

T.C.
MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES IN
PURE AND APPLIED SCIENCES

AN AXIOMATIC DESIGN APPROACH TO
MECHANICAL CAR PARKING SYSTEM DESIGN

Muhammet DEMİRTAŞ

THESIS
FOR THE DEGREE OF MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING

SUPERVISOR

Ass. Prof. Dr. Aykut KENTLİ

İSTANBUL 2012

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ÖZET

MEKANİK ARAÇ PARK SİSTEMİ TASARIMINA AKSİYOMATİK TASARIM YAKLAŞIMI

Otomobiller kullanılmaya başladığından bu yana, insanlar belirli bir alana daha fazla araç park edebilmeye olanak sağlayan teknik sistemler üzerinde düşünmektedirler. Önceleri klasik çok katlı otopark sistemleri geliştirilmiş, ancak bu sistemler giriş ve çıkış rampaları ve/veya araç asansörü, araç ile park yeri arasında koridor bulundurduğu için, daha iyi bir çözüm olan mekanik otopark sistemleri tasarlanmış ve bu sistemler dünya genelinde yaygın olmaya başlamıştır.

Bu tez çalışmasında mevcut mekanik otopark sistemlerinden iki tanesi, 1990'lı yıllarda MIT'de Prof. Nam P. Suh tarafından geliştirilen ve tasarımcıların kötü tasarımlarda oluşan problemlerden kaçınmasını sağlayan aksiyomatik tasarım yöntemi ile incelenmiştir. Aksiyomatik tasarım prensipleri kullanılarak yeni bir mekanik otopark sistemi tasarlanmıştır. Aksiyomatik tasarımın bağımsızlık aksiyomu, zigzaglama ve ayrıştırma işlemleri etkin bir şekilde kullanılmış ve büyük sistemlerin aksiyomatik tasarım yaklaşımı ile tasarlanması işlemi için bir kılavuz oluşturulmuştur. Bağımsızlık aksiyomu uygulandığında, geliştirilen yeni sistemin aksiyomatik tasarımda olması gerektiği gibi ayrışık bir tasarım olduğu görülmüştür. Geliştirilen sistemin ana parçalarına ait statik analizler ANSYS'te yapılmış ve sonuçlar tez içerisinde verilmiştir. Bu tezin, aksiyomatik tasarım yaklaşımının mevcut sistemlerin incelenmesi ve yeni bir ürün geliştirilmesinde nasıl kullanıldığını gösteren güzel bir örnek olduğuna düşünülmektedir.

Mayıs, 2012

Muhammet DEMİRTAŞ

ABSTRACT

AN AXIOMATIC DESIGN APPROACH TO MECHANICAL CAR PARKING SYSTEM DESIGN

As long as there have been automobiles, people have been thinking about technical installations making it possible to park more vehicles in a given volume. Firstly, conventional multilevel parking structures have been developed. Since they include entry and exit ramps and/or car lifts, aisle space between vehicles and parking area, a better solution, mechanical car parking systems have been developed and they are becoming more and more common around the world.

In this thesis, two of these mechanical car parking systems have been analyzed using axiomatic design approach which has been developed at Massachusetts Institute of Technology (MIT) by Prof. Nam P. Suh in 1990s and enables the designers to evade the problems occurred in poor design applications. Using axiomatic design principles, a new mechanical car parking system has been developed. Independence axiom, zigzagging and decomposition processes of axiomatic design approach have been used efficiently, and a guide to design large systems using axiomatic design approach has been created. Applying independence axiom, it has been seen that, developed system is an uncoupled design as it should be in axiomatic design. Static analyses of the main parts of the developed system have been performed in ANSYS and results have been given in this thesis. It is believed that this thesis is a good example to use axiomatic design approach to analyze an existing design and develop a new product.

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SYMBOLS

a	: Drum groves height (mm)
a_{top}	: Thickness of the tighten plate (mm)
b_p	: Width of the tighten plate (mm)
C	: Dynamic load rating
C_{Ta}	: Circumference of the drum (mm)
D_{disc}	: Diameter of the side disc (mm)
d_{Ha}	: Wire rope diameter (mm)
D_{Ta}	: Drum diameter (mm)
(F_a)_A	: Thrust load on bearing A (N)
F_{Ha}	: Force acting on the each wire rope (kg)
F_n	: Life time factor
F_u	: Tangential force (kN)
F_{u perm.}	: Permissible tangential Force (kN)
F_{u Tab.}	: Tangential force from table (kN)
g	: Acceleration due to gravity (m/s ²)
h	: Drum wall thickness (mm)
H	: Distance between ground level and the drum (m)
h_{eff.}	: Efficiency of the electric motor
h₁	: Constant used to determine drum diameter
h₂	: Constant used to determine drum diameter
I_i	: Information content
I_{total}	: Total information
I_x	: Moment of inertia about x axis
I_y	: Moment of inertia about y axis
k	: Factor according to drive system and wire rope type
K_A	: Load factor
L	: Length of the roadside (m)
L_{He}	: Distance between two wire ropes (mm)
L_{KHβ}	: Linear load distribution factor
L_{10h}	: Basic rated life (millions of revolutions)

n	: Rotational speed (rpm)
N	: Number of cars that can be parked along L
N_G	: Teeth number of the gear
N_p	: Teeth number of the pinion
n_{Yi}	: Required groves number for drum
p	: Probability of success
P	: Equivalent dynamic bearing load (N)
P_A	: Equivalent radial load on bearing A (N)
P_B	: Equivalent radial load on bearing B (N)
P_m	: Required electric motor power (kW)
p_{Yi}	: Distance between two groves (mm)
q	: Exponent of the life equation
Q	: Capacity of the lifting system (kg)
Q_{total}	: Total weight includes weights of car, palette, arm and horizontal
R_A	: Applied radial load on bearing A (N)
R_B	: Applied radial load on bearing B (N)
R_{Yi}	: Drum grove radius (mm)
R₁	: Drum grove fillet radius (mm)
s	: Height of the side disc (mm)
S_f	: Safety coefficient
t_b	: Acceleration time (s)
u	: Distance between first wire rope and side disc (mm)
u₁	: Distance between side disc and last idle wire rope (mm)
x	: Distance between two wire ropes tighten by plate (mm)
v	: Speed (m/s)
V	: Lifting speed of the system (m/min)
w	: Thickness of the side disc (mm)
W	: Total weights of the palette, arm, and horizontal channel (kg)
Y_A	: Thrust factor for bearing A from catalogue
Y_B	: Thrust factor for bearing B from catalogue
Z	: Number of wire ropes
μ	: Coefficient of friction

ABBREVIATIONS

CAD	: Computer Aided Design
CNs	: Customer needs
Cs	: Constraints
DPs	: Design parameters
FRs	: Functional requirements
MIT	: Massachusetts Institute of Technology
PVs	: Process variables

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CHAPTER I

INTROCUCTION AND AIM

I.1 INTRODUCTION

Poor design practice results in high cost and long delivery times. In addition, poorly designed products often cost more because they use more materials or parts than do well-designed products [Suh, 1990]. To avoid such kind of problems and waste, decrease design time and decide the best solution, some design methods have been developed and one of such design methods is axiomatic design. Axiomatic design is a methodology that is used to create new systems or analyze and improve existing systems. This method has been developed at Massachusetts Institute of Technology (MIT) by Prof. Nam. P. Suh in 1990s and it enables the designers to focus on the problems occurred in poor design applications. Axiomatic design principles have been applied to many design process, but any study which applies axiomatic design approach to mechanical car parking systems has not been done yet.

In direct projection to the stagnant economy and increase in purchasing power of people, car account in traffic has increased and in consequence, car parking space problem has become more serious. Only one system that makes possible to park two or more cars to a certain space instead of one car can solve this problem. To solve this problem, certain mechanical car parking systems have been designed and manufactured. There is no doubt that the most important aim of mechanical car parking system design is creating a system which makes possible to park maximum number of cars to the minimum space. During the design process, investment costs, safety and applicability should be considered. According to axiomatic design approach, simple design is better, because complex design applications will increase the investment cost without providing any additional benefits. So, application of axiomatic design approach to mechanical car parking system design will help to find a simpler and better design.

I.2 OBJECTIVE OF THE THESIS

In this thesis, some existing mechanical car parking systems are analyzed and a new system is designed by using axiomatic design approach. With this aspect, this study guides to the designers and the students for analyzing an existing design with many components within the scope of axiomatic design. Providing a resource for students and designers about applying axiomatic design approach to new product design is one of the most important aims of this thesis. For this reason application of independence axiom to the new product design is explained in detail.

I.3 SCOPE OF THE THESIS

This thesis consists of five chapters. First chapter includes introduction to the problem, objective and scope of the thesis. Chapter II outlines the basic concept of axiomatic design and gives detailed information about mechanical car parking systems. Literature review related to the study is also given in this chapter. Application of axiomatic design approach to mechanical car parking systems is given in Chapter III. Two of the existing mechanical car parking systems are analyzed in this chapter and a new mechanical car parking system is developed. Independence axiom is used to analyze the existing systems and develop the new system. Static analyses results and calculations of the main parts of the proposed system are given in Chapter IV. Finally Chapter V includes conclusion and results of the work done in Chapter III.

CHAPTER II

REVIEW OF AXIOMATIC DESIGN PRINCIPLES AND MECHANICAL CAR PARKING SYSTEMS

II.1 AXIOMATIC DESIGN

Engineering design process becomes more and more important to shape modern world. It can be defined as the process of dreaming of things that never were and asking why not [Brown, 2006]. Planning, conceiving, analyzing, comparing, and selecting components and system to fulfill some desired function are the contents of the engineering design. No matter a design process is new or old and has problems, large or small, complex or simple, a formal approach to the engineering design and a general design framework that can be applied to all design activities is obviously necessary. Before axiomatic design hasn't been developed many authors had developed rules for design in various situation as well as general methodologies, but these methods are either applicable for a specific situation or are not generalizable [Suh, 1990]. So, a new methodology which can be applied to all design fields should has been developed.

Axiomatic design methodology has been developed at Massachusetts Institute of Technology (MIT) by Prof. Nam P. Suh in 1990s and it enables the designers to focus on the problems occurred in poor design applications. Prof. Nam P. Suh states that axiomatic design approach provides a general theoretical framework for all design fields [Suh,1995] and the theory is applicable to many different kinds of systems, including machines, large systems, software systems, organizations, and systems consisting of a combination of hardware and software [Suh,1998]. The basis goal of the axiomatic approach is to establish a scientific foundation for the design field, so as to provide a fundamental basis for the creation of products, processes, systems, software and organizations [Suh, 1990]. Axiomatic design shows that the engineering of good designs can be taught as a science [Brown, 2005], and it reduces product development risk, reduces cost and speeds time to market by [Sarioğlu, 2009]:

- 1) Formalizing the conceptual design process into a continuous and measurable activity driven by requirements.
- 2) Communicating the state of the design to all stakeholders at the earliest possible moment, well before traditional CAD documentation.
- 3) Improving quality of design by analyzing and optimizing design architectures.
- 4) Providing explicit traceability from Customer Needs to Requirements to Design Logic to Design.
- 5) Clearly documenting and communicating the logical How and why of a design, not just the What of CAD documentation.
- 6) Permitting design issues to be identified early and resolved without the cost of design-build-test-redesign cycles.
- 7) Providing project management with the dependency structure of the design, enabling optimal scheduling and risk mitigation.

There are four main concepts that should be explained in axiomatic design [Suh, 1990]:

- 1) Domains
- 2) Design axioms
- 3) Hierarchies
- 4) Zigzagging

II.1.1 Design Domains

The domains are the different kinds of the entities that make up the design. The four domains of the axiomatic design are the Customer, Functional, Physical and Process Domains. Most commonly used domains are the Functional Domain which describes the function of the design and Physical Domains which describes how that function is fulfilled. The design domains and their components are listed in Table II.1.1.

- **Customer Needs (CNs):** The customer domain describes what the customer wants and it involves Customer Needs. CNs are the starting points for the design and they might be supplied by a marketing department or by the customer.

Table II.1.1: The design domains [Brown, 2006]

<i>Domain</i>	Customer	Functional	Physical	Process
<i>Elements</i>	Customer Needs	Functional Requirements	Design Parameters	Process Variables
<i>abbreviations</i>	CNs	FRs	DPs	PVs
<i>grammatical form</i>	Anything	Imperative: begins with a verb	Adjectives and nouns	Present participle
<i>Notes</i>	What is needed	What it does	How it looks	How to create it
<i>Other</i>		Constraints Cs		

- **Functional Requirements (FRs):** Functional requirements (FRs) are a minimum set of independent requirements that completely characterize the functional needs of the design solution in the functional domain [Suh, 1990]. The FRs are determined by taking into consideration the CNs and it describes what the design does, the functions. Selection of the FRs is the most important step in design, because FRs set the starting point, the direction and the destination [Brown, 2006]. No design can be better than its FRs, so choosing the FRs correctly is very important in a design process. Choosing of the FRs is left to the designers and success of designers in this process makes them good or not-so-good designers. One of the attributes of a good designer is the ability to satisfy the perceived needs with a minimal set of independent FRs. Because as the number of FRs increases, the solution becomes more complex [Suh, 1990]. FRs begin with the verbs and have an imperative form such as “provide personal transportation” or “provide hot water” [Brown, 2006]

- **Design Parameters (DPs):** DPs are the key variables that characterize the physical entity created by the design process to fulfill the FRs [Suh, 1990]. In an ideal design there must be one and only one DP corresponding to each FR. DPs begin with nouns or adjectives such as “personal transportation device” or “hot water system.” DPs can also be computer code, education modules, or slot of time in an agenda [Brown, 2006].

- **Process Variables:** Process variables (PVs) are the key variables (or other equivalent terms in the case of software design, etc.) in the process domain that characterize the process that can generate the specified DPs.

- **Constraints:** Constraints (Cs) are the bounds on an acceptable solution. There are two kinds of constraints: input constraints and system constraints. Input

constraints are imposed as part of the design specifications. System constraints are constraints imposed by the system in which the design solution must function. The input constraints are usually expressed as bounds on size, weight, materials, and cost, whereas the system constraints are interfacial bounds such as geometric shape, capacity of machines, and even laws of nature. An important difference between Cs and the FRs is that a constraint does not have to be independent of other Cs and FRs. Another distinguishing feature of constraints is that they do not normally have tolerances associated with them, whereas FRs typically have tolerances [Suh, 1990, 2003].

Design process is the interplay between what we want to achieve and how we achieve it. This is called mapping from domain to domain. Once we identify and define the perceived customer needs (or the attributes the customer is looking for in a product), these needs must be translated into FRs. This must be done within a "solution-neutral environment." This means that the FRs must be defined without ever thinking about something that has already been designed or what the design solution should be. After the FRs are chosen, we map them into the physical domain to conceive a design with specific DPs that can satisfy the FRs. The mapping process is typically a one-to-many process, that is, for a given FR, there can be many possible DPs. We must choose the right DP by making sure that other FRs are not affected by the chosen DP and that the FR can be satisfied within its design range [Suh, 2003]. This process is illustrated in Figure II.1.1

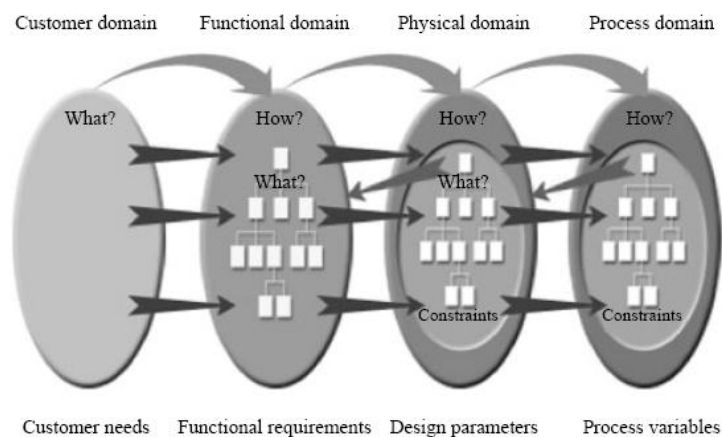


Figure II.1.1: Mapping process in axiomatic design [Park, 2007]

II.1.2 Design Axioms

The basic postulate of the axiomatic approach to design is that there are fundamental axioms that govern the design process. Axioms are defined as the

fundamental truths that are always observed to be valid and for which there are no counterexamples or exceptions. There are two design axioms that govern a good design. The first axiom is called the *Independence Axiom*. It states that the independence of FRs must always be maintained. The second axiom is called the *Information Axiom*, and it states that among those designs that satisfy the Independence Axiom, the design that has the smallest information content is the best design. Because the information content is defined in terms of probability, the second axiom also states that the design with the highest probability of success is the best design. In an ideal design, the information content should be zero to satisfy the FR every time and all the time. The axioms are formally stated as [Suh, 1990, 2003]:

Axiom 1: The Independence Axiom

Maintain the independence of the functional requirements (FRs).

Axiom 2: The Information Axiom

Minimize the information content of the design.

II.1.2.1 The Independence Axiom

The independence axiom states that during the design process, as we go from the FRs in the functional domain to the DPs in the physical domain, the mapping must be such a perturbation in a particular DP must affect only its referent FR [Suh, 1990]. In an ideal design each DP should affect only its corresponding design parameters. The relationship between FRs and DPs is expressed as the following design equation:

$$\{FR\} = [A]\{DP\} \quad (II.1.1)$$

Where $\{FR\}$ is the functional requirement vector, $\{DP\}$ is the design parameter vector and $[A]$ is the design matrix. Each line of the vector equation above may be written as

$$FR_i = \sum_j A_{ij} DP_j \quad (II.1.2)$$

If we have three FRs and three DPs, the design equation becomes

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad (II.1.3)$$

Designs are divided into three groups according to independence axiom as shown in the Table II.1.2. To satisfy the independence axiom, the design matrix must be either diagonal or triangular. If the design matrix is a diagonal matrix, it is an uncoupled design. In an uncoupled design each DP affects only its corresponding DP. The uncoupled design perfectly satisfies the independence axiom. When the design matrix upper or lower triangular as shown in the second case of the Table II.1.2, the design is a decoupled design. In this case the independence of the FRs can be assured if we adjust the DPs in a particular order; thus Axiom 1 is satisfied. If we vary DP_1 first, then the value of FR_1 can be set. Although it also affects FR_2 and FR_3 , we can then change DP_2 to set the value of FR_2 without affecting FR_1 . Finally, DP_3 can be changed to control FR_3 without affecting FR_1 and FR_2 . If had reversed the order and changed DP_3 first to set FR_3 , and then DP_2 to set the value of FR_2 , the value of FR_3 would have changed while changing DP_2 . If the design matrix is neither diagonal nor triangular, the design becomes a coupled design and it violates the independence axiom. A coupled design will be difficult to adjust or control and suffer from unintended consequences, because every time you adjust one thing, something else that is important goes out of adjustment. The only way to you may be able to adjust everything is to iterate, and this iteration is a waste of the time. [Brown, 2006; Park, 2007; Suh, 1990].

Table II.1.2: FR–DP relationship according to the design matrix [Park, 2007]

	Design equation	Design process
Uncoupled design	$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ 0 & 0 & A_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix}$	$\begin{aligned} FR_1 &= A_{11} \times DP_1 \\ FR_2 &= A_{22} \times DP_2 \\ FR_3 &= A_{33} \times DP_3 \end{aligned}$
Decoupled design	$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ A_{21} & A_{22} & 0 \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix}$	$\begin{aligned} FR_1 &= A_{11} \times DP_1 \\ FR_2 &= A_{21} \times DP_1 + A_{22} \times DP_2 \\ FR_3 &= A_{31} \times DP_1 + A_{32} \times DP_2 \\ &\quad + A_{33} \times DP_3 \end{aligned}$
Coupled design	$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix}$	$\begin{aligned} FR_1 &= A_{11} \times DP_1 + A_{12} \times DP_2 \\ &\quad + A_{13} \times DP_3 \\ FR_2 &= A_{21} \times DP_1 + A_{22} \times DP_2 \\ &\quad + A_{23} \times DP_3 \\ FR_3 &= A_{31} \times DP_1 + A_{32} \times DP_2 \\ &\quad + A_{33} \times DP_3 \end{aligned}$

II.1.2.2 The Information Axiom

Information axiom is used to select best design from alternatives that comply with axiom one. To do that there must be at least two alternatives that comply equally with the independence axiom. According to information axiom the best design is the one with the minimum information. Information content is the comparison criteria for the designs. The information contents of a design may be defined as the logarithm of the probability of fulfilling the specified FR, and it is formulated as

$$I_i = \log_2 1/p \quad (\text{II.1.4})$$

where p is the probability of success. If we have an uncoupled design with three FRs and three DPs such in equation II.1.3, the total information I_{total} is

$$I_{total} = \sum_{i=1}^3 I_i = \sum_{i=1}^3 \log_2 \left(\frac{1}{p_i} \right) \quad (\text{II.1.5})$$

p_1 , p_2 and p_3 , are the probabilities of satisfying FR_1 , FR_2 and FR_3 , with DP_1 , DP_2 and DP_3 .

Using these two axioms, the flowchart of the application of axiomatic design is shown in the Figure II.1.2.

