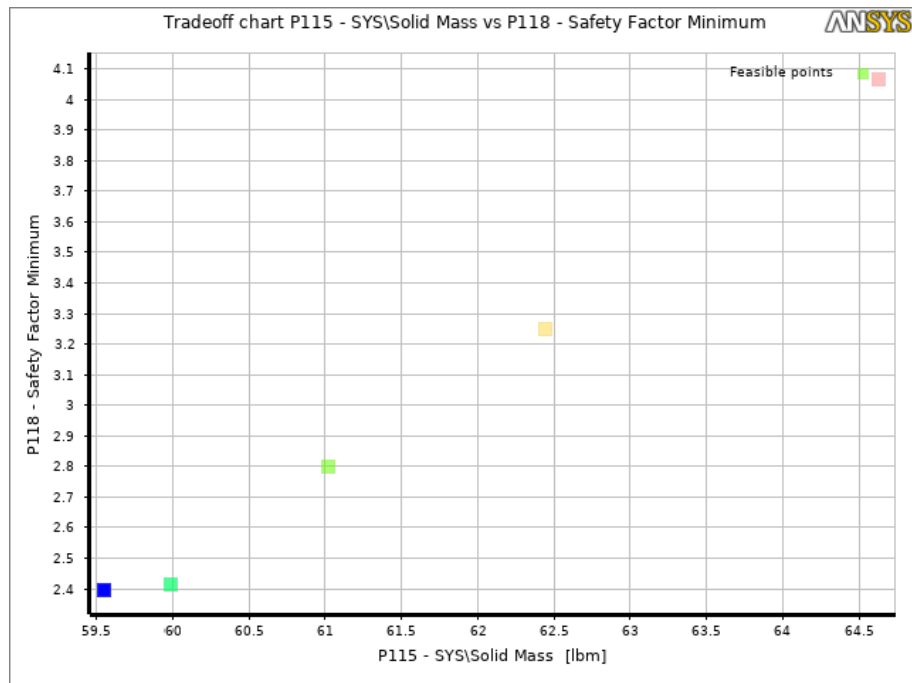


Figure 7.9 – Constrained GA, Total mass VS Safety Factor

### 7.5.2.2 NLPQL results

Candidate point 3 of Unconstrained GA result – which is candidate point 2 of Constrained GA results (see Figures 7.4 and 7.5) – is selected as the feasible initial solution for NLPQL algorithm. Figures 7.10, 7.11, and 7.12 show the convergence criteria and the candidate solutions, as well as the relation between optimization parameters.

Optimization Study				
Minimize P115	Goal, Minimize P115 (Default importance)			
P116 <= 0.2 in	Strict Constraint, P116 values less than or equals to 0.2 in (Default importance)			
P118 >= 1.5	Strict Constraint, P118 values greater than or equals to 1.5 (Default importance)			
Optimization Method				
NLPQL	The NLPQL method (Nonlinear Programming by Quadratic Lagrangian) is a gradient-based algorithm to provide a refined, local, optimization result. It supports a single objective, multiple constraints and is limited to continuous parameters. The starting point must be specified to determine the region of the design space to explore.			
Configuration	Approximate derivatives by Forward difference and find 3 candidates in a maximum of 20 iterations.			
Status	Not Converged.			
Candidate Points				
	Starting Point DP 384	Candidate Point 1	Candidate Point 2	Candidate Point 3
P1 - T1_L1 (in)	2.328	2.25	2.25	2.3262
P2 - T1_250 (in)	0.22719	0.1875	0.20946	0.21519
P5 - T1_L2 (in)	1.9377	2.0176	1.9668	1.8836
P13 - T_2_1875 (in)	0.13563	0.125	0.125	0.12502
P18 - T2_L2 (in)	0.97699	0.7549	0.88689	0.93408
P24 - T2_L1 (in)	1.207	1.1893	1.1375	1.1344
P67 - T_3_065 (in)	0.068565	0.071204	0.070578	0.069899
P68 - T3_L1 (in)	1.5466	1.538	1.4839	1.479
P71 - T3_L2 (in)	0.76566	0.77522	0.73645	0.71114
P115 - SYS\Solid Mass (lbm)	✖✖ 59.889	★★ 55.711	★★ 56.456	★★ 56.735
P116 - Total Deformation Maximum (in)	★★ 0.052564	★★ 0.065616	★★ 0.060207	★★ 0.056695
P118 - Safety Factor Minimum	★★ 1.9095	★★ 1.5282	★★ 1.9495	★★ 1.7852

Figure 7.10 – NLPQL, convergence criteria, and candidate solutions

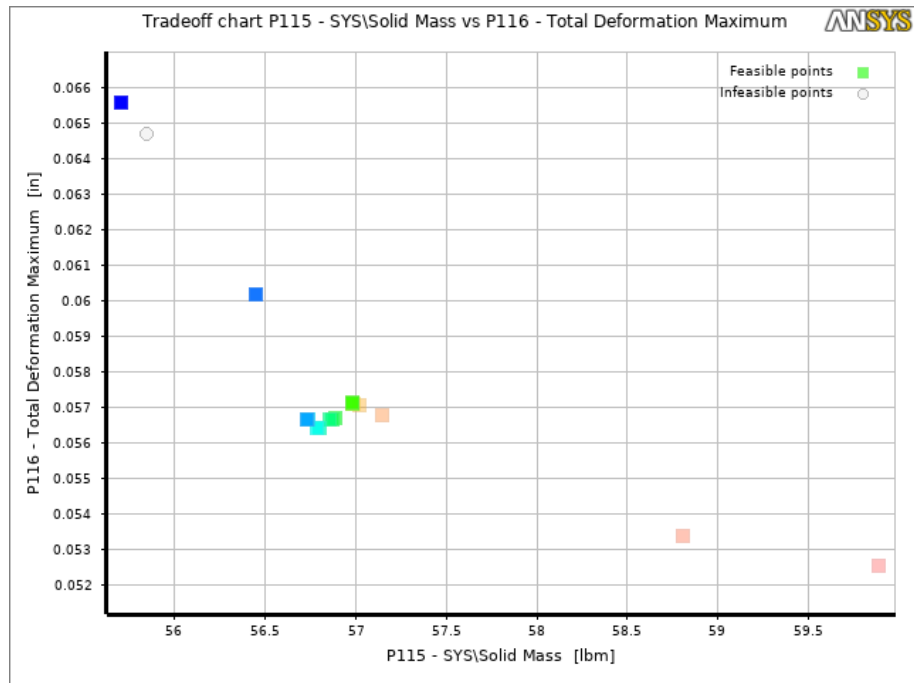


Figure 7.11 – Total mass VS Total Deformation

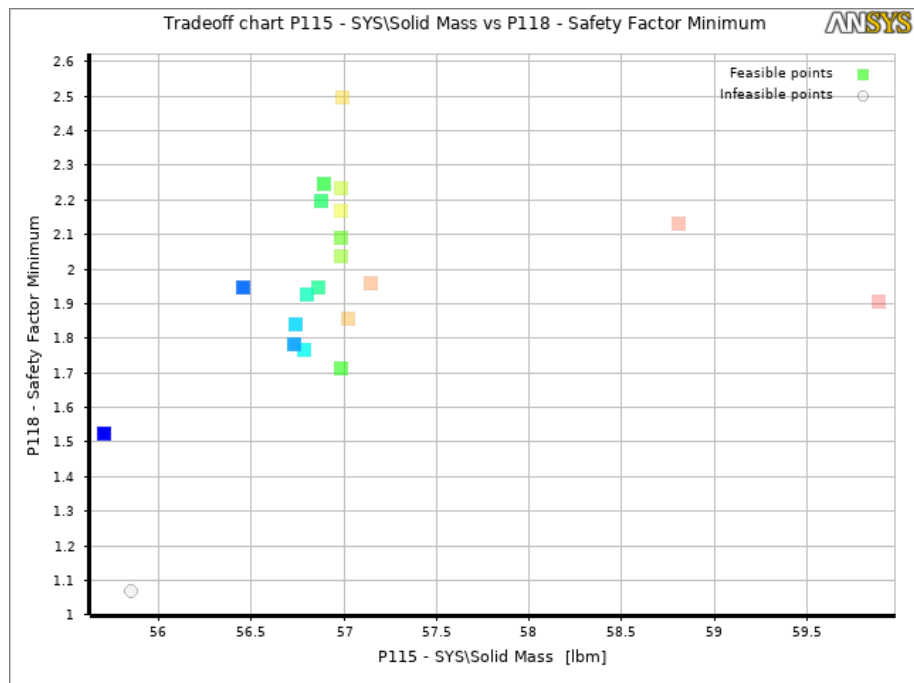


Figure 7.12 – Total mass VS Safety Factor

## 7.6 Conclusion

Both GA and NLPQL methods resulted in candidates which has lesser mass than the original design while fulfilling the design/optimization essential criteria, being allowed minimum SF and maximum total deformation. Table 7.2 presents the candidate solutions parameters generated by the optimization process by either algorithm.