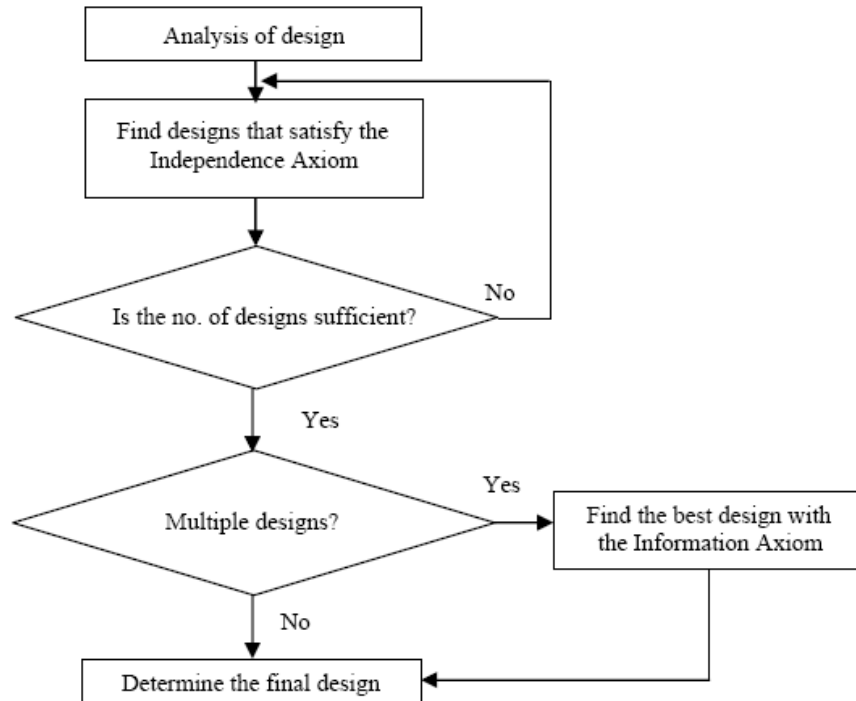


Figure II.1.2: Application of axiomatic design [Park 2007]

II.1.3 Hierarchies (Decomposition of the Design Process)

Designs, unless they are extremely simple, need to be decomposed vertically into hierarchies. In other words there is a hierarchy in both functional and physical space. Vertical hierarchies organize the design in levels of detail from general to specific. This vertical, hierarchical decomposition in levels of detail is essential for creation, evaluation, and manipulation of the design. The decomposition structure goes from general at the top to specific at the bottom [Brown, 2006]. For example, in designing an automobile speed control system, a top-level DP is the transmission system: automatic or manual. Further decomposition of the problem will produce the following lower-level DPs: gearing subsystem, transmission fluid subsystem, clutch subsystem, pump subsystem, and so on [Suh, 2003]. A decimal kind of notation is used, so that the top FR is FR_0 and the upper level FRs are FR_1 , FR_2 , FR_3 , and their children are $FR_{1.1}$, $FR_{1.2}$, $FR_{1.3}$, and $FR_{2.1}$, $FR_{2.2}$, $FR_{2.3}$, etc., as shown in Table II.1.3. The entities in Table II.1.3 would have to be further decomposed in the design, so that $FR_{1.1}$ would have children designated as $FR_{1.1.1}$, $FR_{1.1.2}$ and so on, with corresponding DPs, which would address the generation of power. A parent and its children are called a branch. In Table II.1.3 FR_1 and its children could be called the power branch, while FR_2 and its children could be called the control branch [Brown, 2006].

Table II.1.3: Example of a the top levels of a vertical hierarchy [Brown, 2006]

FR_0 provide personal transportation	DP_0 device for personal transportation
FR_1 provide power for motion	DP_1 system for power for motion
$FR_{1.1}$ generate power	$DP_{1.1}$ system for power generation
$FR_{1.2}$ convert power to motion	$DP_{1.2}$ system for power conversion
$FR_{1.3}$ transmit power	$DP_{1.3}$ system for power transmission
FR_2 provide control	DP_2 system for control
$FR_{2.1}$ provide steering	$DP_{2.1}$ system for steering
$FR_{2.2}$ provide stopping	$DP_{2.2}$ system for stopping
FR_3 support rider	DP_3 system for rider support

II.1.4 Zigzagging

Zigzagging refers to the process of defining the FRs for the functional decomposition on one level, then selecting DPs to satisfy these FRs, then going back to define the FRs at the next level on each of the branches. This process continues

down each of the branches until the solution is obvious [Brown, 2006]. The zigzagging process is shown graphically in Figure II.1.3. The arrows in Figure II.1.3 show the direction of the flow and the order is indicated by the numbers on the arrows.

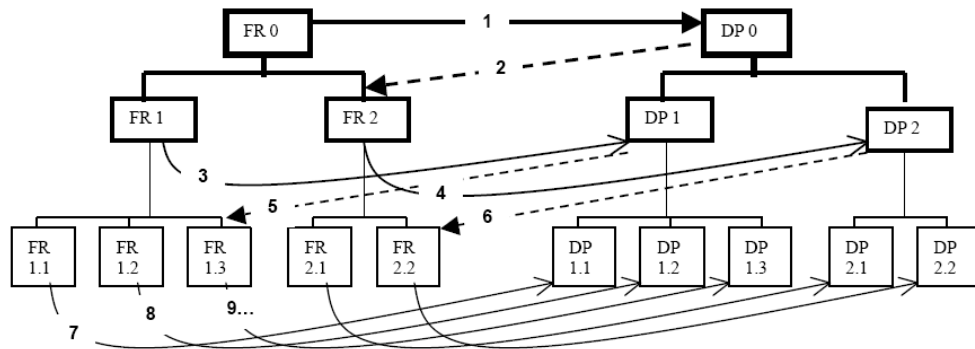


Figure II.1.3: Zigzagging [Brown, 2006]

FRs at the i th level cannot be decomposed into the next level of the FR hierarchy without first going over to the physical domain and developing a solution that satisfies the i th level FRs with the all corresponding design parameters because DPs at one level provide constraints on lower level FRs. The steps for the zigzagging process are like below [Brown, 2006].

- 1) Identify the customer needs (CNs)
- 2) Develop FR₀ and DP₀ – highest level design objectives – consistent with CNs
- 3) Develop top level FRs
- 4) Select corresponding DPs
- 5) Check developed FRs and selected DPs against Axiom 1 & 2 and constraints
- 6) Modify and consider alternatives as necessary to assure compliance with the axioms
- 7) Go to the next level down or adjacent branch and start with 1 again
- 8) Repeat until the solution is obvious

II.2 MECHANICAL CAR PARKING SYSTEMS

Mechanical car parking systems use machines, lifts, elevator or other mechanical devices to move vehicles from the ground level to an elevated parking stall and back to the ground level [Chrest at el, 2001]. On the contrary to the

conventional multilevel parking systems, mechanical car parking systems doesn't require any ramp to reach high levels. For this reason they are more efficient and cost effective design. The oldest mention of a mechanical parking system is the Garage Rue de Ponthieu in Paris by the architect Auguste Perret and it was constructed in 1905. In this system vehicles were parked to the first or second floor by the attendant at either side of the corridor. Although this was basically a semiautomatic system, this layout is still surprisingly common in modern parking systems [Hamelink, 2011].

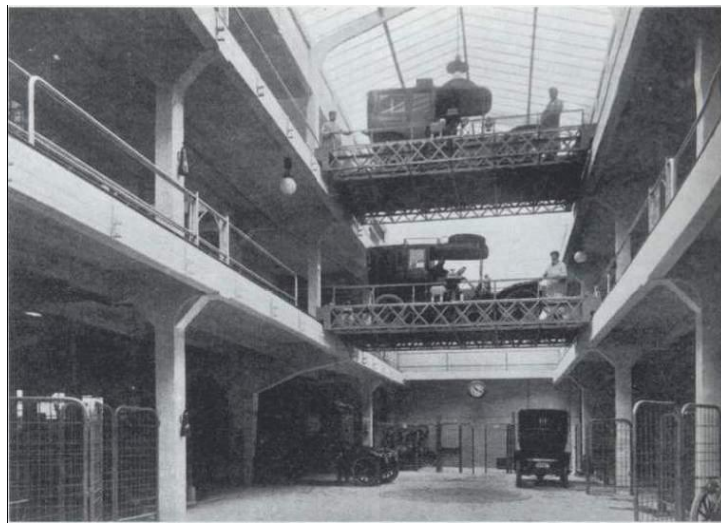


Figure II.2.1: Garage Rue de Ponthieu [Hamelink, 2011]

In the 1920's some parking systems were constructed throughout the USA in cities like New York, Chicago and Los Angeles. 30 years later, in the period up to the late 1950's more than 70 systems have been built in the USA. A central elevator with an operator, capable of moving sideways through a corridor, parked the cars to either side of the corridor. From the 1970's more technically advanced systems were developed and built throughout Europe, Asia and Central America. By the 1980s, advances in technology allowed for faster, safer and more reliable systems. In Europe mechanical parking is gaining significant popularity more or less since the 1980's. Production being focused in Germany and Italy the annual production seems to be steadily growing, although no accurate numbers are available [Chrestet al, 2001; Hamelink, 2011].

Benefits of mechanical car parking systems can be listed like below [Rombarch, 2010; KIPDC,2009].

- 1) Excavating a conventional basement is expensive and sometimes difficult. If you need to dig down and add a level or levels, mechanical parking will save money. A parking stall in a stacker generally costs between \$ 5,000 - \$ 20,000 depending on model and quantity, compare with \$ 35,000 for a ground-floor space and \$ 50,000 for a stall built underground in urban areas.
- 2) Accommodates maximum cars in minimum space. A normal parking stall requires around 300 to 350 square feet. That allows for the stall and a modest amount of circulation and drive aisles; whereas with a mechanical parking system, this dimension is closer to 200 square feet per stall, reducing area usage by 1/3.
- 3) Mechanical parking systems can increase parking capacity as much as possible to add value to the building. Providing additional parking can frequently add value to units.
- 4) Reduces parking and retrieval time. Saves time spend in searching for empty parking slots and time spend is searching the parked car. Retrieval on average is 2 to 3 minutes
- 5) Cost effective in terms of maintenance over the conventional parking systems.
- 6) Provides improved security, safety for the cars. Cars parked are free from theft and damages that can e caused while parking and retrieving.
- 7) Environment friendly. As the car engines are shut during the automatic parking process there is no pollution.
- 8) State of the art modular design makes the system look very attractive.

II.2.1 Types of Mechanical Car Parking Systems

Mechanical car parking systems are classified according to three criteria: operation type, dependency and parking technology. We will focus on the parking technologies, but before that other classification criteria will be described also.

Mechanical car parking systems are classified as *fully-automatic* or *semi-automatic* systems according to operation type. In a fully-automatic parking garage no people enter into the garage during operation. The driver leaves his car in a transfer cabin and parking system will move the car to the storage and retrieval unit and put into the nearest available parking space. Upon the request of the user the car is move to the transfer cabin again. All this will be operated automatically. In these

systems the vehicles can be stored lengthwise or perpendicular to the driving direction. In semi-automatic parking facilities the user drives the car in the parking garage to a platform where he parks his car. When parked the users can leave the car and operate the system so that through the lifting and/or shifting of platforms more parking places become available. This way the capacity of a parking lot can be doubled or tripled while the general layout of the facility remains similar to a conventional situation [Hamelink, 2011; Rombarch, 2010].

According to dependency, mechanical car parking systems are classified as *dependent access* and *independent access* mechanical car parking systems. In the dependent parking systems, the lower car or cars must be moved by the user or operator to access the top car as seen from Figure II.2.2. In these systems, user of the lower car must leave his car's key to the parking system operator after he park the car so that the top car can be moved from the system. In the independent access mechanical car parking systems no cars need to be removed to access the top cars.

Different parking technologies are used in mechanical car parking systems. These systems will be explained in the following section.

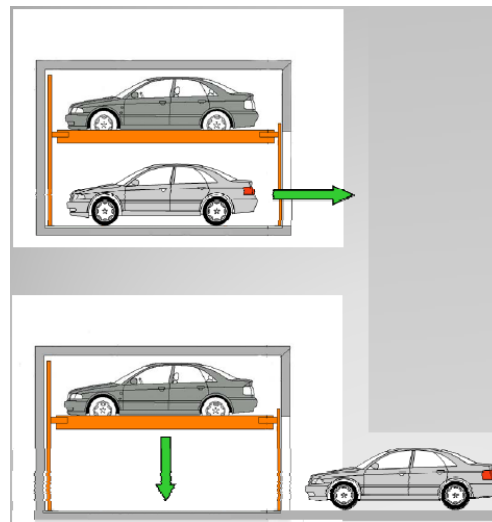


Figure II.2.2: Dependent access mechanical car parking system [Rombarch, 2010]

II.2.1.1 Puzzle Type Mechanical Car Parking Systems

This system is a multilevel system and can have more than two levels of parking. In puzzle type mechanical parking system, a combination of horizontal and vertical movement of pallets takes place to park cars to and take from the system. This system provides independence access to all cars parked to the system and it is

fully-automatic. As it is seen from Figure II.2.3 at least one cell must remain vacant at each level beside the top level so that the required pallet is lowered or raised.



Figure II.2.3: Puzzle type mechanical car parking system [GmbH, 2011]

While the entrance level pallets move only sideways, the top layer pallets can move up and down and the pallets at the middle level(s) can move either left to right or up and down. As a result, the vehicles on the higher layer can be moved to ground so as to realize the parking and retrieving. Figure II.2.4 shows the working principle of the puzzle type mechanical car parking system. The red one is wanted to be taken from the system. As it is seen the cars with the colors of violet and turquoise are moved to the sides so that provide an empty space into which the red one is lowered to the ground level. Same procedure is applied to put cars to the system. Investment cost of this system per car is between € 20.000 and € 27.000 [Hamelink, 2011]

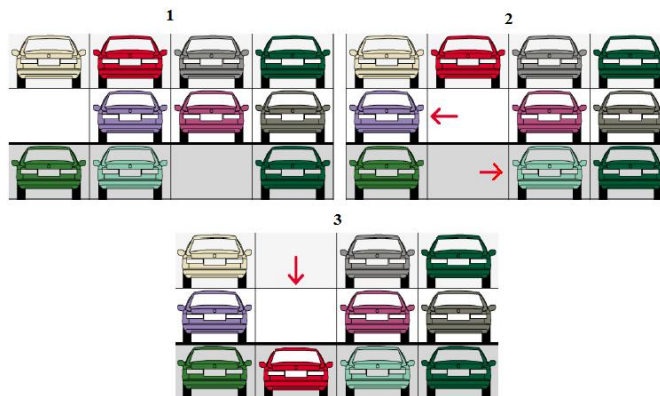


Figure II.2.4: Working principle of the puzzle type parking system [Poddar, 2011]

II.2.1.2 Elevator Type Mechanical Car Parking Systems

These parking systems often called parking tower. Car elevators are used to move vehicles from one floor to another by means of hoisting a platform on which

the car can be placed. The system moves the vehicles on a pallet vertically on the elevator, it then transfers it horizontally left or right for storage (Figure II.2.5). Compared to other types of mechanical parking systems it has the advantage that most users are familiar with using elevators, so acceptance of this solution is usually no problem [Hamelink, 2011; KIPDC,2009].

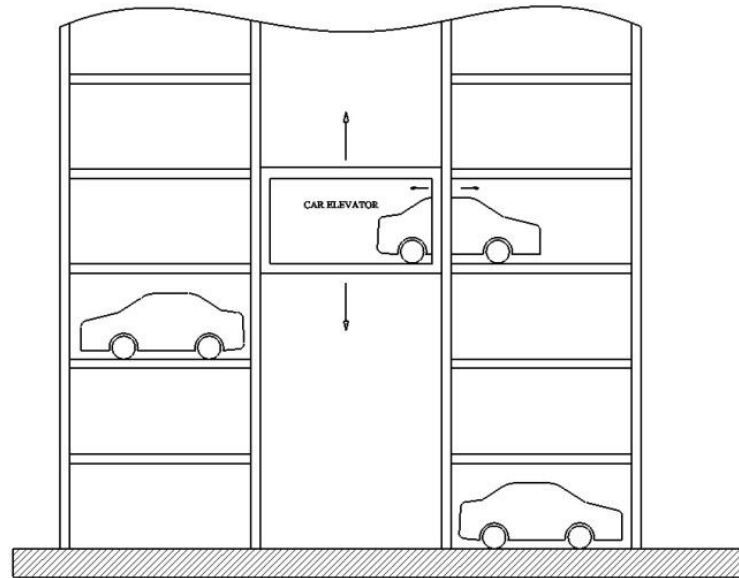


Figure II.2.5: Elevator type mechanical car parking system

II.2.1.3 Rotary Type Mechanical Car Parking Systems

Vertical rotary parking system circulates the palettes vertically in which the cars are taken up and down by a big chain similar to Ferris wheel. (Figure II.2.6).

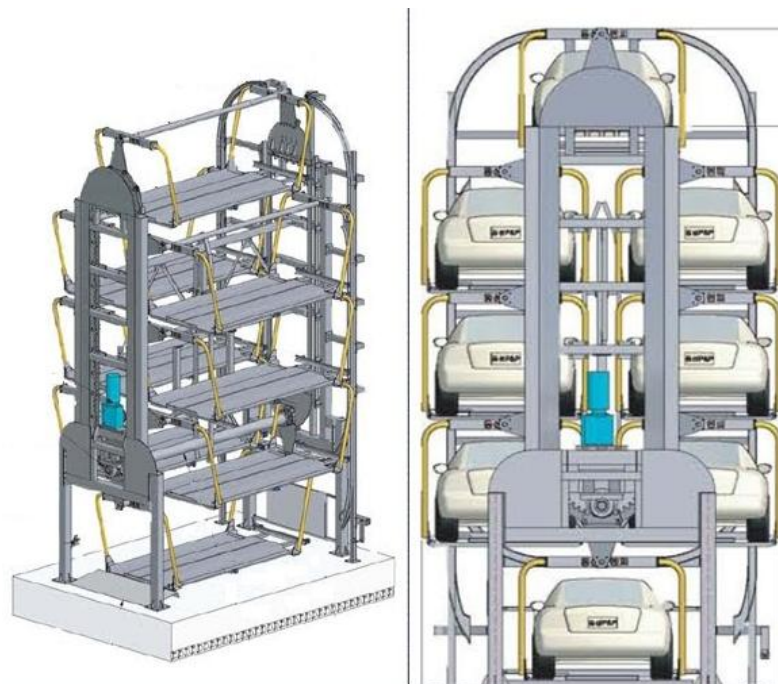


Figure II.2.6: Vertical rotary parking system [APC, 2011]

The system enables to park either 7,8,10, or 12 vehicles in the space of only 2. There is no need for a parking attendant, after putting car on the palette, drivers insert the key and press parking space number and the pallet will rotate either clockwise or counter clockwise. It will automatically sense which way to rotate by space number. This system is an independent access and fully automatic mechanical car parking system [Chrest et al, 2001; KIPDC, 2009]. Compared to other mechanical car parking systems, investment cost of this system a little bit low. For a system with eight car capacity, investment cost is approximately € 70.000 (Özen, 2011).

II.2.1.4 Multi Floor Type Mechanical Car Parking Systems

The Multi-Parking system has been designed to automatically move the vehicles by lift which then transfers it to a waiting cart on one of the multi- levels (Figure II.2.7). The carts then travel horizontally and place the vehicle in its appropriate slot. This system is suitable for middle and large-scale buildings as well as independent public parking garage. The multi-parker can accommodate as little as 20 vehicles to several thousand units. It is therefore suitable for large scale projects. It can move more than 2 vehicles at the same time for maximum efficiency [KIPDC,2009].



Figure II.2.7: Multi floor type mechanical car parking system [KIPDC,2009].

II.2.1.5 Multi Floor Type Mechanical Car Parking Systems-Circulation Type

These systems have elevators on each end cars are raised to desired level by these elevators (Figure II.2.8). The garage consists of several levels where the vehicles are moved horizontally which rotate the pallets in conjunction with the elevators. The multi floor circulation type is suitable for small and mid-sized buildings because of its high space efficiency [KIPDC,2009].



Figure II.2.8: Multi floor type mechanical car parking system-circulation type [KIPDC,2009]

II.2.1.6 Pallettes

Pallets are another way to move cars around, they are especially useful in situations where there is not enough ceiling height to stack cars and a pit is not possible. They can provide independent access to what would be a row or rows of land locked cars [Rombarch, 2010]. Pallets are fully automatic mechanical car parking systems.



Figure II.2.9: Palette type mechanical car parking systems [Rombarch, 2010]

II.2.1.7 Car Lifts

These systems are low cost and may be constructed as two or three high. Cars are generally lifted by hydraulic cylinders or electro-mechanical systems using chains and geared motors. Car lifts may be both dependent and independent accesses. Typically used in apartments or condos where both cars on the lift are for the same unit. Dependent access systems are useful for valet use. The upper lifts are usually reserved for longer term parking and the bottom space for short term parkers [Rombarch, 2010]. Independent access systems may be two or three high. In Figure II.2.10, a three high independent access model is seen. In this system, cars at the first or three levels are lowered or raised to the ground level to be put to or taken from the system. During this process no cars need to be removed from the system.



Figure II.2.10: Dependent access car lift [Rombarch, 2010].



Figure II.2.11: Independent access car lift [Rombarch, 2010].

II.2.2 Comparison Criteria for Mechanical Car Parking Systems

Mechanical car parking systems are compared to each other by using following criteria [Hamelink, 2011].

II.2.2.1 Compactness

This is the main specification. How much space does one parking place in the system take on average? This figure can be split into the average number of square meters per parking place and the average height of each parking level (the product of which obviously make the average volume used).

II.2.2.2 Speed

Although there are more ways of defining the speed of a parking system, we focus for now on this definition: “How long does a driver have to wait on average until his car arrives after he demands for it?” Especially during rush hours speed becomes more important. No one wants to wait for long time to get his/her car from the parking system.

II.2.2.3 Price Per Parking Place

By this we mean the investment costs of the technical system. Including and excluding costs are listed in Table II.2.1

Table II.2.1: Including and excluding costs used in comparison [Hamelink, 2011].

Including	Excluding
Installation Commissioning	Structural works Ventilation system Fire extinguishing installation Lighting Energy consumption Maintenance

II.2.2.4 Maximum Number of Parking Places Behind One Entry/Exit Box

Derived from the speed specification this tells how many parking places can be served through one entry/exit box without losing too much performance in peak traffic. This tells you given a desired number of parking places, how many entry/exits you have to take in account.

Of course there are many other important specifications (like availability, noise production, etc, etc) but main criteria have been listed and explained above.

Any study on axiomatic design approach to mechanical car parking system is not found in literature even though there are many applications that axiomatic design approach has been used to design or analyze many systems vary from manufacturing methods [David, 2000], e-commerce applications [Martin, 2001], demand forecasting applications [Kayhan, 2003], automotive industry [Lee and Park, 2004], control system design [Özyiğit, 2006], education [Thompson, 2009] to heat transfer applications [Sarioğlu, 2009]. It is believed that axiomatic design approach to existing mechanical car parking systems will be useful to see the deficiencies of these systems and let to improve them. In addition, it is aimed to develop a new mechanical car parking system by using axiomatic design approach in this study.

CHAPTER III

AXIOMATIC DESIGN OF MECHANICAL CAR PARKING SYSTEMS

III.1 THE ANALYSIS OF THE EXISTING MECHANICAL CAR PARKING SYSTEMS USING AXIOMATIC DESIGN APPROACH

Many kinds of mechanical car parking systems are designed and developed according to capacity and uses. As mentioned in Chapter II some existing mechanical car parking systems are puzzle type, elevator type, rotary type, multi floor type, multi floor-circulation type mechanical car parking systems, palettes and car lifts. In this chapter, two of these mechanical car parking systems will be analyzed using axiomatic design approach: vertical rotary parking system and puzzle type mechanical parking system, and the necessity to develop a new mechanical car parking system will be determined.

The same kind of products having the same functional requirements at the first level may have different FRs at the next or lower levels [Lee, et al, 2004]. For example, if it is decided to design a vehicle one of the first level FRs will be ability to stop [Suh, 1990]. The DP to satisfy this FR is a braking system. At this point the designer can choose this braking system as hydraulic or electronic system. If it is decided this braking system should be electronic, so an first level DP would be “Electronic braking system”, then lower level FRs would refer to supplying the needs of an electronic system, e.g., “supply electric power” as opposed to a hydraulic system where the lower level FR might be “supply hydraulic pressure [Brown, 2006].” Similarly, mechanical car parking systems differ from each other by used parking technology. If elevator is used to park cars to the system, the lower level FRs should be determined to satisfy the necessity of the elevator system and these FRs will be different from the lower level FRs of the other kinds of mechanical parking systems. The first level FRs and generic DPs will be same for all mechanical car parking systems, and they will be different in the next levels according to the parking method. Here, it is needed to be explained the generic DPs. Table III.1.1 shows the first level of the design hierarchy for personal transportation.

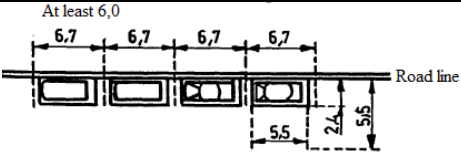
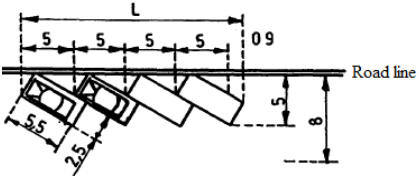
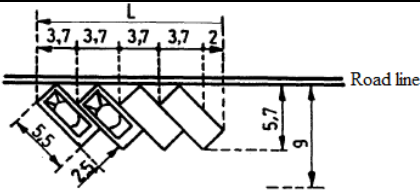
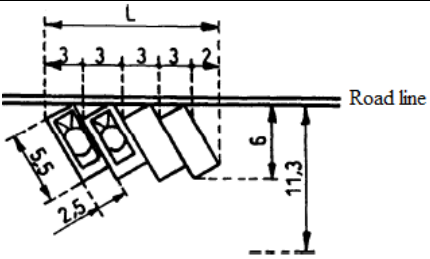
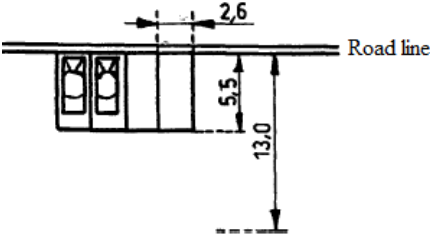
Table III.1.1: The upper level of the design hierarchy [Brown,2006]

FR ₀ provide personal transportation	DP ₀ device for personal transportation
FR ₁ provide power for motion	DP ₁ system for power for motion
FR _{1.1} generate power	DP _{1.1} system for power generation
FR _{1.2} convert power to motion	DP _{1.2} system for power conversion
FR _{1.3} transmit power	DP _{1.3} system for power transmission
FR ₂ provide control	DP ₂ system for control
FR _{2.1} provide steering	DP _{2.1} system for steering
FR _{2.2} provide stopping	DP _{2.2} system for stopping
FR ₃ support rider	DP ₃ system for rider support

At this point the design is at such a high level, containing only abstract descriptions, that there is still flexibility to arrive at many kinds of devices for personal transportation from a bicycle to a car. As it is seen from Table III.1.1 all DPs are generic. They are still flexible, in that they have not been narrowed to thermal, mechanical, electric, pneumatic, or hydraulic. If DP_{1.1} is chosen as rider's leg to generate power, it moves the design towards a conventional bicycle. Likewise, before starting to analyze mechanical car parking systems individually, the top level and the first level FRs and corresponding DPs is needed to be determined as generically without classification. After that the first level and next levels DPs for each mechanical car parking system will be determined and design equation will be written to check whether the system is coupled, uncoupled or decoupled.

In direct projection to the stagnant economy and increase in purchasing power of people, car account in traffic has increased and in consequence, car parking space problem has become more serious. For on and off street parking garage the minimum space requirement to park cars is determined in TS 10551, titled as Cars-Design Criteria of Auto Parking Facilities in Urban Areas [TS-10551, 1992]. This standard is about, design criteria of on and off street parking garage facilities for cars and the other motor vehicles similar dimension, in urban areas. Table III.1.2 shows different parking options, space requirements and number of cars that can be parked along 100 m long roadside.

Table III.1.2: Parking angle options in on street parking garage [TS-10551, 1995]

Parallel		$N = \frac{L}{6,7}$	15 Cars (L=100m)
30 Degree		$N = \frac{L - 0,9}{5}$	19,8 Cars (L=100m)
45 Degree		$N = \frac{L - 2}{3,7}$	26,5 Cars (L=100m)
60 Degree		$N = \frac{L - 2}{3}$	32,6 Cars (L=100m)
90 Degree		$N = \frac{L}{2,6}$	38,5 Cars (L=100m)

Where L is length of the roadside, N is the number of cars that can be parked along L and all units are in meter. When a certain surface area is wanted to be used as parking space there must be an aisle between cars parked each side. For 30 degree parking option, required aisle dimension is shown in Figure III.1.1 [TS-10551, 1995] According to the Table III.1.2 in 30 degree parking option 38,4 cars can be parked each side of the 100 m long aisle. Width of the parking space is seemed as 13 meters in Figure III.1.1. It means that 38,4 cars can be parked in a space with an area of 1300 m².

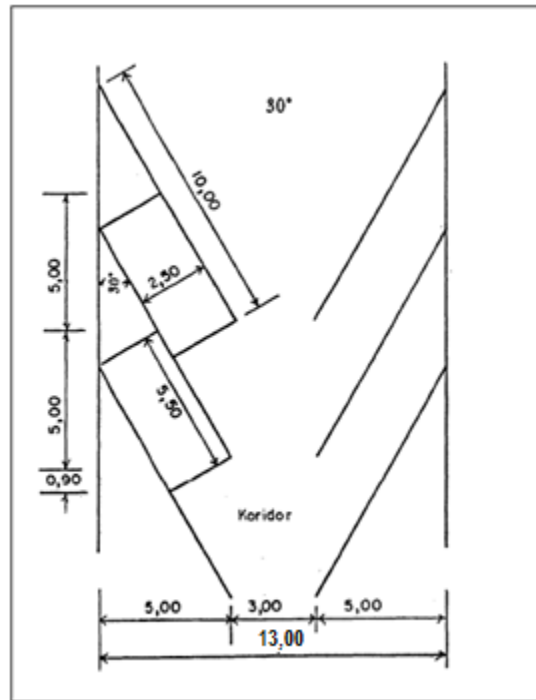


Figure III.1.1: Dimension of the aisle and width of the parking space according to 30 degree parking option [TS-10551, 1995].

If a system is developed to use this 1300 m² parking space more effectively, parking space problem will be solved. Using parking space more effectively is possible if and only if more than 38,4 cars can be parked in this area. So the top level functional requirement can be stated as:

FR₀: Design an efficient car parking system

There are more than one DP options to fulfill this FR. Such as conventional multilevel parking system can be used for this purpose. Because it can be underground, above ground or both under and above ground structure and allows parking more cars to a certain place instead of one car. A conventional multilevel parking system includes entry and exit ramps and/or car lifts, aisle space between vehicles and parking area. The ramp or car lifts and aisle between vehicles eat up much parking area that may be used to park cars. So there must be a better solution to use parking space more effectively. A solution that doesn't require ramps to arrive and leave the parking area, and minimize places that can't be used for parking should be developed. Mechanical car parking systems will be a better solution to solve parking space problem. Because in these systems cars are parked by mechanisms and places which used to build ramp in conventional multilevel parking systems can be used to park cars. In addition to this, cars can be parked very close to

each other, because there is no need extra place to rotate cars parking to appropriate parking lots in mechanical car parking system. After these considerations, top level DP can be stated as:

DP₀: Mechanical car parking system.

Having chosen the mechanical car parking system as the product to use parking space more effectively in physical domain, we now go back to the functional domain to determine the first level FRs. As it was discussed above, the expectations from the system are making possible to park more cars to a single space and parking cars to the system mechanically. The first level FRs should be determined considering these expectations. So, two first level FRs can be chosen;

FR₁: Enable to park more cars instead of one car to a single space

FR₂: Enable to park cars mechanically

Design is defined as the mapping process from the functional space to the physical space to satisfy the specified FRs. Therefore we now go back to the physical domain again to specify first level DPs. Parking more cars instead of one car to a single place is only possible with a multilevel system. If the system has three floors, it means that three cars can be parked to a single space instead of one car and that is what we want to be happened. This system may be underground, above ground or both under and above ground, and it may has a rectangular, circular or any other kind of shapes. It doesn't matter how shape the system has and which kind of it is, the main idea is being multilevel. Then the DP to satisfy FR₁ can be determined as

DP₁: Multilevel structure

The system will be multilevel and it doesn't wanted to be any ramp to reach the floors of the system. As FR₂ indicates this process should be done mechanically. To do that there must be a mechanism to move cars to the floors and put to and take from the appropriate cabinets. So it means that the second DP is a parking mechanism.

DP₂: Parking mechanism.

First level design parameters have been chosen as generic, they are still flexible that is to say. The system will be multilevel but it isn't known yet if it will be above ground, underground or both under and above ground. The same thing goes for parking mechanism. It hasn't been dictated that the system will be elevator type, rotary type, pneumatic, or hydraulic. It's just known that there will be a mechanism

to park cars. The details will come on further decomposition, and several competing DPs will be considered in parallel.

Mechanical car parking systems have names based on used parking technology e.g. vertical rotary system, puzzle system etc. If vertical rotary parking system is considered, it means that vertically rotating mechanism has been chosen to satisfy FR_2 established above. Now, two of these mechanical car parking systems will be analyzed according to axiomatic design approach.

III.1.1 Vertical Rotary Parking System

Before analyzing the system using axiomatic design approach, it will be explained how it operates. First, as shown in Figure III.1.2 [Park, 2004], a vehicle is loaded on a hanger that is located adjacent to the ground, and the driving motor is driven. As shown in Figure III.1.5 [Park, 2004], the power of the driving motor passes through the motor sprocket and the driving sprocket and rotates the driving shaft. At this time, the annular rotating body is rotated with respect to the annular fixing body by a rotation of the pinion. When the hanger support plate of the suspension chain enters on a path along which the pull blocks rotate, the end of one of the pull blocks enters between the dogs of the hanger support and attached to them. Hence, when the annular rotating body rotates, the suspension chain circulates in the direction of the rotation of the annular rotating body. As described above, the suspension chain is circulated by the pulling of the pull blocks, and when the hanger support plate departs from the path along which the pull blocks rotates, the pull blocks is detached from the dogs of the hanger support plate. At this time, the other pull block pulls another hanger support plate. In this way, the suspension chain continuously circulates.

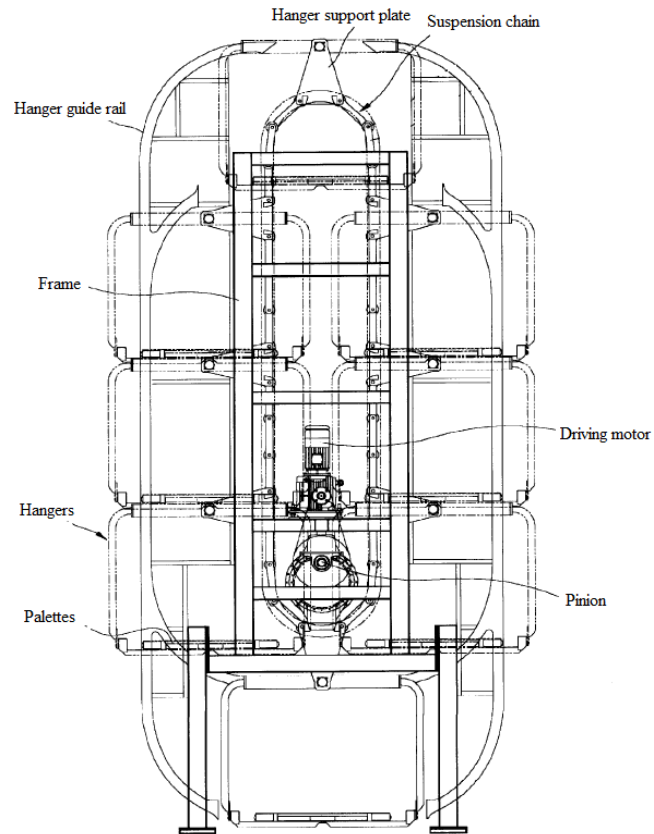


Figure III.1.2: Schematic view of a rotary parking system [Park, 2004]

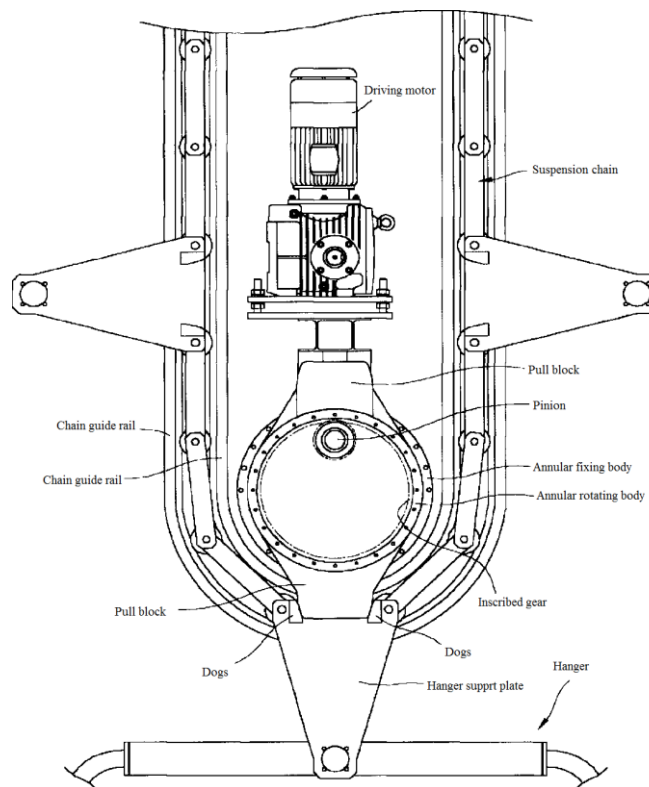


Figure III.1.3: Major portion extracted from Figure III.1.2 [Park, 2004]

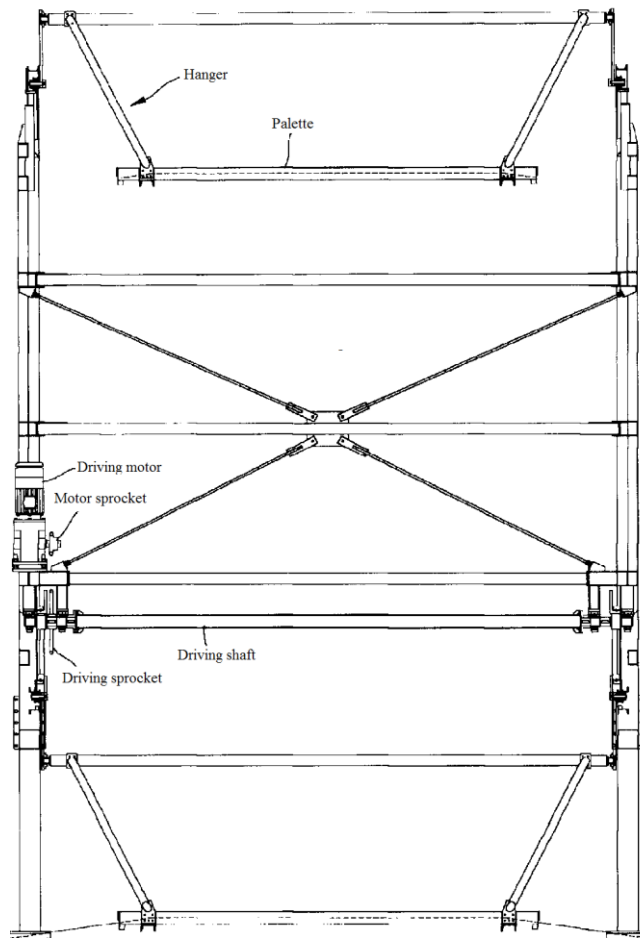


Figure III.1.4: Side view of Figure III.1.2 [Park, 2004]

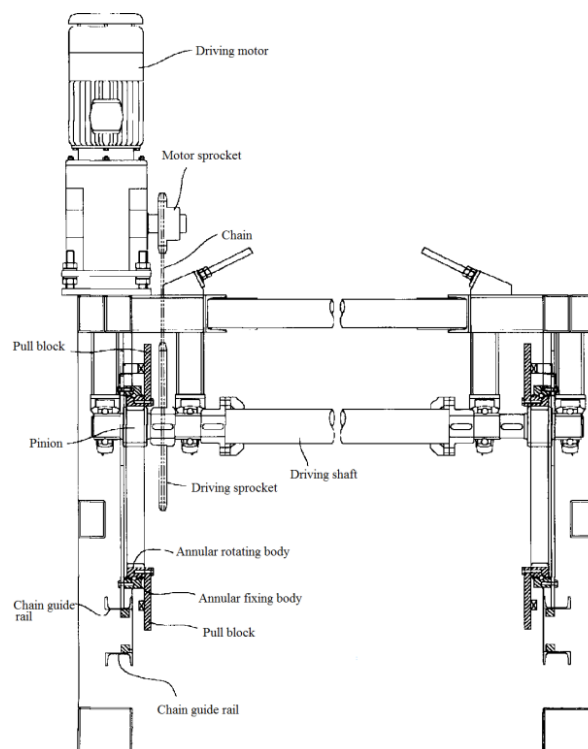


Figure III.1.5: Major portion extracted from Figure III.1.4 [Park, 2004]

In the previous section the first level FRs and DPs of a mechanical car parking system have been determined as follows:

FR₁: Enable to park more cars instead of one car to a single space

FR₂: Enable to park cars mechanically

DP₁: Multilevel structure

DP₂: Parking mechanism

Now these generic DPs will be chosen as more specific for vertical rotary parking system. The vertical rotary parking system allows parking up to 12 cars on the surface area required to park 2 cars. This is done by an above ground multi level structure. Actually the system can be built as an underground system also but most vertical rotary parking system applications are above ground. For this reason we will chose the system as an above ground multi level system. As is evident from its name parking process is performed by a vertical rotary parking mechanism. So the first level DPs to fulfill FR₁, FR₂ may be stated as

DP₁: An above ground multi level structure.

DP₂: Vertically rotating mechanism

Now DPs and FRs will be decomposed to the next levels. After all DPs and FRs are specified at each level, they will be decomposed to the next level to be detailed more.

Firstly the system should have places on which cars will be parked. Since the system will be a rotary parking system, places that will be used to put cars should be kept horizontal to the ground when they are being rotated. To enable to park more cars instead of one car to a single space, FR₁ can be decomposed as follows:

FR₁₁: Provide places to put cars

FR₁₂: Keep places that will be used to put cars horizontal to the ground at any time

FR₁₃: Support the system

New set of DPs should be determined to fulfill these FRs. On other saying DP₁ will be decomposed also. In vertical rotary parking system frame and the hanger guide rail make possible to locate steel palettes on which cars will be parked vertically and forms an above ground multilevel system. Hanger guide rail keeps palettes horizontal to the ground at any time. So the second level DPs can be stated as

DP₁₁: Steel palettes with hangers

DP₁₂: Hanger guide rail

DP₁₃: Frame

At this step design equation will be written to check if the system is coupled, decoupled or uncoupled. Design equation can be written as follows:

$$\begin{bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \end{bmatrix} \quad (III.1.1)$$

Since the design matrix is diagonal the system is an uncoupled design.

Vertically rotating mechanism which has been chosen to fulfill FR_2 is expected to rotate palettes vertically. To do that mechanism should generate motion and use this motion to rotate cars. After this explanation FR_2 can be decomposed as

FR₂₁: Generate motion to the system

FR₂₂: Use motion to rotate palettes

The vertical rotary parking system has a suspension chain which is being circulated along an endless track by a driving unit. Hangers which support palettes on which vehicles are loaded are connected to the suspension chain by hanger support plates. So palettes are circulated by the suspension chain and cars are put to and taken from the system by this method. In other words required motion is generated by the driving unit and this motion is transmitted to the palettes by the suspension chain system. So new DPs can be determined as

DP₂₁: Driving unit

DP₂₂: Suspension chain system

The design equation is;

$$\begin{bmatrix} FR_{21} \\ FR_{22} \end{bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{bmatrix} DP_{21} \\ DP_{22} \end{bmatrix} \quad (III.1.2)$$

The system is an uncoupled design, because the design matrix is diagonal.

Because all FRs and corresponding DPs have been determined in the second level, now it is time to decomposition to the next level. DP_{11} , DP_{12} and DP_{13} will not be decomposed to the next level because we are analyzing an existing design and these physical entities have been detailed enough to analyze the system. On the other hand DP_{21} and DP_{22} should be decomposed because it is not clear enough what driving unit and chain system will include. In the driving unit there should be a power supply and power generated by this supply should be converted to the motion.

Finally motion will be transmitted to the chain system to rotate palettes. It means that FR_{21} will be decomposed as

FR₂₁₁: Generate power to the system

FR₂₁₂: Convert power to the motion

FR₂₁₃: Transfer motion to the suspension chain system

DPs to fulfill these FRs are:

DP₂₁₁: Electricity

DP₂₁₂: Electric motor

DP₂₁₃: Motion transfer system

Design equation for this level is like below

$$\begin{bmatrix} FR_{211} \\ FR_{212} \\ FR_{213} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP_{211} \\ DP_{212} \\ DP_{213} \end{bmatrix} \quad (III.1.3)$$

As a result of being diagonal, the system is an uncoupled design.