Table 7.2 Candidate solutions

		Total Mass (lb)	Total Deformation (in)	Safety Factor
Original Design		62.132	0.04061	2.59
GA, Unconstrained				
	Candidate 1	59.557	0.047287	2.4
	Candidate 2	62.449	0.042191	3.25
	Candidate 3	59.993	0.052532	2.42
GA, Constrained				
	Candidate 1	59.557	0.047287	2.4
	Candidate 2	59.993	0.052532	2.42
	Candidate 3	61.204	0.056007	2.8
NLPQL				
	Candidate 1	55.711	0.065616	1.53
	Candidate 2	56.456	0.060207	1.95
	Candidate 3	56.735	0.056695	1.79

It is obvious from table 7.2, that NPLQL method has resulted in a lighter storage bin than the GA method, however, this has to be considered that obtaining good results from the NLPQL algorithm is very much dependant on a right initial solution which has been generated by GA method. In other words, NLPQL has started from an already optimized solution, which has enabled the algorithm to generate more suitable candidate solutions.

From Table 7.2, the champion solution candidates generated by GA and NLPQL are candidate 1 and candidate 2, respectively. Table 7.3 compares these two solutions.

Table 7.3 Champion solutions of each algorithm

	Total Mass (lb)	Total Deformation (in)	Safety Factor
GA, Candidate 1	59.557	0.047287	2.4
NLPQL, Candidate 2	56.456	0.060207	1.95

Table 7.3 illustrates that NLPQL has resulted in a better solution than GA. Considering that the primary purpose of optimization was to minimize the total mass of the storage bin, it is evident that NPLQL solution, compared to the original design, offers a higher mass reduction (~%9) than GA (~%4). However, even though both have a lower safety factor than the original design (2.59), the GA solution offers a higher SF (2.4) than the NLPQL solution (1.95). The total deformation for both solutions is well below the maximum limit.

Although the optimization results present a solution with which a total of %9 reduction in the total mass of storage bin combine with an acceptable deformation and safety factor is achievable, but a closer look at the dimensions of the proposed profile elements may not be easily obtainable.

There are three different HSS profiles used in the structure of the storage bin, 2.5X2X.25" Angle bar, 1X1X0.1875" Angle bar, and 1.5X0.75X0.0625" Rectangular box, Table 7.4 presents dimensions of the champion candidate solutions

Table 7.4 Dimensions of storage bin profiles, original and optimized design

Dim.	Angle Bar 1			Angle Bar 2			HSS Box		
	L	W	T	L	W	T	L	W	T
Original Design	2.5	2	0.25	1	1	0.1875	1.5	0.75	0.0625
GA	2.33	1.94	0.2272	1.21	0.977	0.136	1.547	0.766	0.0686
NLPQL	2.25	2.02	0.1875	1.19	0.755	0.125	1.484	0.7365	0.0706

The main objective of optimization, as it was mentioned before, is to minimize the mass of the storage bin so that it consequently reduces energy consumption and manufacturing cost. One of the standard practices in cost reduction is to use off-the-shelf parts because they are more cost-effective than custom-made ones. The generated solutions by both algorithms, however, are not regular off-the-shelf sizes and must be custom made. Nevertheless, these optimization solutions offer a good starting point to search and locate the closest available off-the-shelf sizes. For instance, considering the NLPQL solution, off-the-shelf profiles which are close to the solution can be found. Table 7.5 offers a New candidate.

Table 7.5 New profile dimensions, suggested based on NLPQL results

Dim.	Angle Bar 1			Angle Bar 2			HSS Box		
	L	W	T	L	W	T	L	W	T
Original Design	2.5	2	0.25	1	1	0.1875	1.5	0.75	0.0625
NLPQL	2.25	1.967	0.2095	1.138	0.887	0.125	1.484	0.736	0.0706
New	2.5	2	0.25	1	1	0.125	1.5	0.75	0.0625

The offered new solution is much easier to be procured through the regular market and has a lower mass than the original design and fulfills the requirements of deformation and safety factor. It is no surprise, however, that the optimization results are close to the original design. During the design iterations, many dimension combinations of the three profiles were used and tried to obtain an optimum design; the optimization results verify design parameters. Table 7.6 compares the result of the new candidate with the original design as well as the NLPQL candidate.

Table 7.6 New suggestion for profile dimensions, based on NLPQL results

	<b>Total Mass (lb)</b>	<b>Total Deformation (in)</b>	<b>Safety Factor</b>
Original Design	62.132	0.04061	2.59
NLPQL, Candidate 2	56.456	0.060207	1.95
New Candidate	58.161	0.047	2.28



## Chapter 8. Conclusion and Future work

The world population is growing every day and consequently, cities and urban areas grow larger and larger. This ubiquitous growth results in more and more urban and environmental issues both individually and socially. More people mean more cars on the streets, more traffic and pollution, depreciation of social health, and longer commute times, and more cost.

To address these issues and to improve both inner-city travel and social health, cities, and transit planners have integrated more active solutions in their plan and have designed active transportation plans for large urban areas. The goal is to integrate a more active, healthy mode of commutes, such as cycling, into the public transit system to encourage the public to leave their cars at home, adopt a healthier lifestyle, and decrease the collective carbon footprint.

Meanwhile, cycling has become a growing trend in most metropolitan areas and cities, last decades have witnessed significant growth in the number of commuters who chose bicycles as the main mode of travel. However, to enhance public enthusiasm and encourage more people to adopt an active mode of transportation, certain infrastructures and facilities must be planned for and provided through executing active transportation plans.

Regarding cycling, one of the important facilities is secure and efficient bicycle parking at the commute destinations, i.e. whether a commuter decides to use a bicycle to a transit hub to ride public transit to a destination or simply drive a car there can rely merely on the availability of a proper parking facility at the said transit hub.

Although the transit and city authorities usually provide parking facilities at the major transit hub, these solutions are not effective and encouraging. The existing traditional parking facilities for bicycles, i.e. bike racks and cages, are insecure, messy, and space inefficient. A bicycle locked to a bike rack or in a bike cage is accessible by the public and easily subjected to acts of theft or vandalism, which is a discouraging and deterrent factor in enhancing active transit, a better solution is needed. To address and remedy the existing parking problem, an automated storage system has been studied, designed, manufactured, and installed to offer a secure easy parking experience to the cyclists.

First, different types of automated storage and retrieval systems (AS/RS) underwent extensive study. The aspects and characteristics of such systems as well as their operation and working logic created a baseline for this research and its outcome. The carousel systems, in particular, possess many required operational and logical fundamentals which are essential to the design of the automated bicycle storage system.

Next, the existing automated bicycle storage systems were studied to obtain a better understanding of the requirements, operational and performance characteristics as well as their specifications and technical data. By combining the result of the study of the storage system with the requirements of different types of customers- i.e. cyclists, developers, cities, etc. - the design requirements and objectives for the proposed system were defined.

Afterward, the design process started. The general concept of the system as well as various equipment, subsystems and parts were designed. As the concept design progressed, the SolidWorks model of these parts and equipment generated and integrated to ensure the compatibility and matching of the equipment in the complete system.

Once the design was over and the drawings for manufacturing were prepared and generated, the manufacturing started and then manufactured sections of the system were assembled. The complete system underwent vigorous testing to certify the performance of the system as well as compliance with design objectives. The tests showed that the designed and manufactured automated bicycle storage system provides the users with security and space efficiency with reliable performance.

Finally, optimization was performed to reduce the weight of storage bins so that less material, as well as power, would be required for the system. ANSYS software was utilized to perform an evolutionary algorithm optimization on the elements of the storage bin to optimize its mass.

## **8.1 Future work**

The installed automated bicycle system is the first of its kind in North America. It is the first, hopefully of many to come. Therefore, some areas can be studied and improved further. In first glance, the improvements can be divided into three categories; 1- reducing the cost of the system through simplification, 2- reducing the required energy

and power by decreasing the weight of moving parts, and 3- enhancing and improving the performance of the system.

The followings are some example of future work recommendations:

- Simplifying the truss ring by reducing its members and optimizing the mass of the elements. Since the truss ring is part OF the rotating mass its weight reduction will result in less power consumption. It also may result in a smaller system diameter without compromising the required maintenance space, if just two circular members are used instead of four.
- Decreasing the cycle time of the operation- i.e. increasing the speed of system- by using servo equipment. The existing system benefits from the low cost of regular inductive motors compare to the servo ones, however, the servo equipment can offer faster more accurate positioning operation
- Simplifying and improving the control system can be achieved by studying the designed system against alternatives for different control elements. For instance, the existing system uses absolute encoders in a closed-loop feedback to control the positioning of main moving sections of the system. However, a combination of RFID reader and tags with several sensors instead of expensive absolute encoders may prove more cost and performance effective. This approach will necessitate adjustment and changes in control logic and programming.