DPs to generate motion to the system have been determined and this motion will be used to rotate palettes. Vertical rotary parking system has more than one palette and these palettes are expected to have continuous circulation along an elliptical path. To circulate palettes, motion generated by driving unit and transferred to the suspension chain should be transferred to the palettes. Palettes will have a length of approximately 5 meters and they are needed to be rotated from both sides to avoid compaction. Now FR_{22} can be decomposed as

FR₂₂₁: Provide continuous circulation

FR₂₂₂: Enable to follow an elliptical path

FR₂₂₃: Enable to rotate palettes from both sides

FR₂₂₄: Transfer motion to the palettes

These necessities in functional domain will be satisfied physical entities in physical domain. New set of DPs can be stated as

DP₂₂₁: Suspension chain

DP₂₂₂: Chain guide rail

FR₂₂₃: Second suspension chain- chain guide rail system opposed to the first one

DP₂₂₄: Hanger support plate

$$\begin{bmatrix} \text{FR}_{221} \\ \text{FR}_{222} \\ \text{FR}_{223} \\ \text{FR}_{224} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} \text{DP}_{221} \\ \text{DP}_{222} \\ \text{DP}_{223} \\ \text{DP}_{224} \end{bmatrix} \quad (\text{III.1.4})$$

Chain system is an uncoupled design because design matrix is diagonal. DP_{211} and DP_{212} , electricity and electric motor that is to say are clear enough but DP_{213} is needed to be detailed more, because motion transfer system is still a little bit generic. This transmit system will get motion from the electric motor and transfer to the suspension chain at both sides. Vertical rotary parking system will be used to park up to 12 cars and rotating these cars requires really much torque. For this reason torque requirement is need to be reduced also. FR_{213} is decomposed as

FR₂₁₃₁: Get motion from the electric motor

FR₂₁₃₂: Transmit motion to the chain systems at both sides

FR₂₁₃₃: Reduce torque requirement

FR₂₁₃₄: Transfer motion to the suspension chain

DPs to fulfill these requirements are

DP₂₁₃₁: Chain-sprocket mechanism

DP₂₁₃₂: Driving shaft

DP₂₁₃₃: Pinion-gear system

DP₂₁₃₄: Pull blocks- dogs system

Design matrix will be written to check if the system is uncoupled, decoupled or coupled.

$$\begin{bmatrix} \text{FR}_{2131} \\ \text{FR}_{2132} \\ \text{FR}_{2133} \\ \text{FR}_{2134} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} \text{DP}_{2131} \\ \text{DP}_{2132} \\ \text{DP}_{2133} \\ \text{DP}_{2134} \end{bmatrix} \quad (\text{III.1.5})$$

This design is also uncoupled because the design matrix is diagonal. We are analyzing an existing design and we will stop here because DPs have been detailed enough. Now, DPs-FRs tree will be written to see parent children relationship more clearly. Total design equation will be written also to check the whole system. Figure III.1.6 shows the hierarchical tree of FRs and DPs. Relationship between DPs and FRs can be seen more clearly from FRs and DPs tree. Total design equation can be seen from Figure III.1.7.

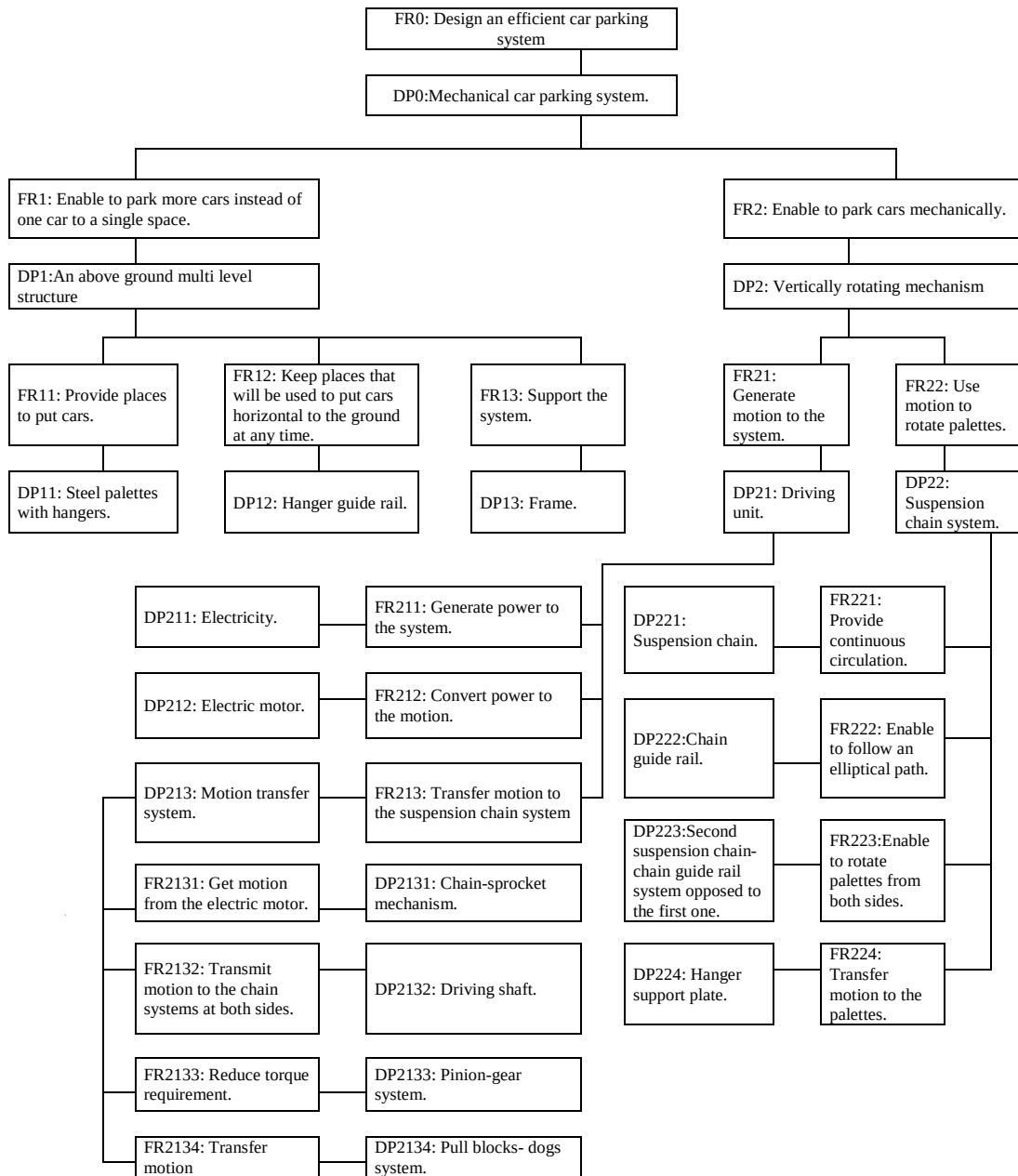


Figure III.1.6: FRs- DPs tree of vertical rotary parking system

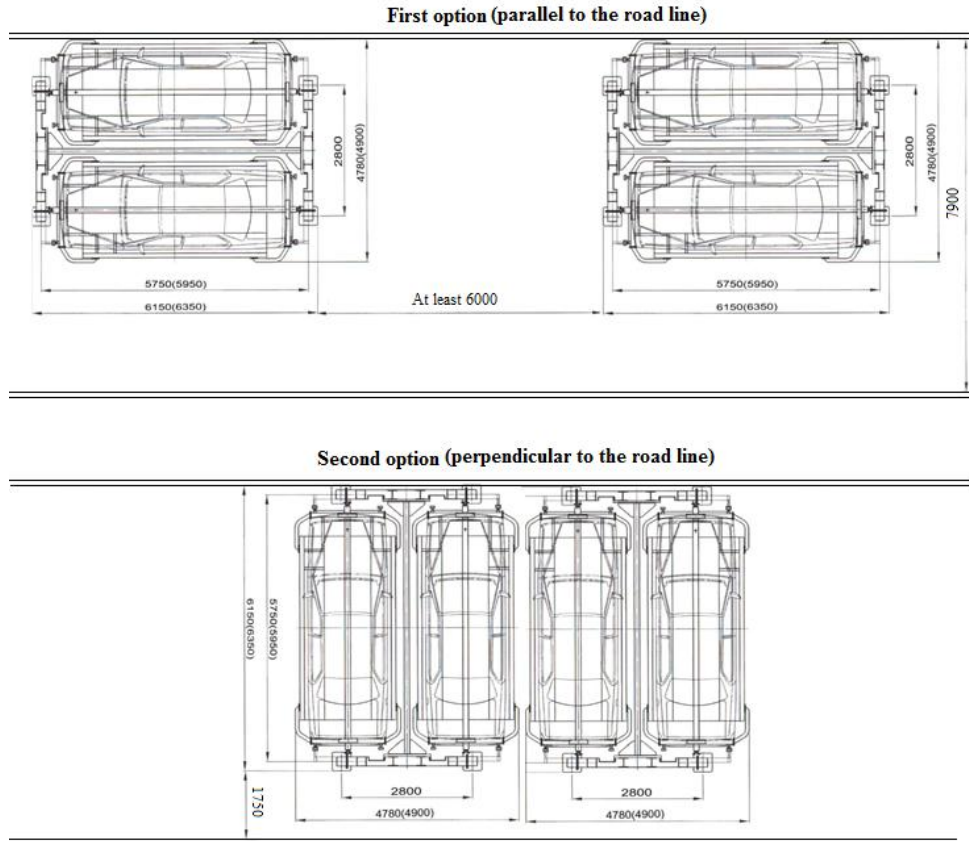


Figure III.1.9: Options to locate vertical rotary parking system to the area

As seen from Figure III.1.9 if the system is placed as parallel to the road line there must be at least 6 meters distance between two systems to let cars in and out. It means that area between two systems couldn't be used to park cars. On the other hand when the system is placed as perpendicular to the road side it doesn't require distance between two systems. However, at this time, cars will not be able enter to the system because there will be only 1750 millimeters gap between systems and the road line. Therefore when mechanical car parking system is wanted to be built in this area vertical rotary parking system would not be a good solution. Same situation will occur for the other parking options given in Table III.1.2. So, different mechanical car parking systems should be developed to use these surface areas more effectively.

III.1.2 Puzzle Type Mechanical Parking System

Puzzle Type Mechanical Parking System and its working principles are explained in Chapter II. In this section puzzle type mechanical car parking system will be analyzed using axiomatic design approach. As it can be remembered the first level FRs have been determined as follows in part III.1

FR₁: Enable to park more cars instead of one car to a single space

FR₂: Enable to park cars mechanically

Puzzle type mechanical car parking system may be both underground or above ground multi level system as well as combination of these systems. Its multilevel structure allows parking more cars to a single space instead of one car. Parking process is carried out by a mechanism similar to puzzle game as explained above. So, when puzzle type mechanical car parking system is considered, FRs specified above are fulfilled by DPs listed below.

DP₁: Above/under ground multilevel structure

DP₂: Puzzle type parking mechanisms

These are the first level DPs of the puzzle type mechanical car parking system. As it can be seen DPs of this system becomes different from the DPs of the vertical rotary parking system. This is because used technology and as a result the requirements of the systems are different from each other. To detail these DPs they will be decomposed to the next level. FR₁ can be decomposed as

FR₁₁: Provide place to put cars

FR₁₂: Support the system

It has been stated that cars are moved vertically and horizontally on palettes in puzzle type parking system. In other words, palettes are used to generate place for cars in this system. These palettes are supported by a steel frame as seen from Figure III.1.11. So second level DPs to fulfill FR₁₁ and FR₁₂ are

DP₁₁: Palettes

DP₁₂: Frame

Design equation is written as;

$$\begin{bmatrix} FR_{11} \\ FR_{12} \end{bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{bmatrix} DP_{11} \\ DP_{12} \end{bmatrix} \quad (III.1.6)$$

Above ground multilevel structure is an uncoupled design, because design equation is diagonal.

Main expectations from the puzzle type parking mechanism are moving palettes vertically and horizontally. In addition to these functions palettes should be lowered through an empty space. By taking into consideration these features FR_1 can be decomposed as below.

FR₂₁: Move palettes horizontally

FR₂₂: Move palettes vertically

FR₂₃: Provide place to raise and lower the palettes

DPs chosen to satisfy these FRs are

DP₂₁: Horizontally moving mechanism

DP₂₂: Vertically moving mechanism

DP₂₃: At least one vacant cell at each level beside the top level

When one of the palettes is wanted to move horizontally and vertically at the same time, if there is a car at the lower cell moving palette vertically is will not be possible. In other words, if there was a FR which states that “move palettes horizontally and vertically simultaneously”, this system would be a coupled design, but with these FRs and DPs it is an uncoupled design. The design equation is written below.

$$\begin{vmatrix} FR_{21} \\ FR_{22} \\ FR_{23} \end{vmatrix} = \begin{vmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{vmatrix} \begin{vmatrix} DP_{21} \\ DP_{22} \\ DP_{23} \end{vmatrix} \quad (III.1.7)$$

Puzzle type parking mechanism is an uncoupled design, because design matrix is diagonal.

DP₁₁ and DP₁₂ will not be detailed more but horizontally and vertically moving mechanisms should be detailed to determine kinds of the moving mechanisms. FR_{21} , move palettes horizontally that is to say can be decomposed as

FR₂₁₁: Generate power to the system

FR₂₁₂: Convert power to the motion

FR₂₁₃: Transfer motion to the palettes to move them horizontally

Figure III.1.10 shows the horizontally and vertically moving mechanisms of the puzzle type mechanical parking system. Details of these mechanisms are shown in the Figure III.1.11.

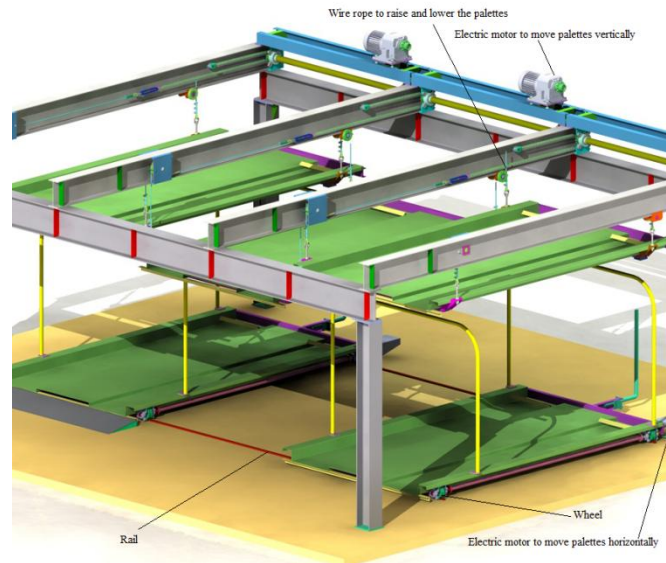


Figure III.1.10: Moving parts of the puzzle type parking mechanism [Simmatec, 2011]

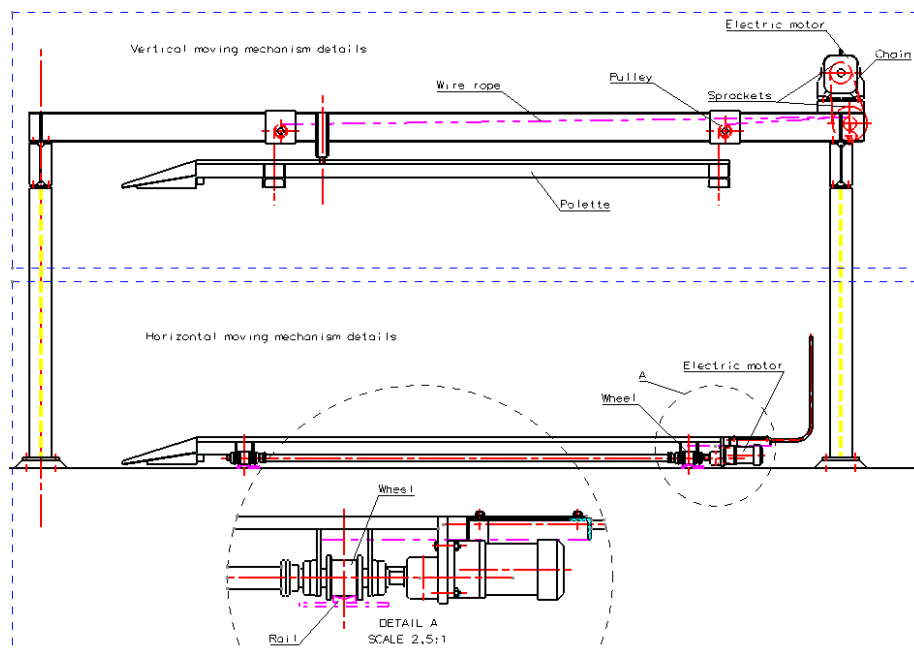


Figure III.1.11: Details of vertically and horizontally moving mechanisms of puzzle type mechanical car parking system [Simmatec, 2011]

As it can be seen from the Figure III.1.11 there is an electric motor and motion generated by this motor is transferred to the palettes by wheel-rail system to move palettes horizontally. So DPs to satisfy FR_{211} , FR_{212} and FR_{213} can be chosen as

DP₂₁₁: Electric supply

DP₂₁₂: Electric motor

DP₂₁₃: Wheel-rail system

Design equation of horizontally moving mechanism is like below

$$\begin{bmatrix} \text{FR}_{211} \\ \text{FR}_{212} \\ \text{FR}_{213} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{bmatrix} \text{DP}_{211} \\ \text{DP}_{212} \\ \text{DP}_{213} \end{bmatrix} \quad (\text{III.1.8})$$

By looking at the design equation we can say that horizontally moving mechanism is an uncoupled design.

Vertically moving mechanism is another system needed to be detailed. Similar to the horizontally moving mechanism FRs of this mechanism can be stated as follows:

FR₂₂₁: Generate power to the system

FR₂₂₂: Convert power to the motion

FR₂₂₃: Transfer motion to the palettes to move them vertically

Physical entities to satisfy these FRs can be written as follows

DP₂₂₁: Electric supply

DP₂₂₂: Electric motor

DP₂₂₃: Motion transfer system

Design equation is:

$$\begin{bmatrix} \text{FR}_{221} \\ \text{FR}_{222} \\ \text{FR}_{223} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{bmatrix} \text{DP}_{221} \\ \text{DP}_{222} \\ \text{DP}_{223} \end{bmatrix} \quad (\text{III.1.9})$$

As it is seen from equation vertically moving mechanism is also an uncoupled design.

All DPs and FRs have been determined at this level. Now DPs needed to be detailed more will be decomposed to the next level. Only DP which is not clear enough is motion transfer system. To detail DP₂₂₃, FR₂₂₃ will be decomposed as

FR₂₂₃₁: Get motion from the electric motor

FR₂₂₃₂: Transfer motion

Vertically moving mechanism contains chain-sprocket mechanism and wire rope-pulley mechanism. These physical entities are designed to transfer motion generated by electric motor to the palettes to move them horizontally. So DPs to satisfy FR₂₂₃₁ and FR₂₂₃₂ can be stated as

DP₂₂₃₁: Chain-sprocket system

DP₂₂₃₂: Wire rope-pulley system

Design equation can be written for motion transfer system as;

$$\begin{vmatrix} FR_{2231} \\ FR_{2232} \end{vmatrix} = \begin{vmatrix} X & 0 \\ 0 & X \end{vmatrix} \begin{vmatrix} DP_{2231} \\ DP_{2232} \end{vmatrix} \quad (III.1.10)$$

Design equation is diagonal. Because of this reason motion transfer system is an uncoupled design.

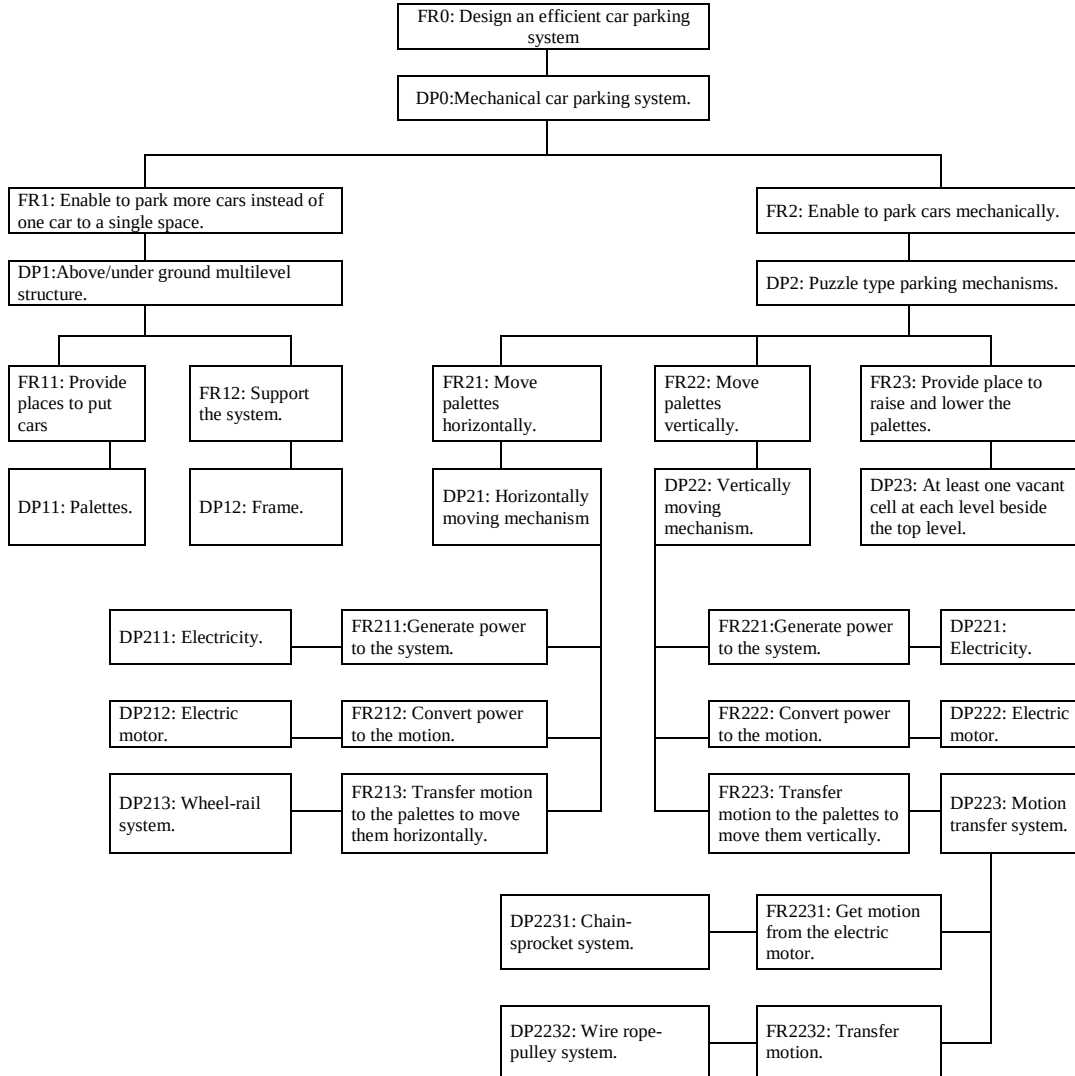


Figure III.1.12: FRs- DPs tree of puzzle type parking system

Figure III.1.12 shows the FRs-DPs tree of the puzzle type parking system. That is to say, it shows the decomposition structure. As it seen from the figure, decomposition structure goes from general at the top to specific at the bottom. FRs have been decomposed first, then DPs have been selected to satisfy them. FRs at lower levels have been determined according to the DPs at upper levels.

[illegible]

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III.2 DEVELOPING A NEW MECHANICAL CAR PARKING SYSTEM USING AXIOMATIC DESIGN APPROACH

Two of the existing mechanical car parking systems have been analyzed according to axiomatic design principles and it has been seen that the vertical rotary parking system and puzzle type mechanical car parking systems are uncoupled designs. On the other hand, vertical rotary parking system has disadvantage in using surface areas as it is explained in section III.1.1. The potential disadvantages of the puzzle type mechanical parking system is that a breakdown of only one cell could prevent retrieval of all the other cars. So a new system should be designed.

The top level and first level FRs and DPs of mechanical car parking systems have been determined as follows in section III.1.

FR₀: Design an efficient car parking system

DP₀: Mechanical car parking system.

FR₁: Enable to park more cars instead of one car to a single space

FR₂: Enable to park cars mechanically

DP₁: Multilevel structure

DP₂: Parking mechanism.

DP₁ and DP₂ will be determined as more specific according to the necessities of the new system. As it seen from Figure III.1.9, vertical rotary parking system is not applicable to a surface area having 7900 mm width. Figure III.2.1 shows the parallel parking option and as it is seen 2,4 m to 6,7 m surface area is needed for each car.

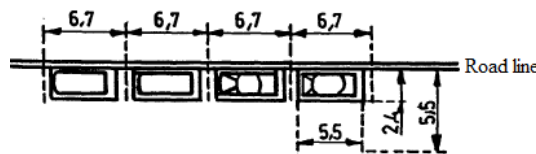


Figure III.2.1: Parallel parking option in on street parking garage [TS-10551, 1992]

New system should be applicable as parallel to the road line contrary to the vertical rotary parking system. To be an acceptable solution, its width should be less or equal to 2,5 m and it should have a rectangular shape to be built as parallel to the road line. Considering these necessities, some constraints need to be added in addition to the FR₁. FR₁ and constraints of the new mechanical car parking system at the first level are determined as follows.

FR₁: Enable to park more cars instead of one car to a single space

C₁: It should have a rectangular shape

C₂: Its width must be less or equal to 2,5 m

By taking into consideration these constraints, DP₁ will be determined at this step. Firstly the system should be multilevel to make possible to park more cars instead of one car to a single space and as prescribed in C₁, it will have a rectangular shape. Mechanical car parking systems generally become buildable as both above ground and underground. In another word, if a system is buildable above ground it can be built also underground when requested. For this reason, it will not stated that the system will be above or underground. It will just be a multilevel structure. So, DP₁ to satisfy FR₁ can be stated as:

DP₁: Multilevel structure with a rectangular shape

Figure III.2.2 shows the side and front views of the system.

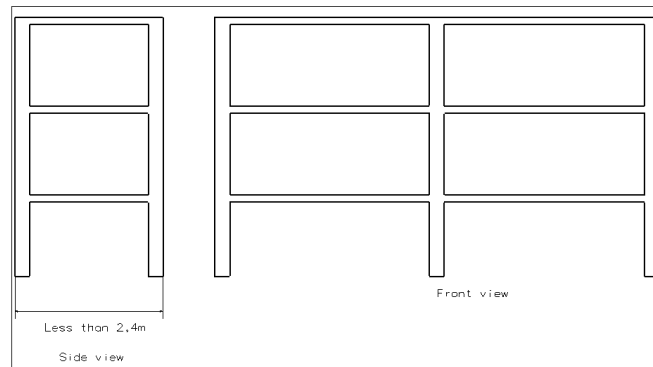


Figure III.2.2: Side and front views of the system

Now a mechanism should be designed to park cars to this system as mechanically by force of the FR₂. While investment cost for the puzzle type mechanical parking system is approximately € 20000-€ 27000 per car [Hamelink, 2011], this value for a vertical rotary parking system is approximately € 8750 [Özen, 2011]. This difference is due to the parking technology used. In puzzle type system two electric motors are used to move each palette vertically and horizontally. However in vertical rotary parking system only one electric motor is used to rotate all palettes. That means investment cost of the system increases in direct projection to the complexity in mechanism and amount of the used mechanical components. To decrease investment cost of the new system, parking process is to be proceeded by one mechanism for all levels at each column. In addition to this condition, if a mechanism which has ability to park cars to two columns is designed, the investment

cost will be reduced significantly. In other saying, one mechanism should be able to park cars to the all cells numbered in Figure III.2.3

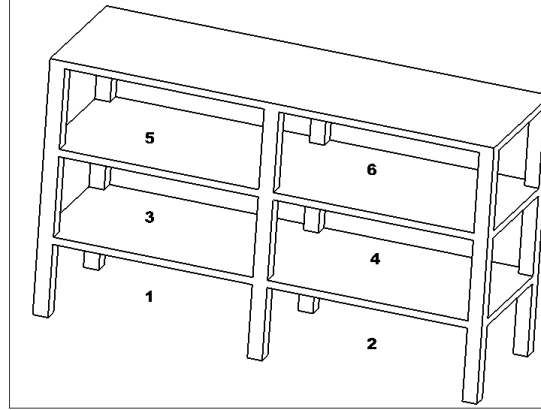


Figure III.2.3: Isometric view of the system

DP_2 may be stated as

DP₂: Mechanism which has ability to park cars to cells in all rows along two columns.

Only the main expectation from the mechanism has been determined but how it will park cars to the system has not been stated, because this will be done at the next levels. Now design equation will be written to check whether this is an ideal design.

$$\begin{vmatrix} FR_1 \\ FR_2 \end{vmatrix} = \begin{vmatrix} X & 0 \\ 0 & X \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \end{vmatrix} \quad (III.2.1)$$

Design equation is diagonal and it means that it is an uncoupled design

III.2.1 Decomposition level 2

Level 2 includes decompositions of multilevel structure with a rectangular shape, and mechanism which has ability to park cars to cells in all rows along two columns.

a) FR₁: Enable to park more cars instead of one car to a single space

DP₁: Multilevel structure with a rectangular shape

Firstly this multilevel system should provide place to put cars. In addition to this, system should be supported to be strong enough to carry cars. FR_1 is decomposed as follows considering these necessities.

FR₁₁: Provide place to put cars

FR₁₂: Support the system

DPs to satisfy these FRs are like below.

DP₁₁: Cells

DP₁₂: Steel frame

Design equation of multilevel structure with a rectangular shape is

$$\begin{vmatrix} FR_{11} \\ FR_{12} \end{vmatrix} = \begin{vmatrix} X & 0 \\ 0 & X \end{vmatrix} \begin{vmatrix} DP_{11} \\ DP_{12} \end{vmatrix} \quad (III.2.2)$$

Because design equation is diagonal, this is an uncoupled design.

b) FR₂: Enable to park cars mechanically

DP₂: Mechanism which has ability to park cars to cells in all rows along two columns.

This mechanism will take cars from the ground level and put to one of the numbered cells in Figure III.2.4 Similarly cars parked to the system will be taken from the system by the same mechanism.

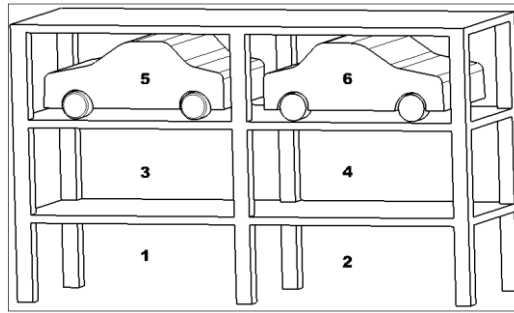


Figure III.2.4: Isometric view of the system with cars

Let's consider that there is a car at the cell 5 and it is wanted to be taken from the system. To accomplish this task, firstly the car should be moved horizontally and then lowered vertically to the ground level by mechanism as seen in Figure III.2.5. The same mechanism should be able to take car from the cell 6 also.

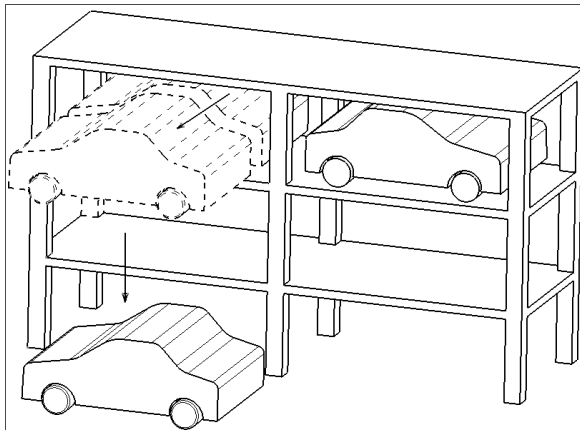


Figure III.2.5: Taking cars from the system

FR₂ can be decomposed as below to satisfy these requirements.

FR₂₁: Move cars horizontally

FR₂₂: Move cars vertically

FR₂₃: Enable to park cars to two columns

These FRs are needed to be satisfied by some DPs. For FR₂₁ and FR₂₂, DPs at this level may be determined as horizontally and vertically moving mechanisms but DP₂₃ should be fully determined.

Figure III.2.6 and Figure III.2.7 shows some DP options to enable to park cars to two columns. In Figure III.2.6, there is a mechanism which carries horizontally and vertically moving mechanisms, horizontally, together. By this means, cars can be parked to the cells in all rows along two columns. However, as it seen in Figure III.2.6 if two systems want to be built on a surface area, there must be an aisle between them, but horizontally moving mechanism will close this aisle. If two or more systems are built side by side, this situation will be a problem when cars want to reach to the second system.

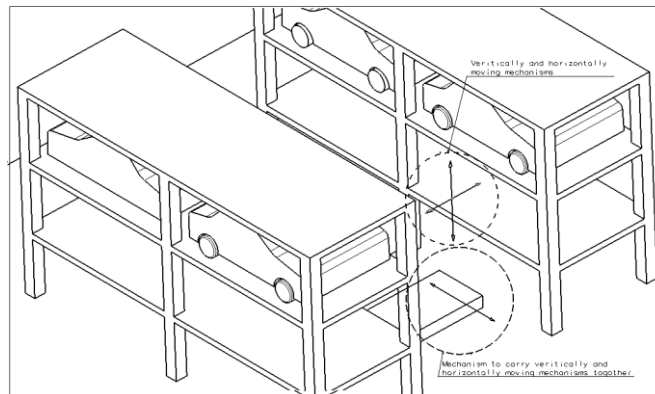


Figure III.2.6: Mechanism to carry vertically and horizontally moving mechanisms together horizontally

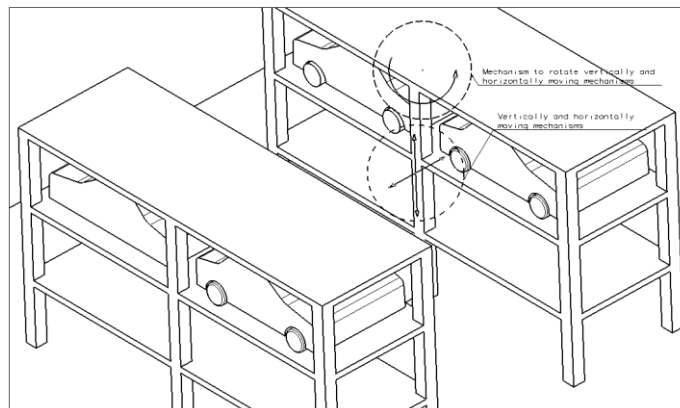


Figure III.2.7: Mechanism to rotate vertically and horizontally moving mechanisms together

Vertically and horizontally moving mechanisms are immovable at the middle of two columns and they are rotated by a mechanism as seen in Figure III.2.7. Thus, aisle between two systems located opposed to each other will be free. For this reason mechanism in Figure III.2.7 is chosen to satisfy FR₂₃.

New set of DPs can be stated as follows:

DP₂₁: Mechanism to move cars horizontally

DP₂₂: Mechanism to move cars vertically

DP₂₃: Mechanism to rotate vertical and horizontal movement mechanisms together

Design equation is written like below.

$$\begin{bmatrix} \text{FR}_{21} \\ \text{FR}_{22} \\ \text{FR}_{23} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{bmatrix} \text{DP}_{21} \\ \text{DP}_{22} \\ \text{DP}_{23} \end{bmatrix} \quad (\text{III.2.3})$$

The design is an uncoupled design. The FRs would be coupled if there were a FR to move cars horizontally and vertically simultaneously, because in this system, cars cannot be moved vertically and horizontally at the same time.

III.2.2 Decomposition level 3

At this level FRs and DPs determined at level 2 will be decomposed to be detailed more.

a) FR₂₁: Move cars horizontally

DP₂₁: Mechanism to move cars horizontally

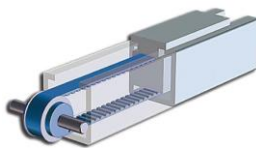
DP₂₁ states that there should be a system which moves car horizontally. This mechanism should generate a linear motion parallel to the ground and transfer this motion to the cars to move them horizontally. So, FR₂₁ can be decomposed as:

FR₂₁₁: Generate linear motion parallel to the ground

FR₂₁₂: Transfer motion to cars to move them horizontally.

Linear motion can be generated directly such in hydraulic and pneumatic cylinders or rotary motion is generated first and then it is converted to the linear motion. At this level for indirect linear motion developing systems, it will be assumed that rotary motion has been developed already and it is wanted to be converted to the linear motion to compare with other systems. Table III.2.1 shows

DP options to satisfy FR₂₁₁ and their place of use, advantages and disadvantages.
[Bamberg, 2006; Ponomareva, 2006; Rao, 2011]

Table III.2.1: DP options for FR₂₁₁				
Functional Requirement	Design Parameter option	References	Advantages	Disadvantages
Move cars horizontally	Hydraulic and pneumatic cylinder 	-Cranes . -Forklifts. - Clamping, shifting, positioning and orienting systems.	- For both systems sophisticated transfer mechanisms are not required. -Both systems are low cost. -Ease at reversion movements. -Installation, operation and maintenance are easy for both systems. -Hydraulic systems provide very quick movements with great force.	-For pneumatic systems compressed air requires good preparation. -In pneumatic systems gas is compressible, making motion control very difficult. - For hydraulic system conditions of operation of a hydraulic actuator (temperature) influence its characteristics -Both systems are not useful for precision motion control. -The hydraulic fluid is flammable and pressurized so leaks could pose an extreme hazard to equipment and personnel. -In pneumatic systems high pressure is a problem.
	Belt drivers 	-Conveying systems .	-Chosen when acceleration and speed are the most important criteria. -No lubrication is required, or desired. -Maintenance is minimal and infrequent.	-Slippage can occur, particularly if belt tension is not properly set and checked frequently -Adverse service environments (extreme temperature ranges, high moisture, oily or chemically filled atmospheres, etc.) can damage belts or cause severe slipping.. -Not useful for precision motion control - Belts require periodic adjustment from wear and stretch, -Low power transmission. -Belts will not provide exact speed ratio because of the slippage.
	Rack and pinion drives 	-Steering mechanisms of cars. - Machine tables. - CNC routers.	-One of the least expensive methods of generating linear motion from rotary motion. - A good choice for high duty applications.	- It is difficult to obtain the "optimal transmission ratio". - A speed reducer is sometimes used with the motor that drives the pinion.
	Lead screw 	-Jack. -Vise. -Machine tools. -Presses.	-High friction may minimize backlash. -Large load carrying capacity.	-Positional accuracy and repeatability are problem -Due to the low efficiency they cannot be used in continuous power transmission applications.

As it seen from Table III.2.1 hydraulic and pneumatic cylinder systems are not useful for precision motion control [Bamberg, 2006]. Belt drivers provide low power transmission and are not useful for precision motion control. In addition to this, belts will not provide exact speed ratio because of the slippage [Rao, 2011]. Lead screws are not good choice for high duty applications and in these systems positional accuracy and repeatability are problem. Considering these properties of linear motion systems, DP₂₁ is determined as rack pinion driver system.

DP₂₁₁: Rack pinion driver system

Linear motion generated by DP₂₁₁ should be transferred to the cars to move them horizontally as stated in FR₂₁₂, but at this level it isn't determined how this process will be done. So, DP₂₁₂ will be in a general form at this level.

DP₂₁₂: Motion transfer system for horizontal movement

Design equation for mechanism to move cars horizontally is

$$\begin{vmatrix} FR_{211} \\ FR_{212} \end{vmatrix} = \begin{vmatrix} X & 0 \\ 0 & X \end{vmatrix} \begin{vmatrix} DP_{211} \\ DP_{212} \end{vmatrix} \quad (\text{III.2.4})$$

Horizontally moving mechanism is also an uncoupled design.

b) FR₂₂: Move cars vertically

DP₂₂: Mechanism to move cars vertically

FR₂₂ will be fulfilled by a mechanism which moves cars vertically. So there must be a system which creates linear motion perpendicular to the ground and this motion should be used to move cars vertically. Horizontally moving mechanism will move cars horizontally. If the vertical movement is transferred to the horizontally moving mechanism, cars will be moved vertically, also. So, FR₂₂ can be decomposed as:

FR₂₂₁: Generate linear motion perpendicular to the ground

FR₂₂₂: Transfer motion to the horizontally moving mechanism

Same approach done to indirect linear motion developing system, to determine horizontally moving mechanism, will be done here also. That is to say, rotary motion will be assumed to have been developed already for indirect linear motion systems.

Table III.2.2: DP options for FR₂₂₁

Functional Requirement	Design Parameter option	References	Advantages	Disadvantages
Move cars vertically	Hydraulic and pneumatic cylinder 	-Cranes -Forklifts -Clamping, shifting, positioning and orienting systems	-For both systems sophisticated transfer mechanisms are not required -Both systems are low cost -Ease at reversion movements -Installation, operation and maintenance are easy for both systems -Hydraulic systems provide very quick movements with great force.	-For pneumatic systems compressed air requires good preparation -In pneumatic systems gas is compressible, making motion control very difficult -For hydraulic system conditions of operation of a hydraulic actuator (temperature) influence its characteristics -Both systems are not useful for precision motion control -The hydraulic fluid is flammable and pressurized so leaks could pose an extreme hazard to equipment and personnel -In pneumatic systems high pressure is a problem
	Electric motor-wire rope system 	-Cranes -Elevators	-High lifting capacity -Applicable to transmit motion to long distances. -Faster	-More expensive
	Rack and pinion drives 	-Steering mechanisms of cars. -Machine tables. -CNC routers.	-One of the least expensive methods of generating linear motion from rotary motion. -A good choice for high duty applications.	-It is difficult to obtain the "optimal transmission ratio". -A speed reducer is sometimes used with the motor that drives the pinion.
	Lead screw 	-Jack. -Vise. -Machine tools. -Presses.	-High friction may minimize backlash. -Large load carrying capacity.	-Positional accuracy and repeatability are problem -Due to the low efficiency they cannot be used in continuous power transmission applications.

Table III.2.2 shows DP options to satisfy FR_{221} . Motion is needed to be transferred to long distances, because the system will be multilevel and it may have a length of 9 or 10 meters. Hydraulic and pneumatic system will take up more space compared to other systems, because bending and buckling will occur due to cars' weight and for this reason system will need to be supported. Lead screw system is not useful for such a long distances due to its slow movement and bucking. To transfer motion to such a long distance, mostly wire rope system is used such in elevators and cranes. After this comparison between DP options, DP_{221} is determined as

DP_{221} : Electric motor-wire rope system

Linear motion generated by electric motor-wire rope system will be transferred to the horizontally moving mechanism by force of FR_{222} . This will be done by DP_{222} .

DP_{222} : Motion transfer system for vertical movement

Like each step, design equation will be written at this step also to check if the design violates independence axiom or not. Design equation is

$$\begin{vmatrix} FR_{221} \\ FR_{222} \end{vmatrix} = \begin{vmatrix} X & 0 \\ 0 & X \end{vmatrix} \begin{vmatrix} DP_{221} \\ DP_{222} \end{vmatrix} \quad (III.2.5)$$

Design equation is diagonal and it means that, it is an uncoupled design.

c) FR_{23} : Enable to park cars to two columns

DP_{23} : Mechanism to rotate vertical and horizontal movement mechanisms together

Vertically movement motion is transferred horizontally moving mechanism by DP_{222} , in this way cars are moved vertically and horizontally. If some rotary motion is developed and transferred to the vertically moving mechanism, it will be possible to park cars to two columns. By taking into these considerations, FR_{23} can be decomposed as follows:

FR_{231} : Generate rotary motion

FR_{232} : Transfer motion to the vertically movement mechanism

DP_{231} can be chosen as electric motor, because electric motor is used in many applications to generate rotary motion.

DP_{231} : Electric motor

Motion generated by electric motor is need to be transferred to the vertically movement mechanism. Cranes and hi-ups can turns with loads and they do this with their slewing units. Expectation from DP_{232} is same as the slewing units of cranes; to

rotate vertically and horizontally moving mechanisms, and slewing unit can be used to satisfy this expectation. At this level, DP_{232} can be stated as;

DP₂₃₂: Slewing unit

Design equation is written as

$$\begin{vmatrix} FR_{231} \\ FR_{232} \end{vmatrix} = \begin{vmatrix} X & 0 \\ 0 & X \end{vmatrix} \begin{vmatrix} DP_{231} \\ DP_{232} \end{vmatrix} \quad (III.2.6)$$

Design equation is diagonal and the design meets the expectation of independence axiom of axiomatic design approach.

III.2.3 Decomposition level 4

In this level new set of FRs will be determined by taking into consideration DPs determined at level 3. Firstly FR_{211} will be decomposed and then DP_{211} will be decomposed to fulfill new set of FRs. This procedure will be applied to the other FRs and DPs of level 3.

a) FR₂₁₁: Generate linear motion parallel to the ground

DP₂₁₁: Rack pinion driver system

Rack pinion driver system firstly generates some rotary motion and then converts this motion to the linear motion. Since the angular velocity of the rotary motion developed by an electric motor is generally too high, it is need to be reduced to desired value. So, FR_{211} can be decomposed as follows.

FR₂₁₁₁: Generate power

FR₂₁₁₂: Convert power to motion

FR₂₁₁₃: Reduce motion to desired value

FR₂₁₁₄: Convert rotary motion to linear motion

DPs to fulfill these FRs are;

DP₂₁₁₁: Electric supply

DP₂₁₁₂: Electric motor

DP₂₁₁₃: Reducer mounted to the exit of the electric motor and movable part of the horizontal motion transfer system.

DP₂₁₁₄: Rack mounted to the stable part of the motion transfer system and pinion mounted to the exit of the reducer.

$$\begin{bmatrix} FR_{2111} \\ FR_{2112} \\ FR_{2113} \\ FR_{2114} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP_{2111} \\ DP_{2112} \\ DP_{2113} \\ DP_{2114} \end{bmatrix} \quad (III.2.7)$$

Since the design equation for rack pinion driver system shown in Figure III.2.8 is diagonal, it is an uncoupled design.