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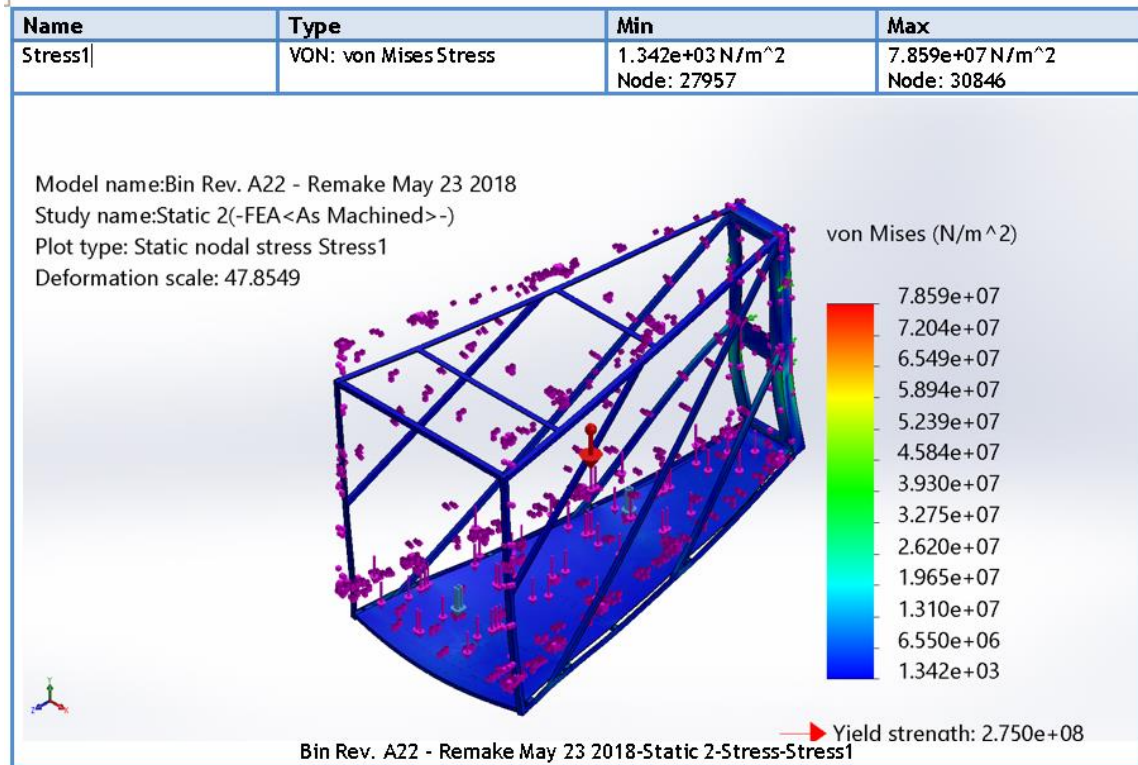
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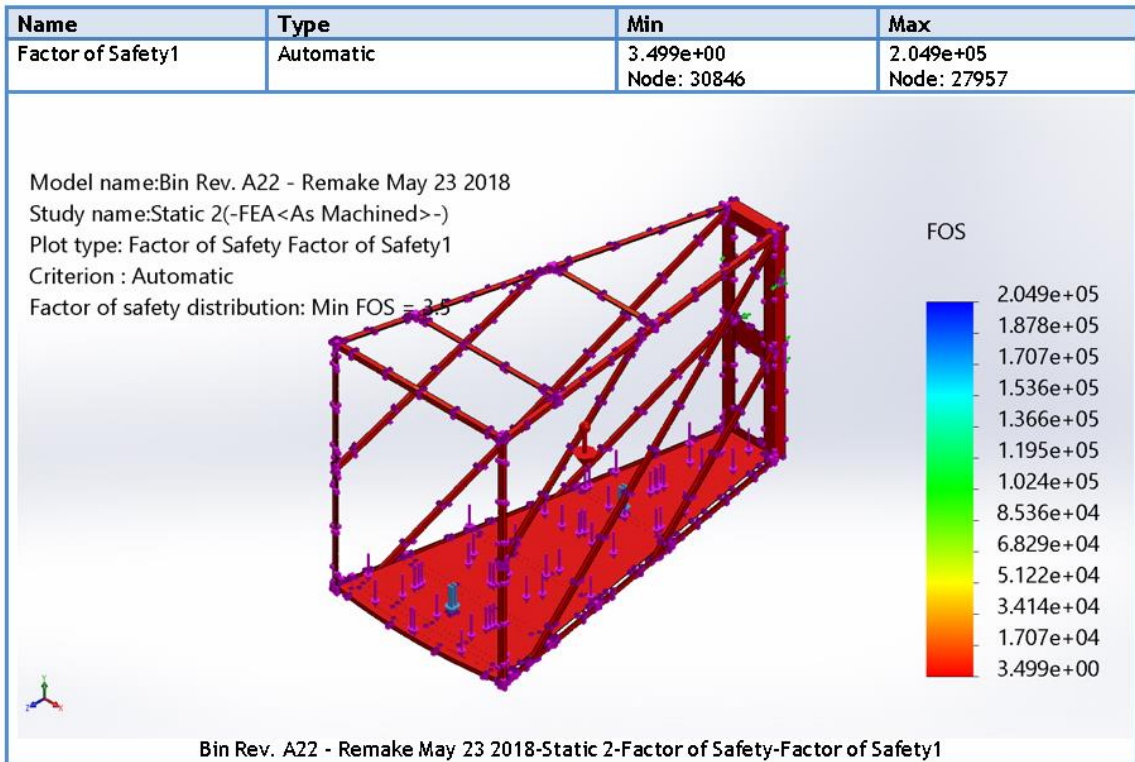
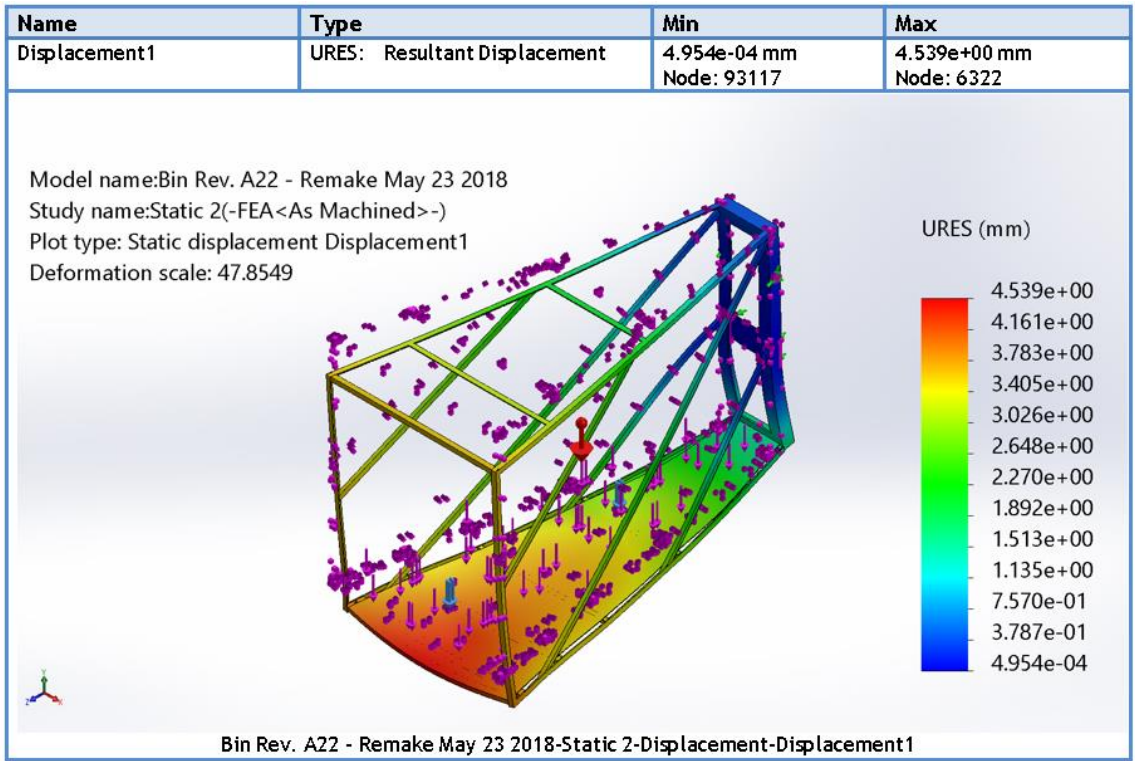
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# Appendix A