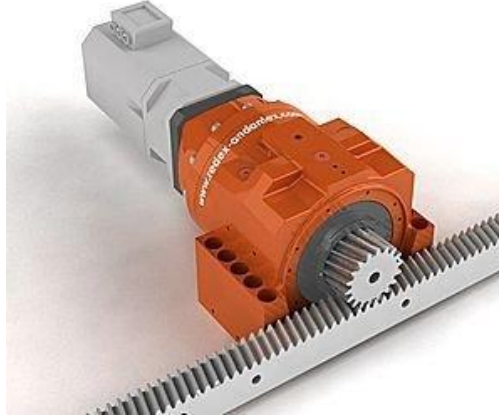


Figure III.2.8: Linear motion generation system

b) FR₂₁₂: Transfer motion to cars to move them horizontally.

DP₂₁₂: Motion transfer system for horizontal movement

As it seen from Figure III.2.5 horizontally moving mechanism is supposed to take cars out from the shelves so that vertically moving mechanism lowers it to the ground level. When cars are taken out from the shelves they are need to be supported to avoid falling them. In addition to this, there should be a pathway parallel to the ground to make possible taking cars out from the system. Finally motion generated by rack pinion driver system should be transferred to the car supporting part to move cars horizontally. Considering these requirements, FR₂₁₂ can be decomposed as follows.

FR₂₁₂₁: Provide a horizontal pathway to make possible taking cars out of the shelves.

FR₂₁₂₂: Support cars

FR₂₁₂₃: Transfer motion to the car supporting member

This system will have some constraints also. In this system horizontally and vertically moving mechanisms will be rotated together as stated by DP₂₃. Figure III.2.9 shows this process.

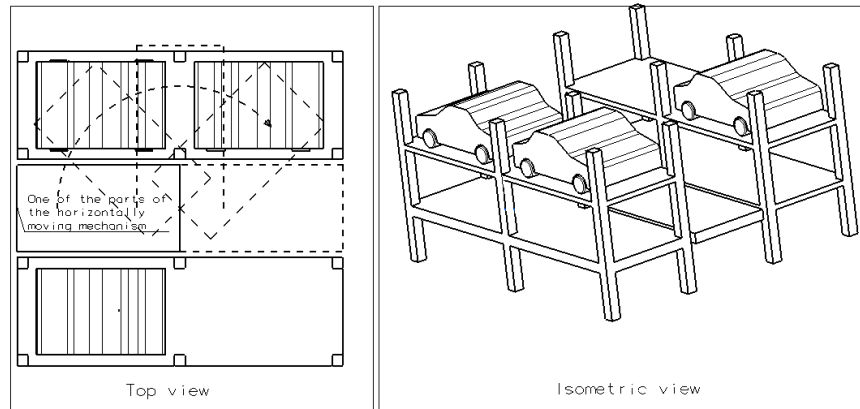


Figure III.2.9: Rotation process of horizontally moving mechanism

When two systems are located opposed to each other, rotation of horizontally moving mechanism will be a problem if it has 6 meters length as shown in Figure III.2.9. Car supporting system need to be at least 5 meters long because it is supposed to support cars from tires. So, when system is rotating, supporting parts shouldn't be rotated. Each car should have its own supporting part, that is to say and length of the rotating part of the horizontally moving mechanism should be less or equal 2,5 meters. So constraints at this level may be stated as follows.

C₁: Maximum length of the rotating part is 2,5m

C₂: Each car should have its own supporting part.

C₃: Supporting parts shouldn't be rotated.

New set of DPs should be determined to satisfy FRs specified above. At this step DPs will be determined without size and strength is considered. Channels with different shapes are used as pathway in engineering. Without considering its shape DP₂₁₂₁ can be determined as channel because its shape will be determined according to new FRs at the next level. Cars don't have to be supported from their tires but they have to be supported from at least four point. Because nobody wants to fall a car which costs \$ 30.000. Supporting cars from four points requires a supporting member with a length of at least 3 meters, because at least one of these four points has to be at the opposed side of the midpoint of the support member. So, tires are the most logical points to support cars. Same as the other kinds of the mechanical car parking systems palettes will be used to satisfy FR₂₁₂₂, but there will be one palette for each car as C₂ has dictate and they won't be rotated. Motion should be transferred to the support member, palettes, by a member which moves along the pathway, channel, to move cars horizontally. This can be done by an arm, but length of it

should be less than 2,5 meters as indicated in C₁. For this reason new set of DPs can be written as

DP₂₁₂₁: Horizontal channel

DP₂₁₂₂: Palettes

DP₂₁₂₃: Arm which moves horizontally along the channel.

New design is shown in Figure III.2.10 and its design equation is written below and seen that, it is an uncoupled design.

$$\begin{vmatrix} FR_{2121} \\ FR_{2122} \\ FR_{2123} \end{vmatrix} = \begin{vmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{vmatrix} \begin{vmatrix} DP_{2121} \\ DP_{2122} \\ DP_{2123} \end{vmatrix} \quad (III.2.8)$$

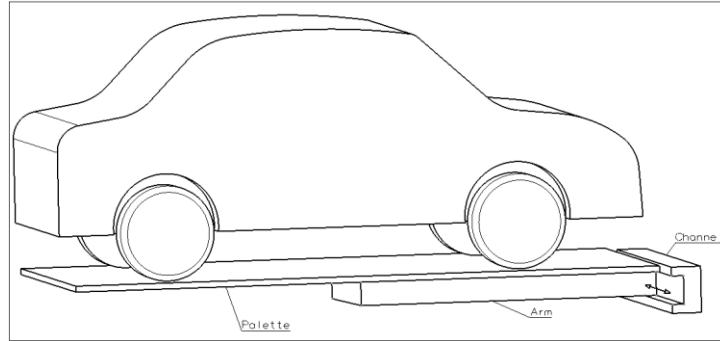


Figure III.2.10: Motion transfer system for horizontal movement

c) **FR₂₂₁:** Generate linear motion perpendicular to the ground

DP₂₂₁: Electric motor-wire rope system

Electric motor-wire rope system is used to transfer motion to long distances. In these systems, rotary motion generated by an electric motor is converted to the linear motion by drum and wire rope system. Same as the slewing unit, rotary motion is need to be reduced to desired value. New set of FRs and DPs to fulfill these FRs are

FR₂₂₁₁: Generate power

FR₂₂₁₂: Convert power to motion

FR₂₂₁₃: Reduce motion to desired value

FR₂₂₁₄: Convert rotary motion to the linear motion.

DP₂₂₁₁: Electric supply

DP₂₂₁₂: Electric motor

DP₂₂₁₃: Reducer mounted to the exit of the electric motor

DP₂₂₁₄: Wire rope system

As seen in Equation (III.2.9), design equation is diagonal, because each DP affects only its corresponding FR. Therefore, electric motor-wire rope system is an uncoupled design.

$$\begin{bmatrix} FR_{2211} \\ FR_{2212} \\ FR_{2213} \\ FR_{2214} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP_{2211} \\ DP_{2212} \\ DP_{2213} \\ DP_{2214} \end{bmatrix} \quad (III.2.9)$$

d) FR₂₂₂: Transfer motion to the horizontally moving mechanism

DP₂₂₂: System which moves vertically along a path.

Vertically moving mechanism is supposed to raise up and set down the cars to make parking process possible. This motion transfer mechanism should move vertically along a pathway and transfer motion generated by electric motor-wire rope system to the horizontally moving mechanism. FR₂₂₂ can be decomposed as follows

FR₂₂₂₁: Follow a vertical pathway.

FR₂₂₂₂: Transfer motion to the horizontally moving mechanism.

In “motion transfer mechanism for horizontal movement” design, a horizontal channel is used to provide pathway. Now, a vertical channel can be used so that the system follows a vertical pathway. To transfer motion to the horizontally moving mechanism, a connection part will be used, but its details are not known yet, because it will be detailed at the next level.

DP₂₂₂₁: Vertical channel

DP₂₂₂₂: Connection part

Design equation for the system shown in Figure III.2.11 is diagonal and the system is an uncoupled design.

$$\begin{bmatrix} FR_{2221} \\ FR_{2222} \end{bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{bmatrix} DP_{2221} \\ DP_{2222} \end{bmatrix} \quad (III.2.10)$$



Figure III.2.11: Motion transfer system for vertical movement

e) **FR₂₃₂**: Transfer motion to the vertically movement mechanism

DP₂₃₂: Slewing unit

Slewing unit will be used to rotate vertically and horizontally moving mechanisms together. In slewing units, rotary motion is transferred to the part which is wanted to be rotated. To rotate something, some torque must be applied on it. For this system, this torque requirement is need to be reduced to rotate the system easily. Since there will be a rotation process, a friction between stable and movable parts will occur and this friction is need to be minimized. In addition to these necessities, motion generated by electric motor is need to be reduced to desired value. Considering these requirements, FR₂₃₂ can be decomposed as follows.

FR₂₃₂₁: Reduce motion to the desired value.

FR₂₃₂₂: Transfer motion to the vertical channel.

FR₂₃₂₃: Reduce torque requirement.

FR₂₃₂₄: Reduce friction during rotation.

FR₂₃₂₅: Support the system.

DPs to satisfy these FRs are.

DP₂₃₂₁: Reducer mounted to the exit of the motor.

DP₂₃₂₂: Machined part mounted to the vertical channel.

DP₂₃₂₃: Gear mounted to the machined part and pinion mounted to the exit of the reducer.

DP₂₃₂₄: Bearings at the ends of the vertical channel.

DP₂₃₂₅: Support member mounted to the frame.

Final design for slewing unit is shown in Figure III.2.12 and design equation is written below. Since the design matrix is diagonal, slewing unit is an uncoupled design.

$$\begin{bmatrix} \text{FR}_{2321} \\ \text{FR}_{2322} \\ \text{FR}_{2323} \\ \text{FR}_{2324} \\ \text{FR}_{2325} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} \text{DP}_{2321} \\ \text{DP}_{2322} \\ \text{DP}_{2323} \\ \text{DP}_{2324} \\ \text{DP}_{2325} \end{bmatrix} \quad (\text{III.2.11})$$

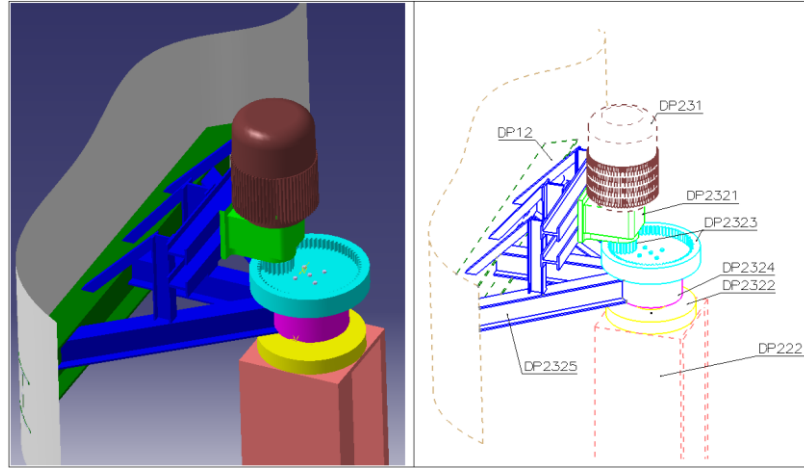


Figure III.2.12: Slewing unit

III.2.4 Decomposition level 5

At this level, FRs and DPs determined in level 4 will be decomposed to be detailed more. Properties of electric motors will be determined at dimensioning and analysis part of this thesis. For this reason they will not be decomposed anymore.

a) FR₂₁₂₁: Provide a horizontal pathway to make possible taking cars out of the shelves.

DP₂₁₂₁: Horizontal channel

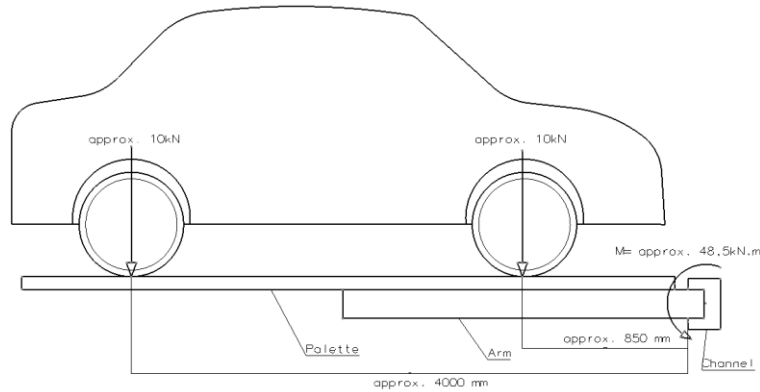


Figure III.2.13: Side view of the horizontally moving mechanism

Figure III.2.13 shows the side view of the horizontally moving mechanism and forces and moment acting on the system. Cars weight has been chosen as approximately 20 kN from appendix A. The heaviest car, BMW 7 Series, is chosen as reference. As it seen from Figure III.2.13, approximately 48,5kN.m moment occurs at the arm and channel connection point due to the force applying on the system. So channel should be resist this moment while it provides a pathway in which arm will move horizontally. Vertical motion will be transferred to the horizontally moving

mechanism by DP_{2221} . So, Channel should have a part so that it connects to the DP_{2221} . In addition to these requirements when the arm reaches ends of the channel it should be prevented from falling. So, FR_{2121} can be decomposed as.

FR_{21211} : Prevent arm to arise from the channel as a result bending.

FR_{21212} : Avoid arm falling at the ends of the channel.

FR_{21213} : Connect to the vertically moving mechanism

C_1 : Connections will be bolted

There are some standard channels designed as guide way for linear motion as seen in Figure III.2.14, but they are not applicable for high moment applications. So a new channel has to be designed to resist high moment acting on the system.



Figure III.2.14: Some standard channels

Figure III.2.15 shows new design for channel.

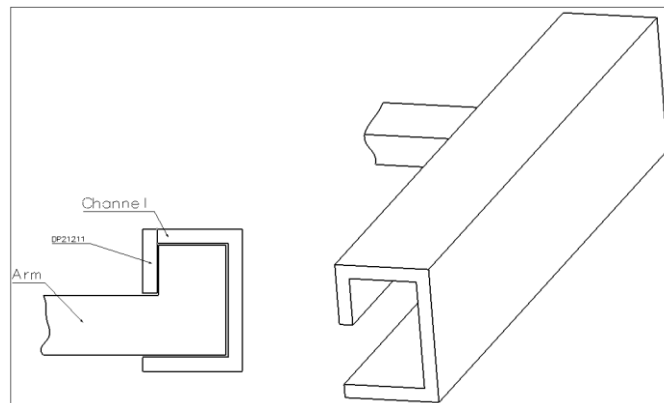


Figure III.2.15: New design for the horizontal channel

Now new set of DPs have to be determined to satisfy FRs. An additional part is added to standard U profile to prevent arms to arise from the channel as shown in Figure III.2.5.

DP₂₁₂₁₁: Additional part to the standard U profile

When arm reaches ends of the channel it isn't wanted falling of the arm. So a cover can be mounted to the ends of the channel.

DP₂₁₂₁₂: Cover bolted to the both ends of the channel

This channel is want to be connected to the vertically moving mechanism. This will be done by a connection member located its longitudinal midpoint.

DP₂₁₂₁₃: Connection member

Design equation is diagonal and it is an uncoupled design.

$$\begin{vmatrix} FR_{21211} \\ FR_{21212} \\ FR_{21213} \end{vmatrix} = \begin{vmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{vmatrix} \begin{vmatrix} DP_{21211} \\ DP_{21212} \\ DP_{21213} \end{vmatrix} \quad (III.2.12)$$

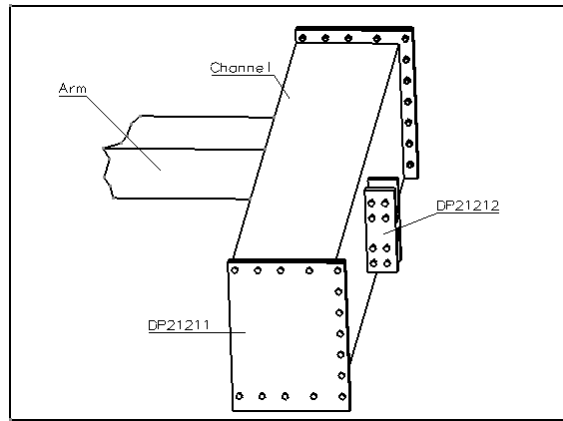


Figure III.2.16: Horizontal channel

b) FR₂₁₂₂:Support cars

DP₂₁₂₂: Palettes

Cars will be taken on the palettes to be lowered or raised. To do that FR₂₁₂₂ will be decomposed and new FRs and Cs will be determined. As it seen from Figure III.2.13 approximately 20 kN load will be applied on it due to cars weight. Firstly the palette should be strong enough to carry this load. It is important to put cars on the palettes correctly and this will be done by drivers. For this reason there should be paths on the palettes for tires to guide the drivers. As it seen from Figure III.2.17 there will be some distance between upper face of the palette and the ground, and it makes difficult to get on the palettes from ground. Something should be done to solve this problem also. One of them is decreasing this distance and the other one is putting some additional part to edge of the palette.

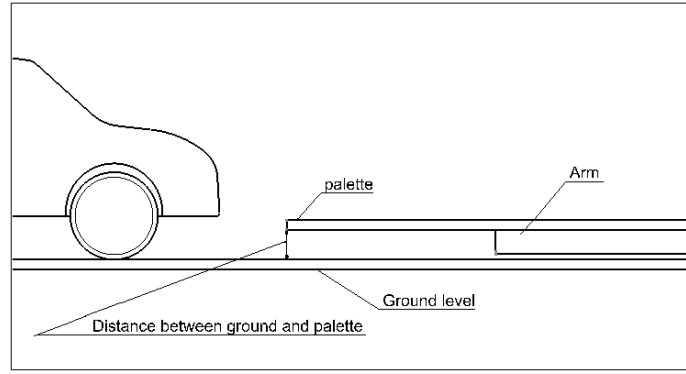


Figure III.2.17: Distance problem between palette and ground

After these explanations FR_{2122} can be decomposed as follows.

FR₂₁₂₂₁: Strong enough to carry 20 kN load.

FR₂₁₂₂₂: Provide paths for tires to make easy driving cars on the palettes.

FR₂₁₂₂₃: Make easy to get on palette from ground

FR₂₁₂₂₄: Minimize distance between upper face of the palette and ground.

This platform will be subjected to stress due to bending moment and it should resist this stress. To resist bending, I beams are used mostly in applications. To make palette strong enough to resist bending a frame is designed by using I beams.

DP₂₁₂₂₁: Steel frame made from I beams

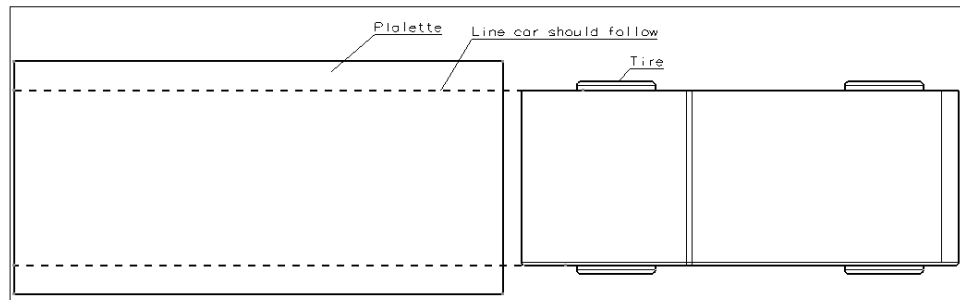


Figure III.2.18: Line which car should follow for optimal parking

Figure III.2.18 shows line which car should follow for optimal parking and it should be provided that drivers follow this line. It is done by bended steel plate in existing systems as seen in Figure III.2.19. We will also use this method to provide drivers to follow proper line when they put cars on the platform.

DP₂₁₂₂₂: Path formed with bended steel plate

DP₂₁₂₂₃: Ramp at the end of the platform

DP₂₁₂₂₄: Cavity at the middle of the palette to allow arm to introduce into it

Palette is an uncoupled design, because design matrix is diagonal.

$$\begin{vmatrix} FR_{21221} \\ FR_{21222} \\ FR_{21223} \\ FR_{21224} \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{vmatrix} \begin{vmatrix} DP_{21221} \\ DP_{21222} \\ DP_{21223} \\ DP_{21224} \end{vmatrix} \quad (III.2.13)$$

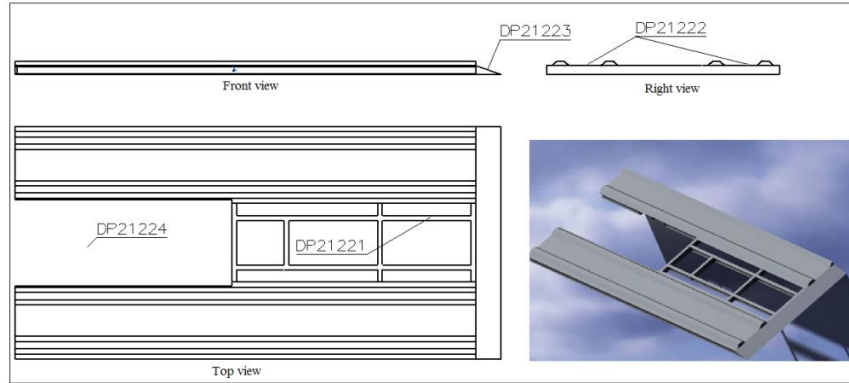


Figure III.2.19: Palette

c) **FR₂₁₂₃**: Transfer motion to the car supporting member

DP₂₁₂₃: Arm which moves horizontally along the channel

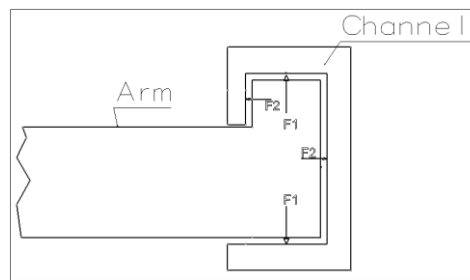


Figure III.2.20: Forces action on the horizontal channel

Figure III.2.20 shows forces acting on the channel due to cars weight. As a result of these forces some friction between arm and channel will occur and this friction should be minimized to avoid problems originating from friction.

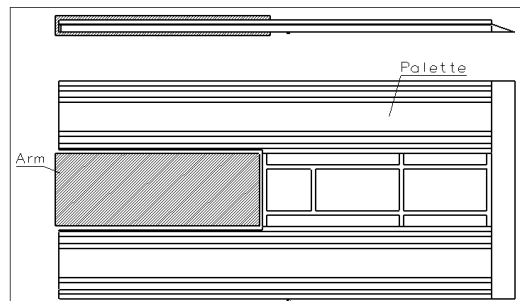


Figure III.2.21: Arm and palette

Arm will introduce into the palette as shown in Figure III.2.21 and when doing that, it should support palette from top and bottom to avoid falling it.