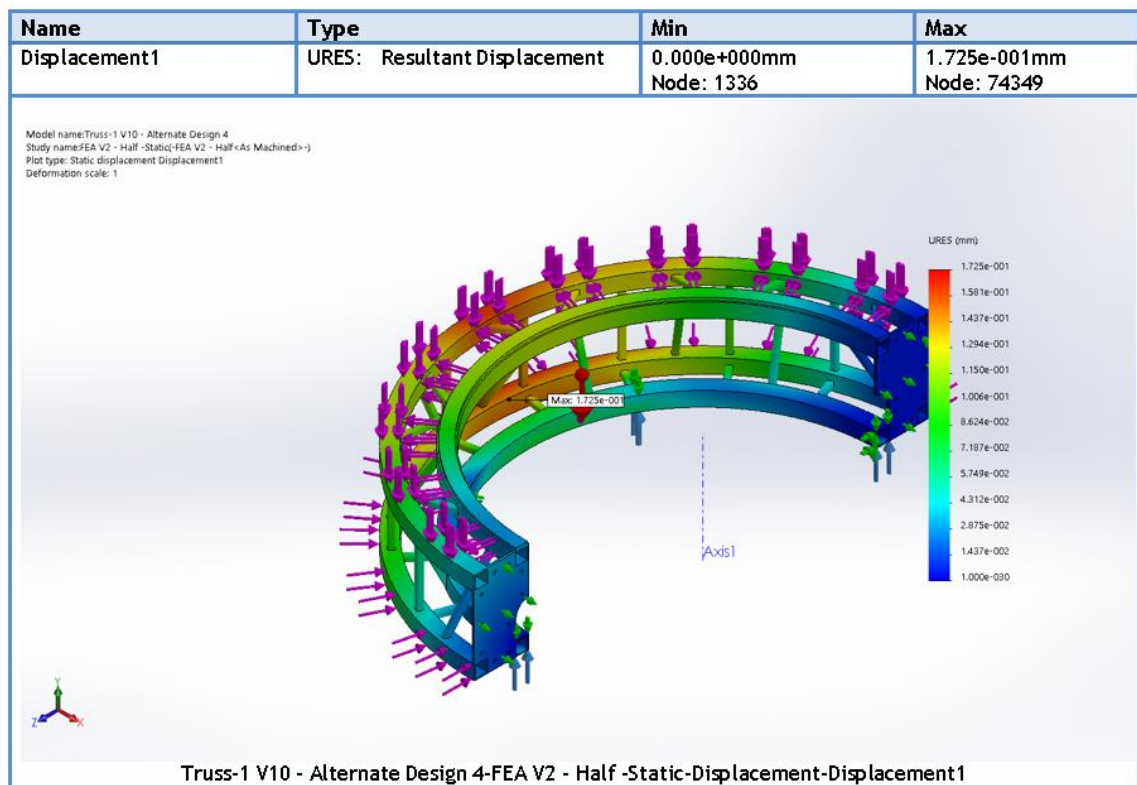
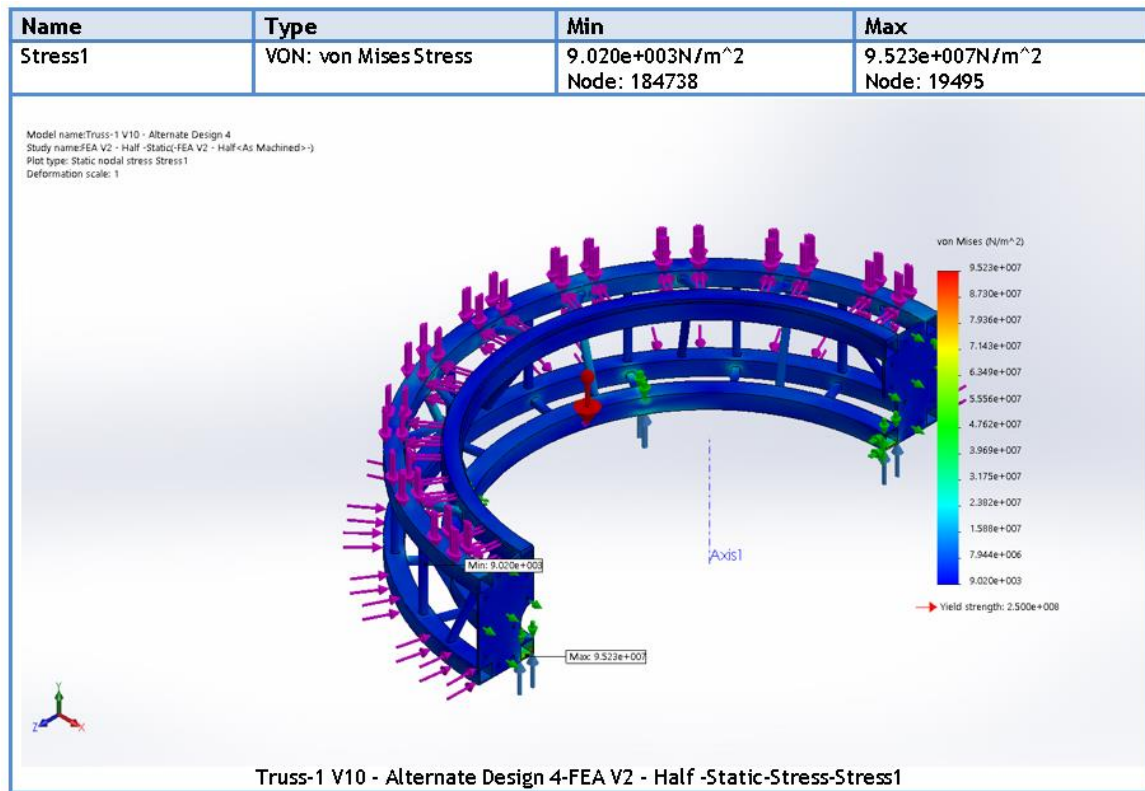
## FEA results

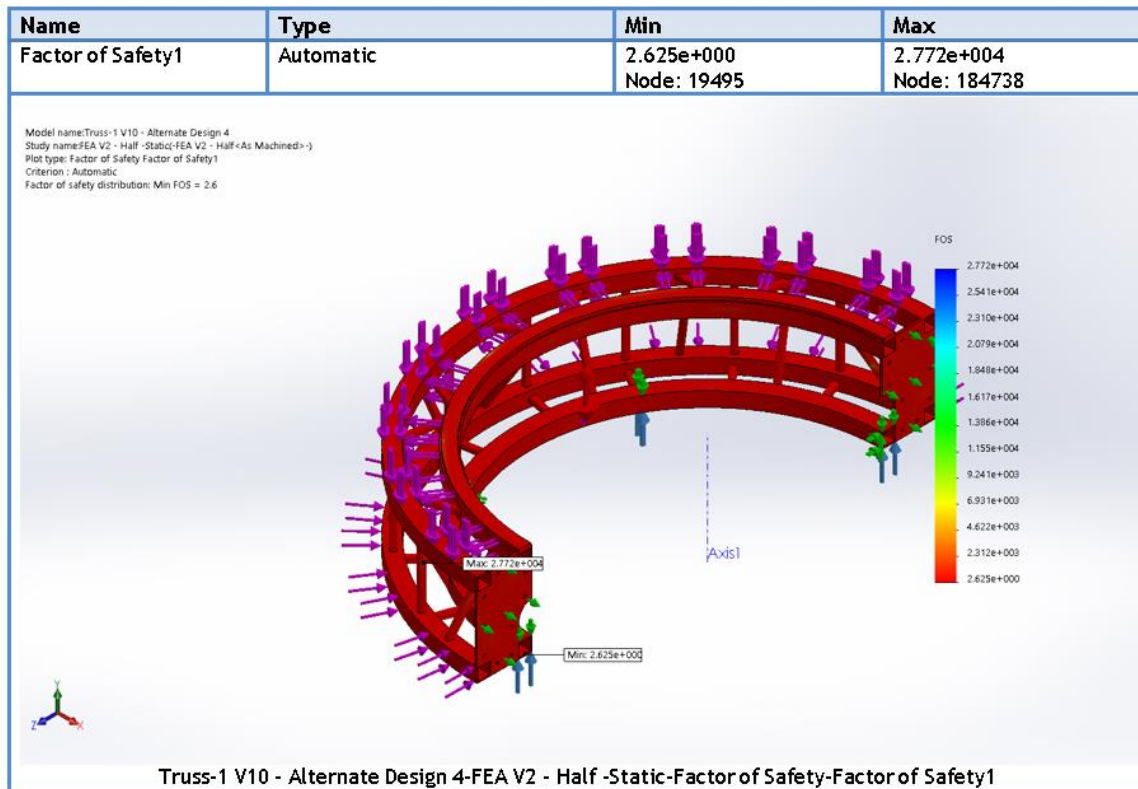
### 1- Storage Bin



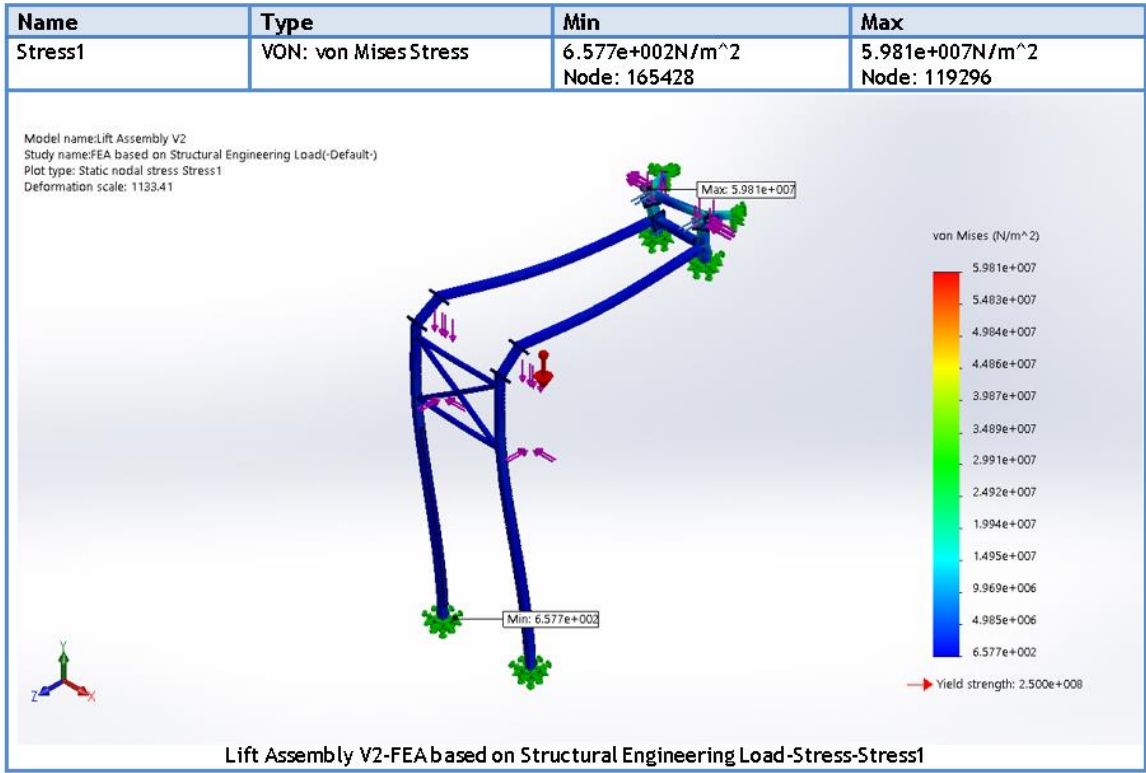


## 2- Truss ring

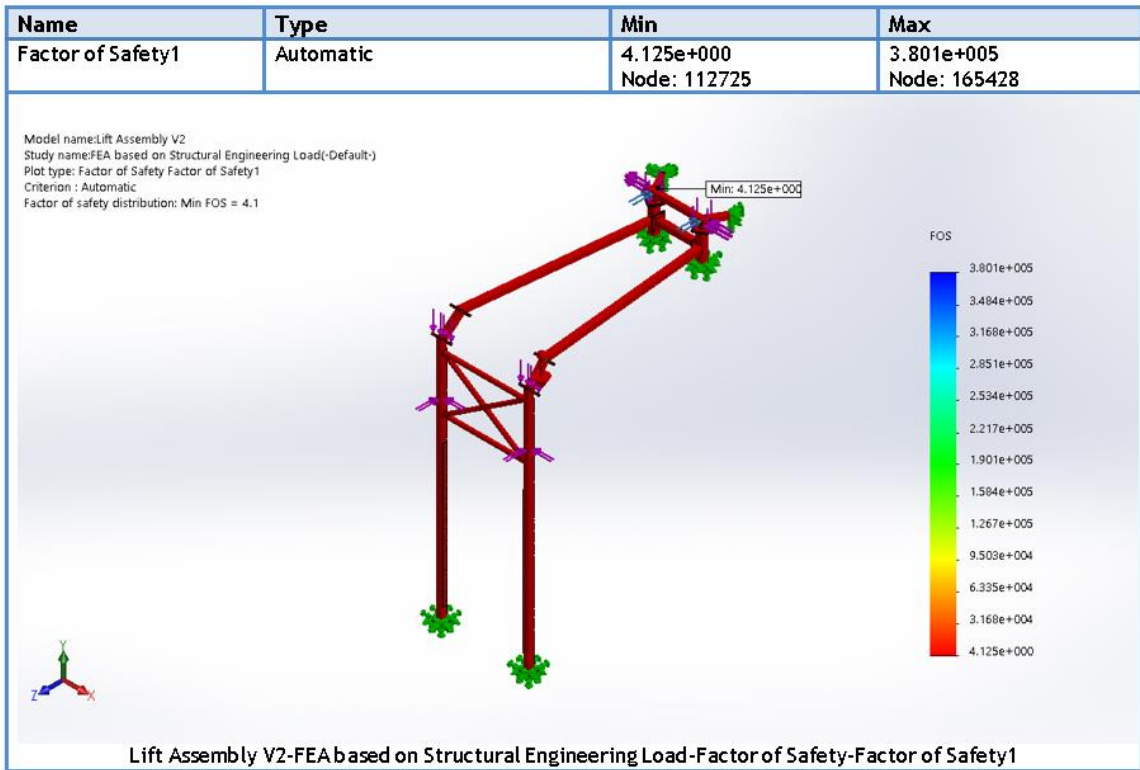
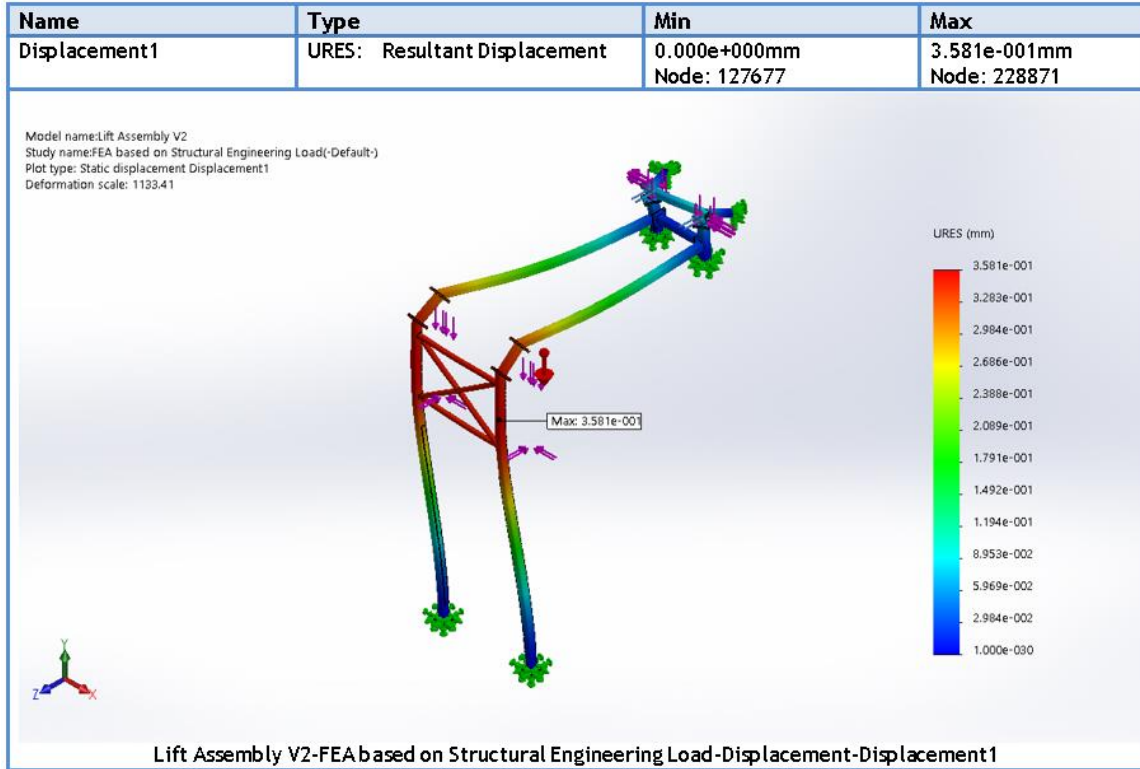