FR₂₁₂₃₁: Reduce friction between arm and the channel

FR₂₁₂₃₂: Strong enough to carry 20 kN load and the palette

FR₂₁₂₃₃: Support palette from bottom

FR₂₁₂₃₄: Support palette from top

Bearings are an efficient method to reduce friction in machine design. Used bearing will be subjected to both radial and axial load and it should be able to carry these loads. As shown in Figure III.2.22, combined bearings have been designed to resist both radial and axial loads and it will be used to reduce friction between arms and the channel. For best solution, combined bearing will be mounted the arm and standard u channel will be mounted to the channel as shown in Figure III.2.23.



Figure III.2.22: Combined bearings

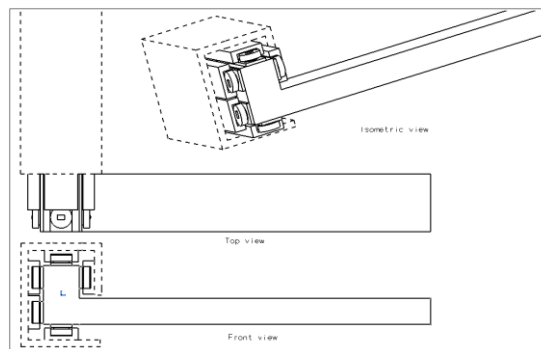


Figure III.2.23: Combined bearings mounted to the arm

Arm will be subjected to high bending moment due to cars weight and efficient method of resisting bending is increasing moment of inertia. This is possible to locate more weight away from the neutral axis. I beams have been designed to resist high bending moment but if standard I beams are wanted to be used, its height will be high. So new design is required similar to I beams but more strong. As shown in Figure III.2.24 steel plates can be welded to each other to increase moment of inertia.

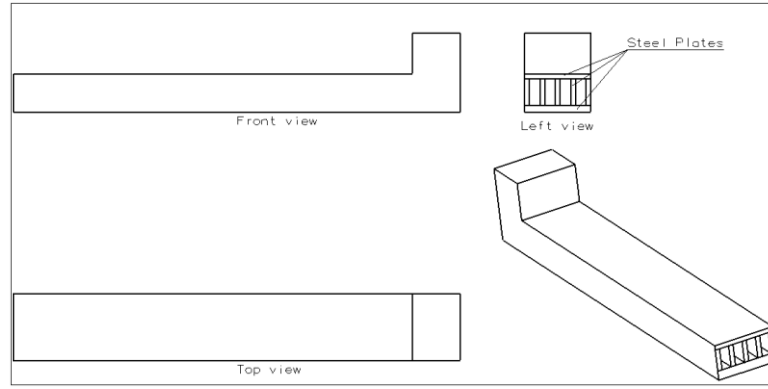


Figure III.2.24: Strong shape to resist high bending moment

When the arm introduce into the palette it should support palette from the bottom. Extending bottom plate to sides in Figure III.2.25 will fulfill FR₂₁₂₃₃.

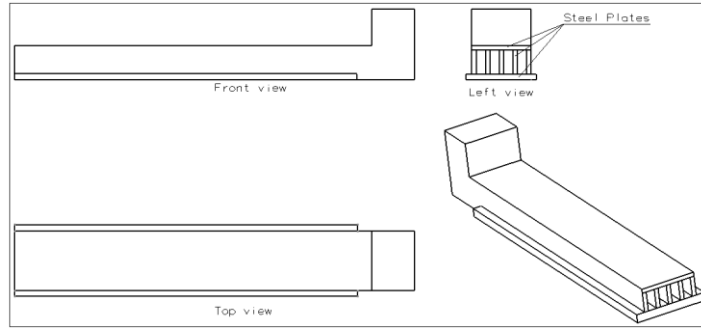


Figure III.2.25: Extended plate to support palette from bottom

To support palette from bottom, arm should introduce into the palette from the bottom. So, supporting palette from the top should take place after the arm introduce into the palette. Arm will take from or put to cars each floors of the system and when it is at the high floor it will not be possible to activate top supporting system by hand. So a mechanical system which doesn't require person to lock or unlock is need to be developed. After these explanations new set of DPs can be stated as follows.

DP₂₁₂₃₁: Combined bearings mounted to the arm and u channels mounted to the channel.

DP₂₁₂₃₂: Steel plates welded to each other to increase moment of inertia of the arm.

DP₂₁₂₃₃: Extended steel plate at the bottom of the arm

DP₂₁₂₃₄: Locking mechanism

$$\begin{vmatrix} \text{FR}_{21231} \\ \text{FR}_{21232} \\ \text{FR}_{21233} \\ \text{FR}_{21234} \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{vmatrix} \begin{vmatrix} \text{DP}_{21231} \\ \text{DP}_{21232} \\ \text{DP}_{21233} \\ \text{DP}_{21234} \end{vmatrix} \quad (\text{III.2.14})$$

To check whether the arm design violates independence axiom or not, design equation is written and it seen that, it is an uncoupled design.

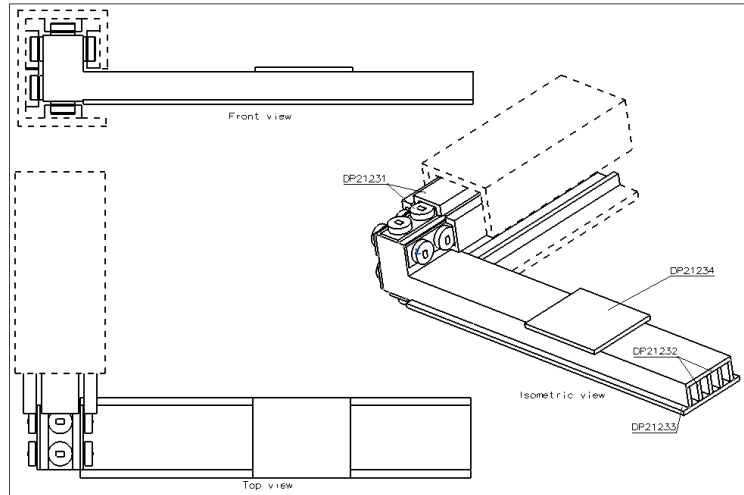


Figure III.2.26: Arm

d) FR_{2214} : Convert rotary motion to the linear motion.

DP_{2214} : Wire rope system

Wire rope system converts rotary motion to the linear motion and transfers linear motion to long distances. To do that, wire rope should be wrapped somewhere so that its length changes. Apart from that, angle between wire rope and the vertical channel is wanted to be constant and they should be parallel to each other at any time. One more requirement is that, this system will raise and lower the cars and it must be safe. By taking into consideration these requirements, FR_{2214} can be decomposed as follows.

FR_{22141} : Transfer motion to long distances

FR_{22142} : Provide place to wrap the wire rope

FR_{22143} : Keep wire rope parallel to the vertical channel at any time

FR_{22144} : Support the system

FR_{22145} : Safe

C_1 : Tension in two wire ropes must be equal at any time.

In these kind of systems, wire rope is wrapped to the drum. To keep wire rope parallel to the vertical channel at any time, pulleys mounted to the vertical channel will be used. As safety device an additional wire rope will be used. If one of these wire ropes breaks for some reason, the other one will avoid cars from falling. So, DPs to satisfy FRs listed above can be determined as follows.

DP₂₂₁₄₁: Wire rope

DP₂₂₁₄₂: Drum mounted to the exit of the reducer, DP₂₂₁₃

DP₂₂₁₄₃: Pulleys mounted to the vertical channel

DP₂₂₁₄₄: Support member on the vertical channel

DP₂₂₁₄₅: An additional wire rope connected to the drum

Design matrix for wire rope system is

$$\begin{bmatrix} FR_{22141} \\ FR_{22142} \\ FR_{22143} \\ FR_{22144} \\ FR_{22145} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP_{22141} \\ DP_{22142} \\ DP_{22143} \\ DP_{22144} \\ DP_{22145} \end{bmatrix} \quad (III.2.15)$$

Design matrix is diagonal and it means that wire rope system is an uncoupled design.

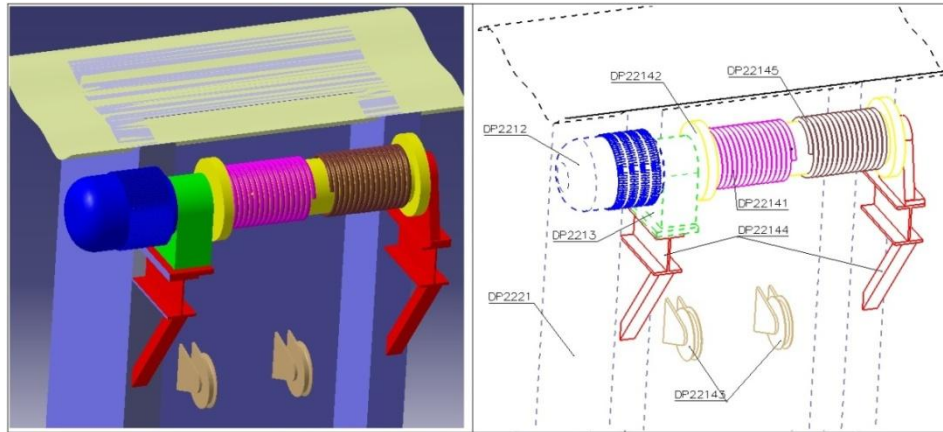


Figure III.2.27: Wire rope system

e) FR₂₂₂₁: Follow a vertical pathway.

DP₂₂₂₁: Vertical channel

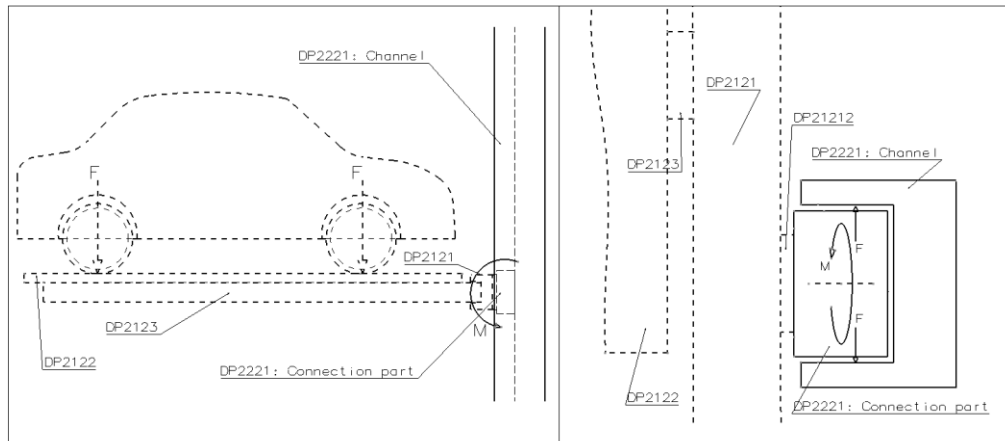


Figure III.2.28: Moment and forces acting on the vertical channel

As it seen from Figure III.2.28, there will be bending moment acting on the channel due to weight of the cars and channel should be strong enough to resist this bending. When horizontally moving mechanism moves cars to the ends of the horizontal channel some force and moment will act on the channel as it is shown in Figure III.2.28. Channel should resist also these forces and moment. So FR_{2221} can be decomposed as follows.

FR_{22211} : Prevent connection part to arise from the channel

FR_{22212} : Resist bending about both axis

FR_{22213} : Resist forces acting sides of the channel

As it has been indicated previously, I beams are designed to resist bending moment. But this channel will be perpendicular to the ground and it will act as a column. HEB or HEA profiles are commonly used as column but we have bending moment about both axis.

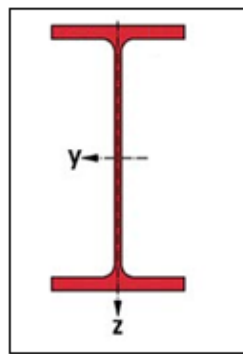


Figure III.2.29: Section view of I beams

I_y in Figure III.2.29 is higher compared to I_x but we need a design whose moment of inertia should be high about both axes. One of the methods to increase moment of inertia about z axis is connecting two I beams by using steel plates as seen from Figure III.2.30.

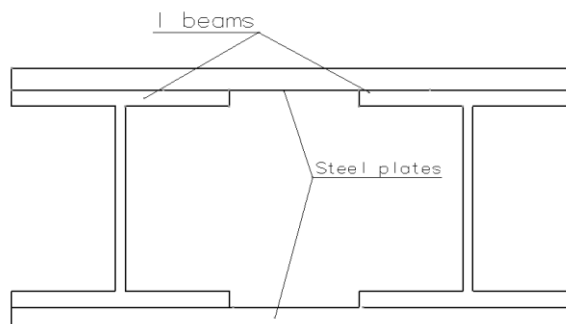


Figure III.2.30: Connecting I beams by using steel plates

Supporting channel with two I beams, connected to each other by using steel plates as seen in Figure III.2.30 will solve bending moment problem about both axes.

Forces action on the sides of the channel will try to open channel to sides. To prevent that, some reinforcement plates will be used. So DP to satisfy FR_{22211} and FR_{22212} can be stated as

DP₂₂₂₁₁: U channels mounted opposed to each other

DP₂₂₂₁₂: I beams connected to each other by steel plates

DP₂₂₂₁₃: Reinforcement plates.

As seen in Equation (III.2.16), design matrix is diagonal and the vertical channel is an uncoupled design.

$$\begin{vmatrix} FR_{22211} \\ FR_{22212} \\ FR_{22213} \end{vmatrix} = \begin{vmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{vmatrix} \begin{vmatrix} DP_{22211} \\ DP_{22212} \\ DP_{22213} \end{vmatrix} \quad (III.2.16)$$

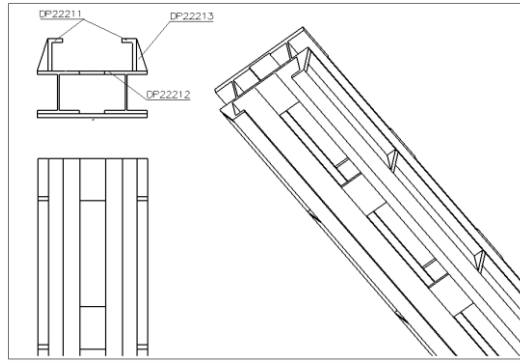


Figure III.2.31: Vertical channel

f) FR_{2222} : Transfer motion to horizontally moving mechanism

DP₂₂₂₂: Connection part

Bending moment shown in Figure III.2.28 will act on the connection part also. Firstly connection part should be strong enough to resist this bending moment. Connection part will move along the channel and of course there will be some friction between connection part and the vertical channel. This friction is need to be reduced. Wire rope will be connected to the connection part to raise up and set down the cars. So, connection part should provide place to connect the wire rope. Finally, connection part will be connected to the horizontally moving mechanism. After these explanations FR_{2222} can be decomposed as follows.

FR₂₂₂₂₁: Resist bending moment

FR₂₂₂₂₂: Reduce friction between connection part and the channel

FR₂₂₂₂₃: Provide place for wire rope to connect it

FR₂₂₂₂₄: Connect to the horizontally moving mechanism

DPs to satisfy these FRs can be stated as follows.

DP₂₂₂₂₁: Steel plates welded to each other

DP₂₂₂₂₂: Combined bearing mounted to the connection member and U channel mounted to the vertical channel

DP₂₂₂₂₃: Two steel plates welded to the connection member

DP₂₂₂₂₄: Connection plates

$$\begin{vmatrix} \text{FR}_{22221} \\ \text{FR}_{22222} \\ \text{FR}_{22223} \\ \text{FR}_{22224} \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{vmatrix} \begin{vmatrix} \text{DP}_{22221} \\ \text{DP}_{22222} \\ \text{DP}_{22223} \\ \text{DP}_{22224} \end{vmatrix} \quad (\text{III.2.17})$$

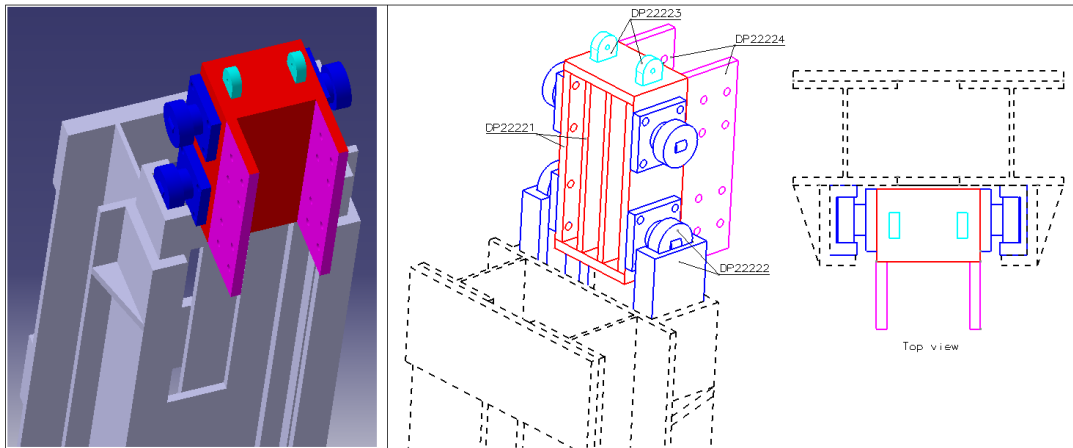


Figure III.2.32: Connection member

III.2.5 Decomposition level 6

a) **FR₂₁₂₃₄**: Support palette from top

DP₂₁₂₃₄: Locking mechanism

This locking mechanism is wanted to support palette from four points to avoid falling it. Because it has been stated that, supporting cars from four points are the most logical choose. In this way, cars will be avoided from falling. Locking and unlocking processes should be fulfilled by one mechanism to prevent complexity and increasing cost. Since the system will not be manual, some motion should be supplied to the mechanism. Decomposition of FR₂₁₂₃₄ is like below.

FR₂₁₂₃₄₁: Support palette from four points

FR₂₁₂₃₄₂: Lock- unlock by one mechanism

FR₂₁₂₃₄₃: Generate motion to lock and unlock processes

FR₂₁₂₃₄₄: Reduce motion to desired value

DPs to satisfy these FRs are determined as

DP₂₁₂₃₄₁: Four steel plates mounted to the arm

DP₂₁₂₃₄₂: Lead screw mechanism

DP₂₁₂₃₄₃: Servo motor

DP₂₁₂₃₄₄: Reducer mounted to the motor.

$$\begin{bmatrix} \text{FR}_{212341} \\ \text{FR}_{212342} \\ \text{FR}_{212343} \\ \text{FR}_{212344} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} \text{DP}_{212341} \\ \text{DP}_{212342} \\ \text{DP}_{212343} \\ \text{DP}_{212344} \end{bmatrix} \quad (\text{III.2.18})$$

Design equation is diagonal. Thus, lock mechanism is an uncoupled design.

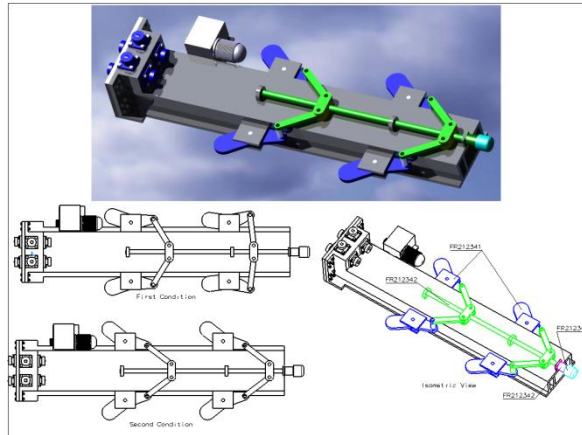


Figure III.2.33: Lock mechanism

b) FR₂₂₁₄₂: Provide place to wrap the wire rope

DP₂₂₁₄₂: Drum mounted to the exit of the reducer

Wire rope will be wrapped to the drum and it is important to wrap it correctly. In other saying, potential overlap should be prevented. Of course, wire rope must be fastened to the drum first to make possible wrapping it to the drum. Two wire ropes and one drum will be used. So, it should be possible to wrap these wire ropes to one drum. In addition, during rotation friction between the drum and the support member, DP₂₂₁₄₄, should be minimized. FR₂₂₁₄₂ can be decomposed as follows considering these requirements.

FR₂₂₁₄₂₁: Make possible to wrap the wire rope on the drum correctly

FR₂₂₁₄₂₂: Fasten the wire rope to the drum

FR₂₂₁₄₂₃: Make possible to wrap two wire ropes to the drum

FR₂₂₁₄₂₄: Make easy to turn for drum

Following DPs are chosen to satisfy these FRs and final design for the drum is seen in Figure III.2.32.

DP₂₂₁₄₂₁: Grooves on the drum

DP₂₂₁₄₂₂: Grooved plates mounted to the drum

DP₂₂₁₄₂₃: Disc which separates the drum two pieces

DP₂₂₁₄₂₄: Bearings at both ends

As it is seen from the design matrix, drum is an uncoupled design.

$$\begin{vmatrix} \text{FR}_{22141} \\ \text{FR}_{22142} \\ \text{FR}_{22143} \\ \text{FR}_{22144} \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{vmatrix} \begin{vmatrix} \text{DP}_{22141} \\ \text{DP}_{22142} \\ \text{DP}_{22143} \\ \text{DP}_{22144} \end{vmatrix} \quad (\text{III.2.19})$$

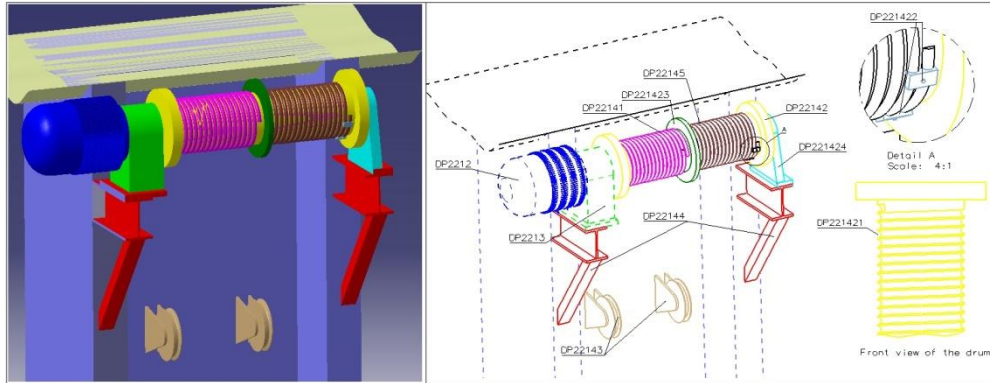


Figure III.2.34: Details of the drum

FR-DP three and total design matrix are seen in Figure III.2.35 and Figure III.2.36. In design matrix, main components are stated and their names are written to the top right-hand corners. In this way relationship between components can be seen easily. As seen from the total design matrix, new system is an uncoupled design. Because all DPs affect only their corresponding FRs and it makes the design an ideal design.