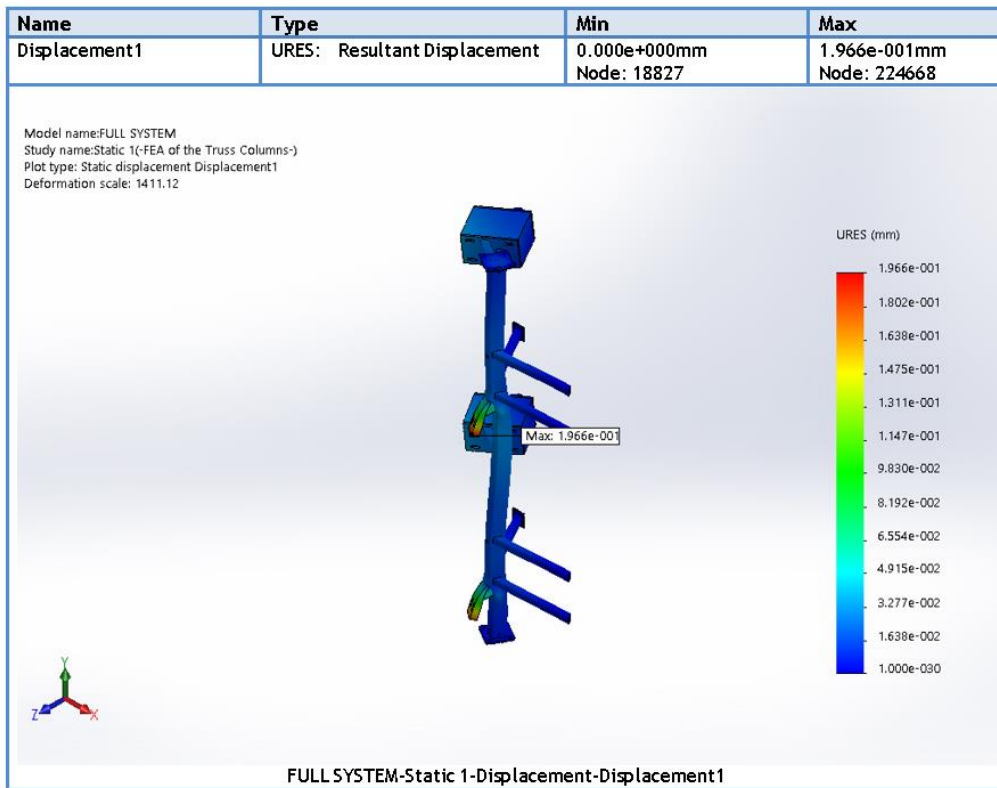
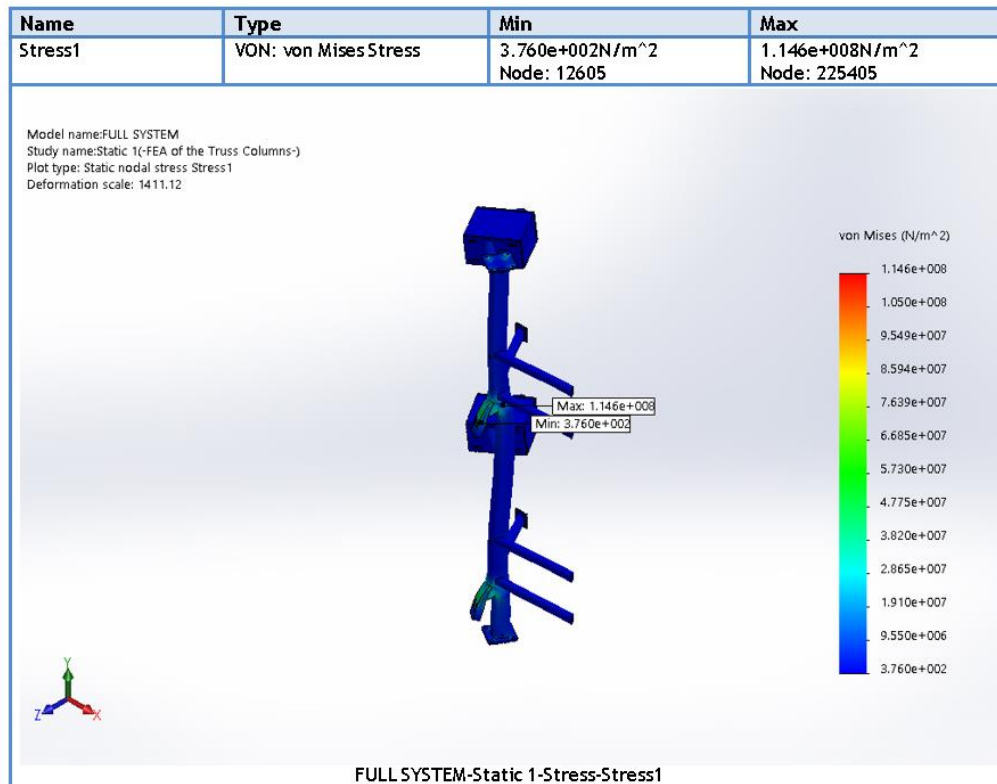
3- Lift Tower



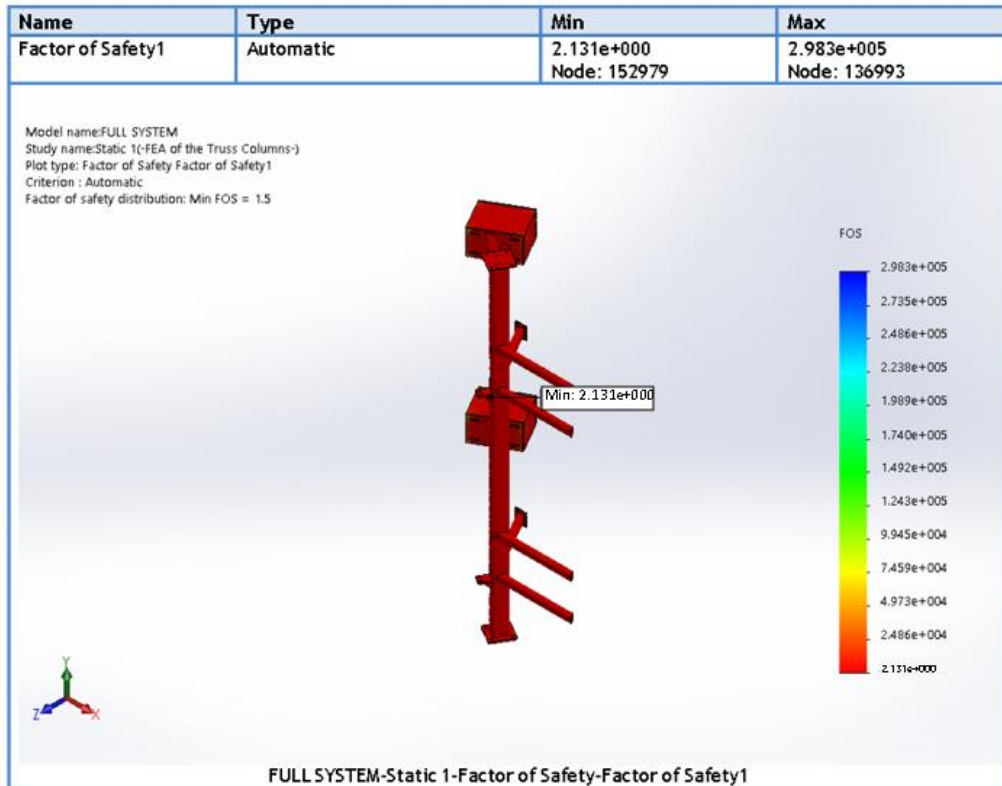




#### 4- Central Column





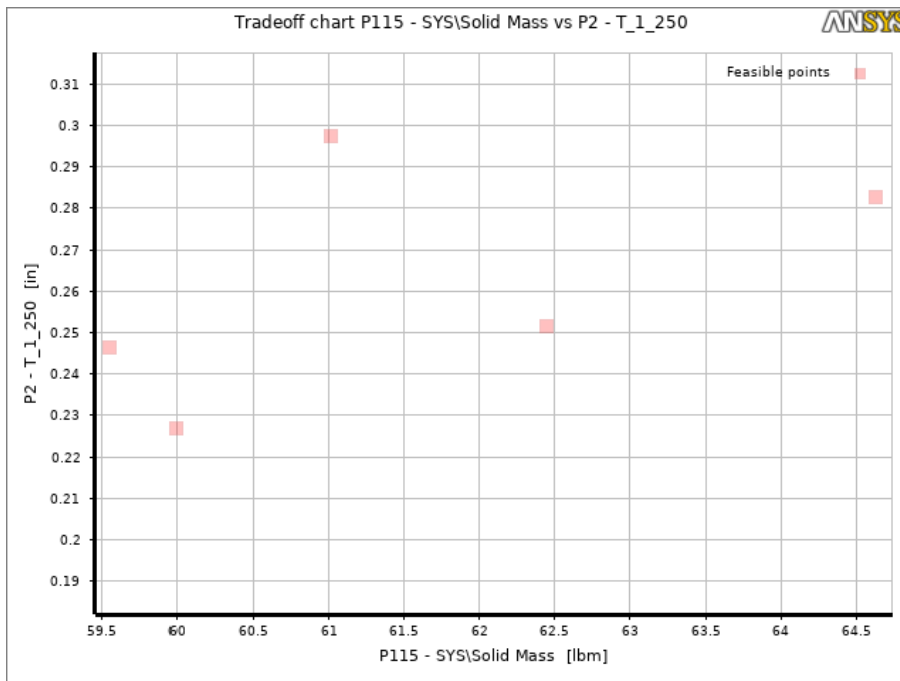


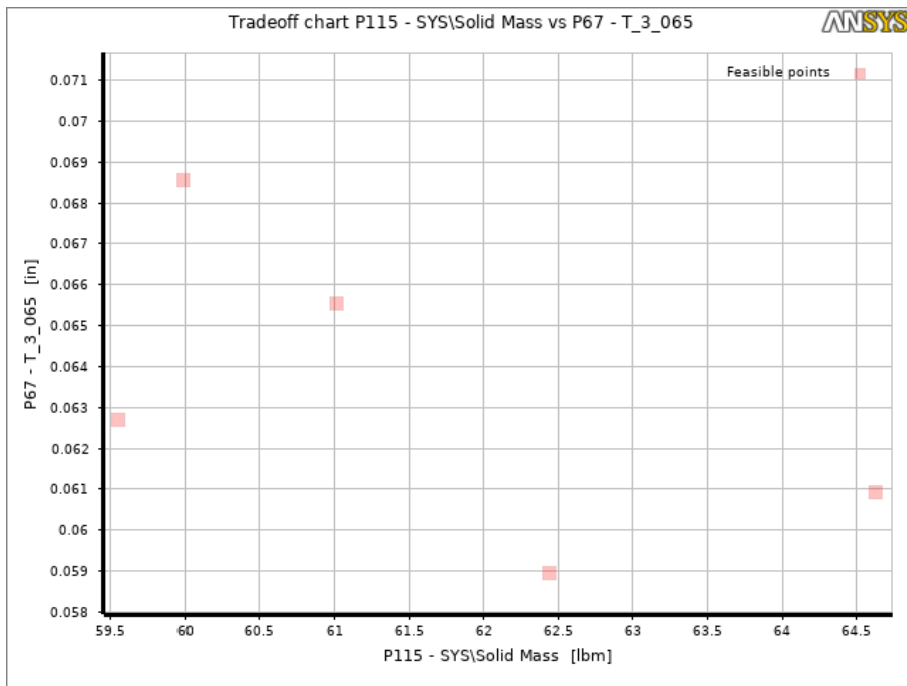
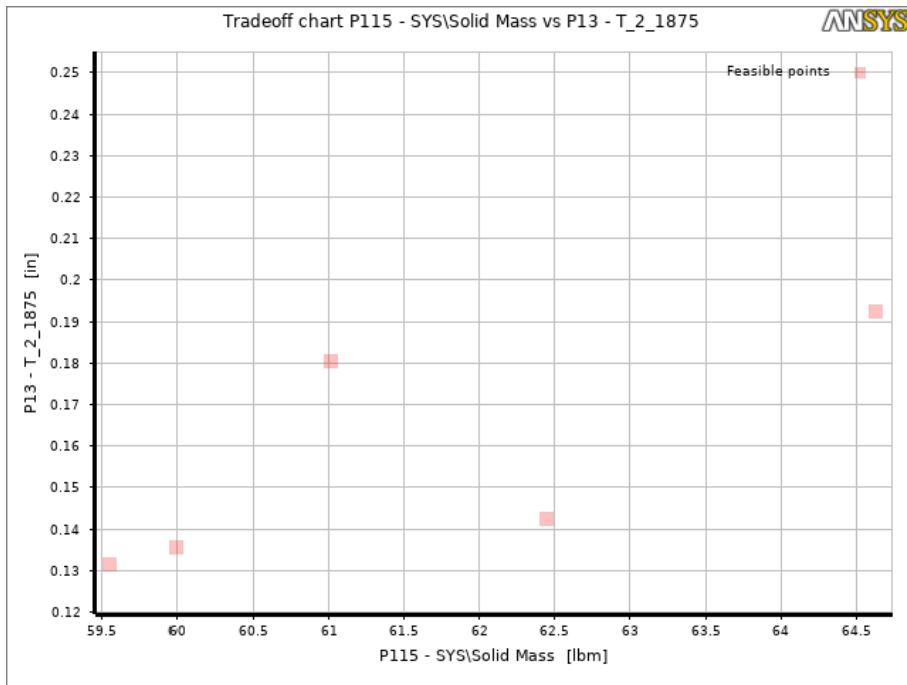
# Appendix B

## Optimization Results

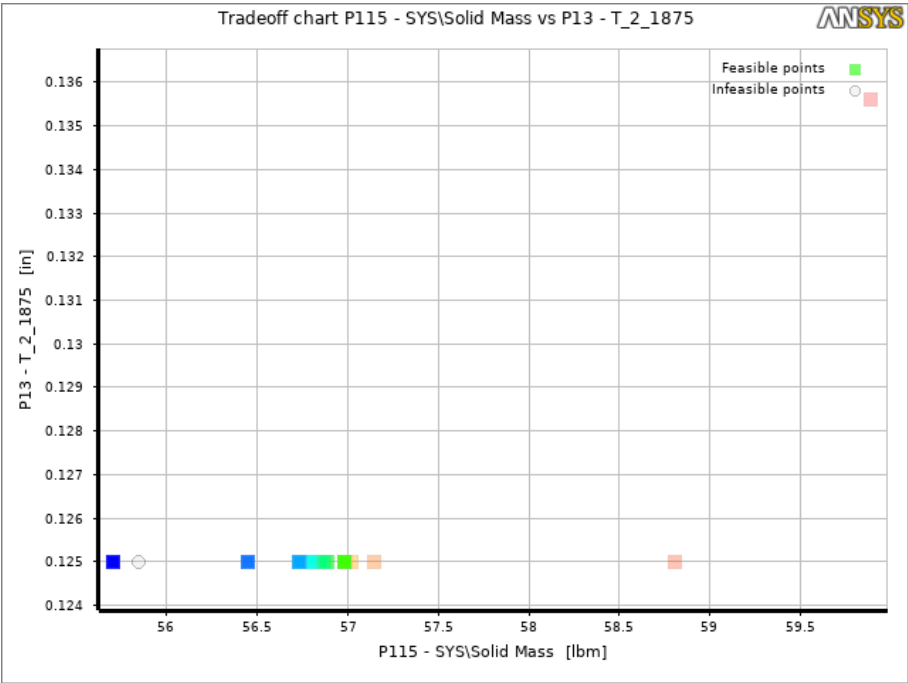
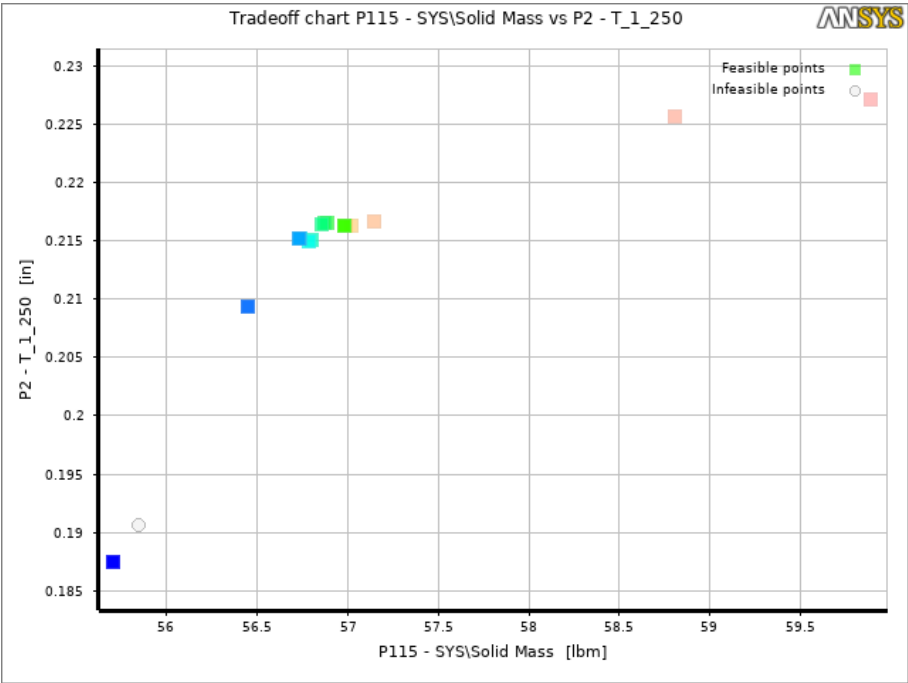
### Total mass VS profile thickness

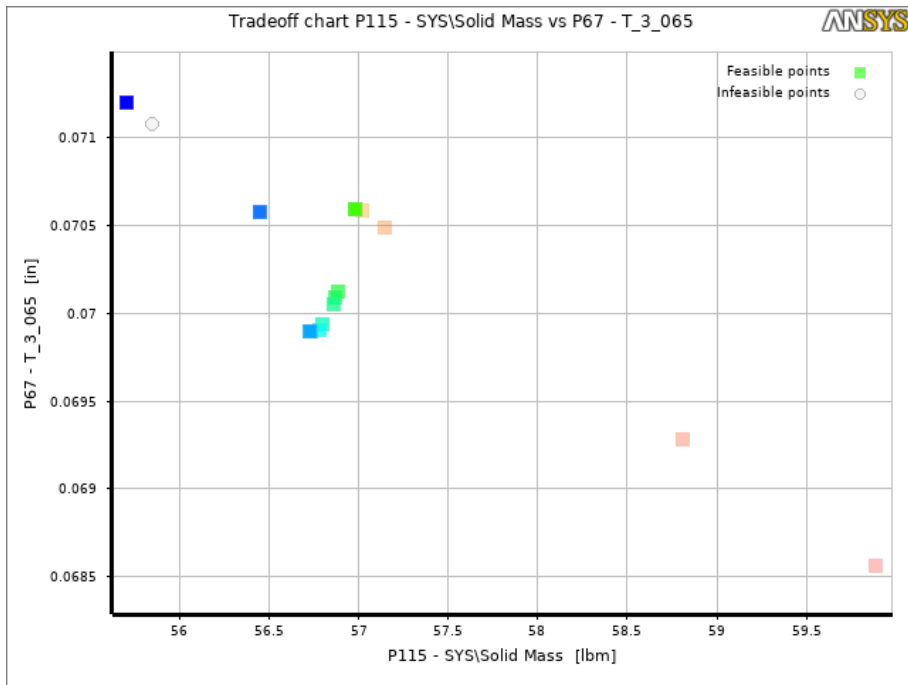
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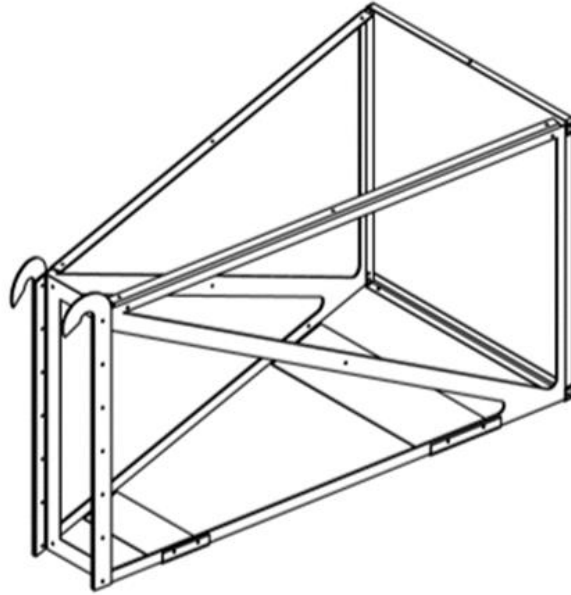




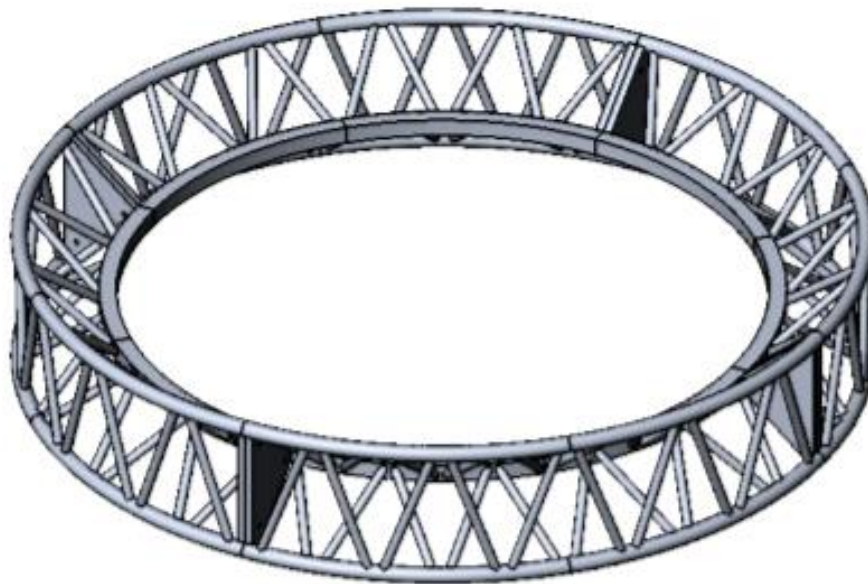
## Appendix C

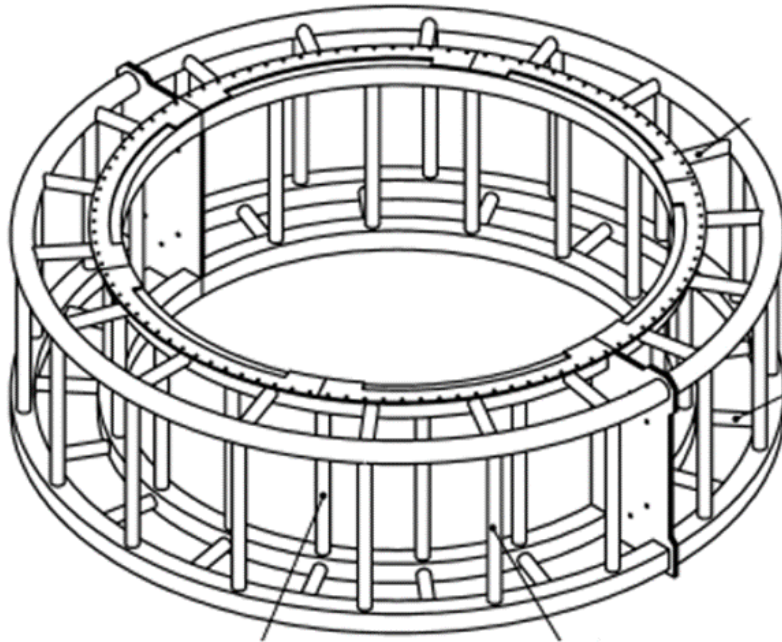
### Alternative concepts and design iteration

Storage bin

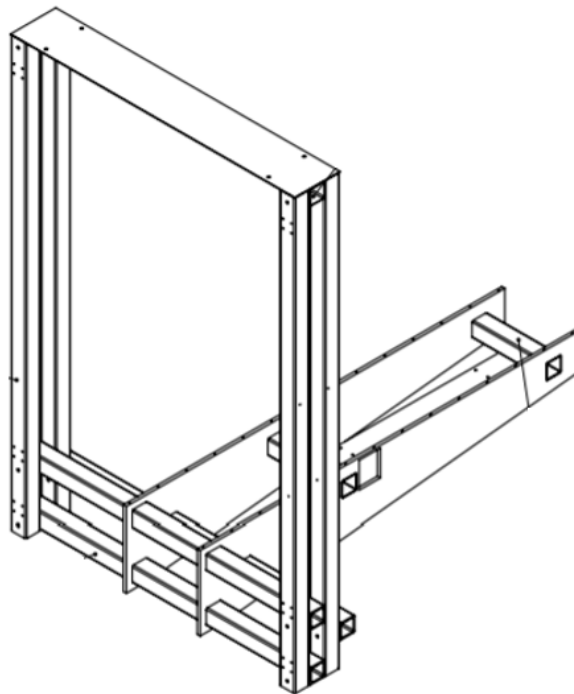


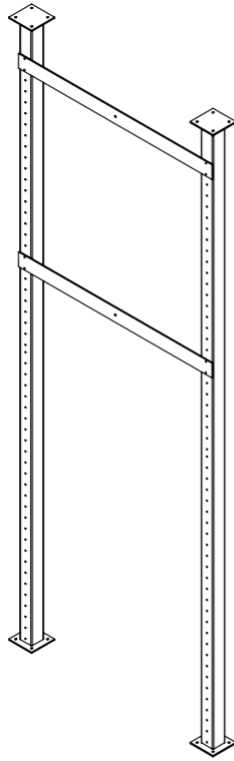
Truss ring





**Lift Frame and tower**





### Central Columns