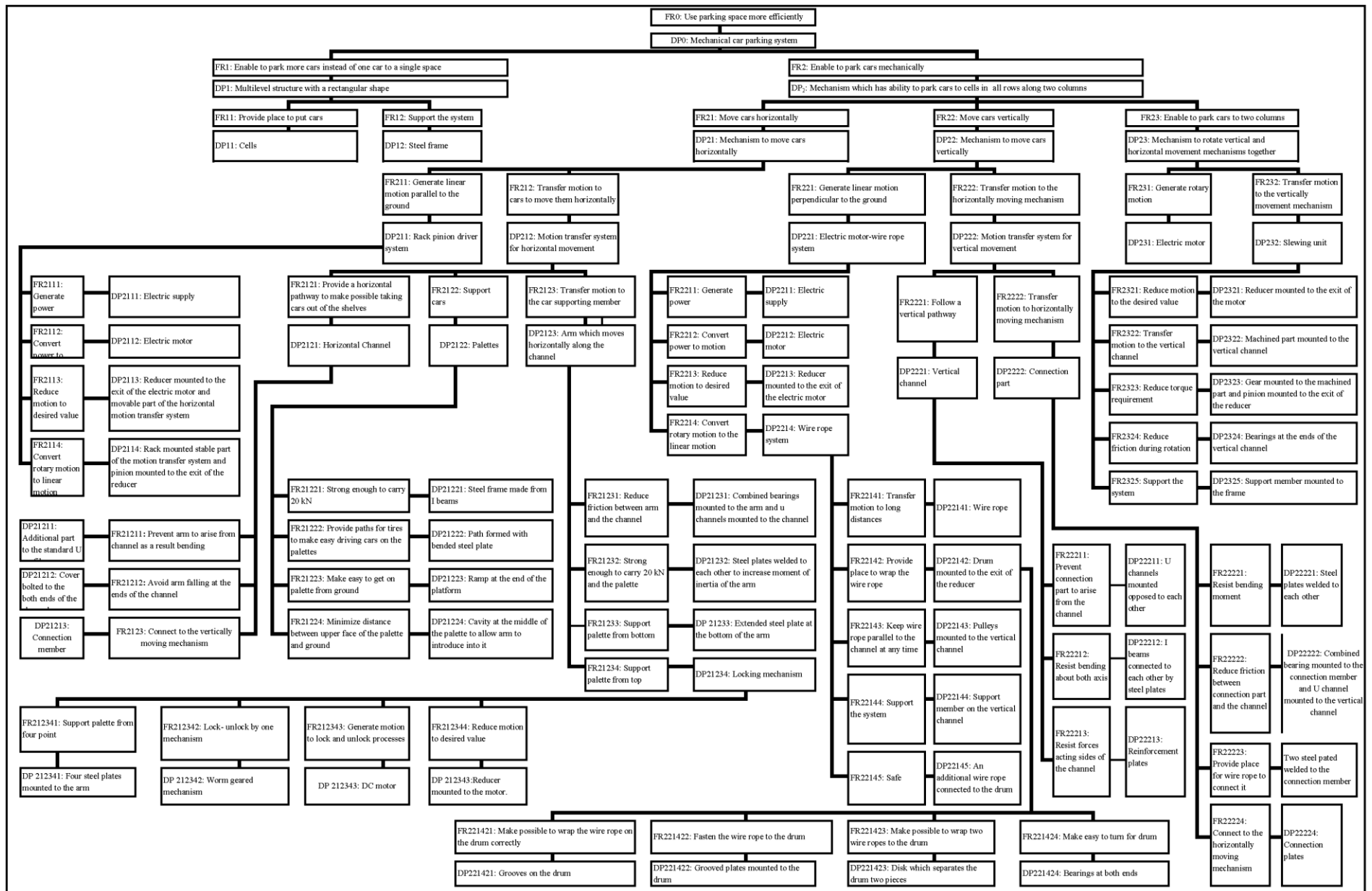


Figure III.2.35: FR-DP tree of new system

The diagram illustrates a hierarchical tree structure for a mechanical system, likely a parking garage. The tree is organized into a grid-like structure with rows and columns representing different levels of the hierarchy.

Root Node: FR0

Level 1 (FR1, FR2):

- FR1: Multilevel structure with a rectangular shape
- FR2: Mechanism to move cars horizontally

Level 2 (FR21, FR22):

- FR21: Rack and pinion driver
- FR22: Motion transfer system for horizontal movement

Level 3 (FR211, FR212, FR213, FR214, FR215, FR216, FR217, FR218, FR219, FR2110, FR2111, FR2112, FR2113, FR2114, FR2115, FR2116, FR2117, FR2118, FR2119, FR2120, FR2121, FR2122, FR2123, FR2124, FR2125, FR2126, FR2127, FR2128, FR2129, FR2130, FR2131, FR2132, FR2133, FR2134, FR2135, FR2136, FR2137, FR2138, FR2139, FR2140, FR2141, FR2142, FR2143, FR2144, FR2145, FR2146, FR2147, FR2148, FR2149, FR2150, FR2151, FR2152, FR2153, FR2154, FR2155, FR2156, FR2157, FR2158, FR2159, FR2160, FR2161, FR2162, FR2163, FR2164, FR2165, FR2166, FR2167, FR2168, FR2169, FR2170, FR2171, FR2172, FR2173, FR2174, FR2175, FR2176, FR2177, FR2178, FR2179, FR2180, FR2181, FR2182, FR2183, FR2184, FR2185, FR2186, FR2187, FR2188, FR2189, FR2190, FR2191, FR2192, FR2193, FR2194, FR2195, FR2196, FR2197, FR2198, FR2199, FR2200, FR2201, FR2202, FR2203, FR2204, FR2205, FR2206, FR2207, FR2208, FR2209, FR2210, FR2211, FR2212, FR2213, FR2214, FR2215, FR2216, FR2217, FR2218, FR2219, FR2220, FR2221, FR2222, FR2223, FR2224, FR2225, FR2226, FR2227, FR2228, FR2229, FR2230, FR2231, FR2232, FR2233, FR2234, FR2235, FR2236, FR2237, FR2238, FR2239, FR2240, FR2241, FR2242, FR2243, FR2244, FR2245, FR2246, FR2247, FR2248, FR2249, FR2250, FR2251, FR2252, FR2253, FR2254, FR2255, FR2256, FR2257, FR2258, FR2259, FR2260, FR2261, FR2262, FR2263, FR2264, FR2265, FR2266, FR2267, FR2268, FR2269, FR2270, FR2271, FR2272, FR2273, FR2274, FR2275, FR2276, FR2277, FR2278, FR2279, FR2280, FR2281, FR2282, FR2283, FR2284, FR2285, FR2286, FR2287, FR2288, FR2289, FR2290, FR2291, FR2292, FR2293, FR2294, FR2295, FR2296, FR2297, FR2298, FR2299, FR2300, FR2301, FR2302, FR2303, FR2304, FR2305, FR2306, FR2307, FR2308, FR2309, FR2310, FR2311, FR2312, FR2313, FR2314, FR2315, FR2316, FR2317, FR2318, FR2319, FR2320, FR2321, FR2322, FR2323, FR2324, FR2325, FR2326, FR2327, FR2328, FR2329, FR2330, FR2331, FR2332, FR2333, FR2334, FR2335, FR2336, FR2337, FR2338, FR2339, FR2340, FR2341, FR2342, FR2343, FR2344, FR2345, FR2346, FR2347, FR2348, FR2349, FR2350, FR2351, FR2352, FR2353, FR2354, FR2355, FR2356, FR2357, FR2358, FR2359, FR2360, FR2361, FR2362, FR2363, FR2364, FR2365, FR2366, FR2367, FR2368, FR2369, FR2370, FR2371, FR2372, FR2373, FR2374, FR2375, FR2376, FR2377, FR2378, FR2379, FR2380, FR2381, FR2382, FR2383, FR2384, FR2385, FR2386, FR2387, FR2388, FR2389, FR2390, FR2391, FR2392, FR2393, FR2394, FR2395, FR2396, FR2397, FR2398, FR2399, FR2400, FR2401, FR2402, FR2403, FR2404, FR2405, FR2406, FR2407, FR2408, FR2409, FR2410, FR2411, FR2412, FR2413, FR2414, FR2415, FR2416, FR2417, FR2418, FR2419, FR2420, FR2421, FR2422, FR2423, FR2424, FR2425, FR2426, FR2427, FR2428, FR2429, FR2430, FR2431, FR2432, FR2433, FR2434, FR2435, FR2436, FR2437, FR2438, FR2439, FR2440, FR2441, FR2442, FR2443, FR2444, FR2445, FR2446, FR2447, FR2448, FR2449, FR2450, FR2451, FR2452, FR2453, FR2454, FR2455, FR2456, FR2457, FR2458, FR2459, FR2460, FR2461, FR2462, FR2463, FR2464, FR2465, FR2466, FR2467, FR2468, FR2469, FR2470, FR2471, FR2472, FR2473, FR2474, FR2475, FR2476, FR2477, FR2478, FR2479, FR2480, FR2481, FR2482, FR2483, FR2484, FR2485, FR2486, FR2487, FR2488, FR2489, FR2490, FR2491, FR2492, FR2493, FR2494, FR2495, FR2496, FR2497, FR2498, FR2499, FR2500, FR2501, FR2502, FR2503, FR2504, FR2505, FR2506, FR2507, FR2508, FR2509, FR2510, FR2511, FR2512, FR2513, FR2514, FR2515, FR2516, FR2517, FR2518, FR2519, FR2520, FR2521, FR2522, FR2523, FR2524, FR2525, FR2526, FR2527, FR2528, FR2529, FR2530, FR2531, FR2532, FR2533, FR2534, FR2535, FR2536, FR2537, FR2538, FR2539, FR2540, FR2541, FR2542, FR2543, FR2544, FR2545, FR2546, FR2547, FR2548, FR2549, FR2550, FR2551, FR2552, FR2553, FR2554, FR2555, FR2556, FR2557, FR2558, FR2559, FR2560, FR2561, FR2562, FR2563, FR2564, FR2565, FR2566, FR2567, FR2568, FR2569, FR2570, FR2571, FR2572, FR2573, FR2574, FR2575, FR2576, FR2577, FR2578, FR2579, FR2580, FR2581, FR2582, FR2583, FR2584, FR2585, FR2586, FR2587, FR2588, FR2589, FR2590, FR2591, FR2592, FR2593, FR2594, FR2595, FR2596, FR2597, FR2598, FR2599, FR2600, FR2601, FR2602, FR2603, FR2604, FR2605, FR2606, FR2607, FR2608, FR2609, FR2610, FR2611, FR2612, FR2613, FR2614, FR2615, FR2616, FR2617, FR2618, FR2619, FR2620, FR2621, FR2622, FR2623, FR2624, FR2625, FR2626, FR2627, FR2628, FR2629, FR2630, FR2631, FR2632, FR2633, FR2634, FR2635, FR2636, FR2637, FR2638, FR2639, FR2640, FR2641, FR2642, FR2643, FR2644, FR2645, FR2646, FR2647, FR2648, FR2649, FR2650, FR2651, FR2652, FR2653, FR2654, FR2655, FR2656, FR2657, FR2658, FR2659, FR2660, FR2661, FR2662, FR2663, FR2664, FR2665, FR2666, FR2667, FR2668, FR2669, FR2670, FR2671, FR2672, FR2673, FR2674, FR2675, FR2676, FR2677, FR2678, FR2679, FR2680, FR2681, FR2682, FR2683, FR2684, FR2685, FR2686, FR2687, FR2688, FR2689, FR2690, FR2691, FR2692, FR2693, FR2694, FR2695, FR2696, FR2697, FR2698, FR2699, FR2700, FR2701, FR2702, FR2703, FR2704, FR2705, FR2706, FR2707, FR2708, FR2709, FR2710, FR2711, FR2712, FR2713, FR2714, FR2715, FR2716, FR2717, FR2718, FR2719, FR2720, FR2721, FR2722, FR2723, FR2724

Figure III.2.36: Total design matrix of new system

CHAPTER IV

COMPUTER AIDED ANALYSIS OF THE PROPOSED SYSTEM

In this chapter, static structural analysis of the proposed system and motor, wire rope, etc. selection will be performed.

IV.1 STATIC STRUCTURAL ANALYSIS

Static structural analysis will be performed on ANSYS and it will go from palette to the vertical channel. Because, weight of the palette will act on the arm as an additional load, and weight of the arm will act on the horizontal channel. That is why analysis will start from palette and end with the vertical channel. Before starting analysis, properties of the cars that will be parked to the system should be determined. To do that, some automobile brands that are commonly used in Turkey have been chosen. Two or three models of these brands have been selected considering usage in Turkey. Selected cars and their physical properties are given in Appendix A. The heaviest of these cars are the reference to determine loads that will act on the system due to cars weight. The widest, longest and highest cars have been selected to determine dimensions of the components of the system. According to these criteria, reference cars are listed below.

The heaviest car : BMW 7 Series, 1840 kg

The longest car : BMW 7 Series, 5072 mm

The widest car : BMW 7 Series, 2134 mm

The highest car : Ford Mondeo, 1550 mm

These information will be used during analysis and dimensioning of the system.

IV.1.1 Static Analysis of the Palette

As it is stated in Chapter III, to make palette strong enough to resist bending, a frame is designed by using I beams. This frame is made using IPE 80 standard profiles. The widest and longest car is the reference car to determine dimensions of the palette. Width of the palette is determined as 2234 mm and this value is 100 mm longer than the width of the widest car, because 50 mm extended place are determined at each side of the car when it is put on the palette. Length of the palette

is chosen as 5252 mm, because 90 mm free place are considered at the front and back of the car. This situation is shown in Figure IV.1.1 clearly.

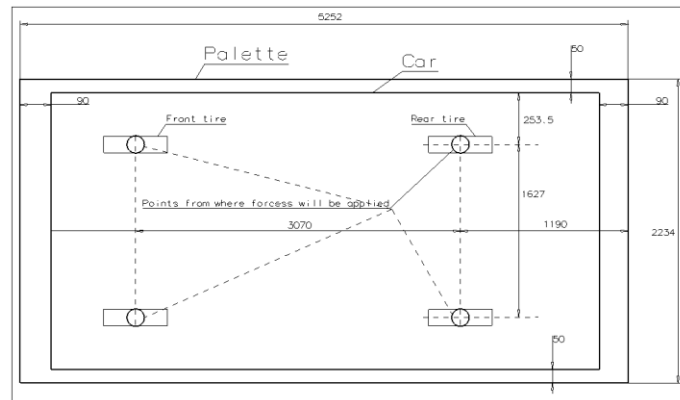


Figure IV.1.1: Dimensions of the palette

Locations of the tires are shown in Figure IV.1.1, and forces due to car's weight will be applied on the palette from these points. 5000 N forces are applied from each front tires and 4000 N forces are applied from each rear tires. Figure IV.1.2 and Figure IV.1.3 show ANSYS analysis results. According to the ANSYS analysis results, maximum equivalent stress due to bending is 141,09 MPa and total deformation is 26,81 mm. Material for IPE 80 is St44-2 and its yield strength is 275 MPa. So, design is in safe region. Static analysis is performed on only the steel frame and other componenets, such as bended steel plate, of the palette will be added on it later. Drawings of the final design for the palette is given at the Appendix D.

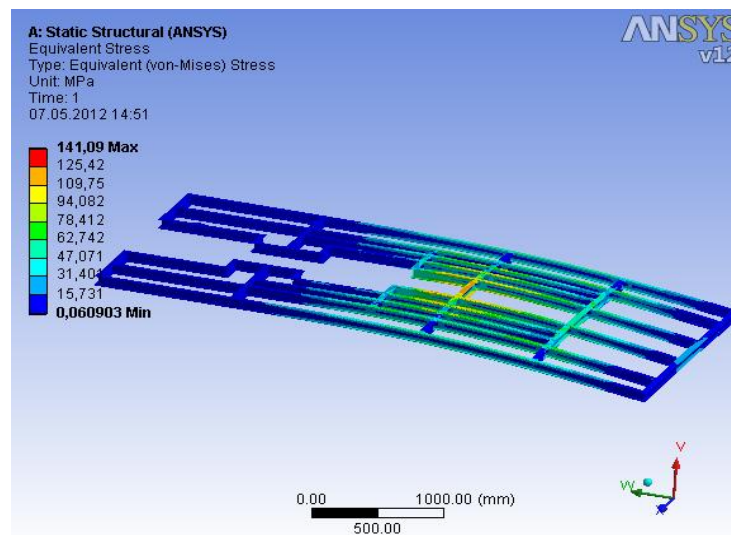


Figure IV.1.2: Equivalent stress on the palette

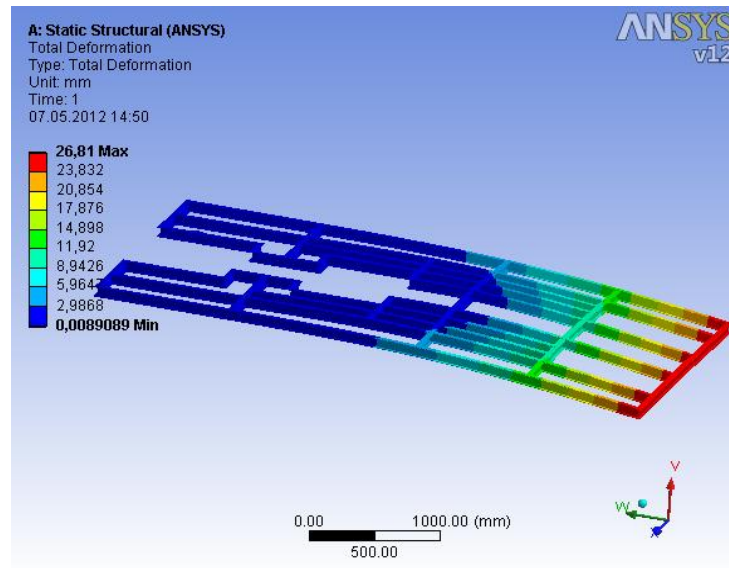


Figure IV.1.3: Total deformation on the palette

IV.1.2 Static Analysis of the Arm and the Horizontal Channel

Arm and the horizontal channel are analyzed together. Before analysis, combined bearing and standard u channel selections have been performed. Combined bearings have been welded to the flange plates first, and then mounted to the arm with bolted connection. U profiles have been welded to the horizontal channel directly. Properties and drawings of combined bearing, flange plate and u channel are given at the appendix B. Winkel 4.058 type combined bearing has been selected, because, it has high load capacities in both radial and axial directions and its diameter is not so large. Winkel 3 Nb standard u channel and AP 3-Q flange plates are the other components selected from the catalogue and their dimensions are shown at Appendix B.

Ten combined bearings are mounted to the arm as shown in Figure IV.1.4. To make assembly possible, a cover is fastened to end of the arm by using M16 bolts. Firstly, six combined bearings located to the sides of the arm will be assembled, and the other combined bearings will be mounted to the cover. After that, cover will be mounted to the arm and assembly will be completed.

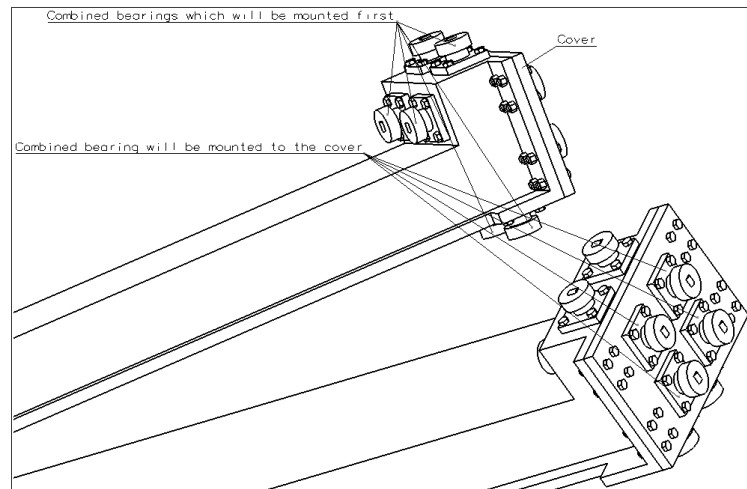


Figure IV.1.4: Combined bearing assembly

Palette, arm and horizontal channel have been assembled together as seen in Figure IV.1.5 so that they are analyzed at the same time. It has been considered that, arm is at the end of the horizontal channel. Because horizontal channel is supported from its midpoint and when arm reaches to the end of it, some additional moment will act on the horizontal channel. This situation is worse than that arm is at the middle of the horizontal channel. So, worse situation should be chosen during analysis. Forces have been applied to the system such in palette analysis. In addition to these forces, weights of the palette, arm and horizontal channel also have been considered.

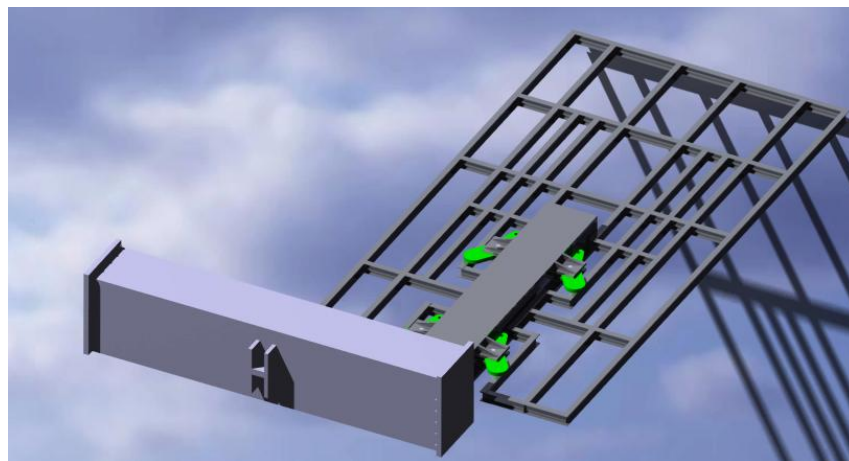


Figure IV.1.5: Palette, arm and horizontal channel assembly

As it seen from Figure IV.1.6, maximum equivalent stress on arm due to car's, palette's and its own weight is 170,46 MPa and it occurs at the end of the arm. Arm is constructed from St 52 grade steel plates and its yield strength is 355 MPa.

So, arm is strong enough to carry loads acting on it. Figure IV.1.7 shows the total deformation and its maximum value is 11,01 mm. Total weight of the arm is 1000 kg.

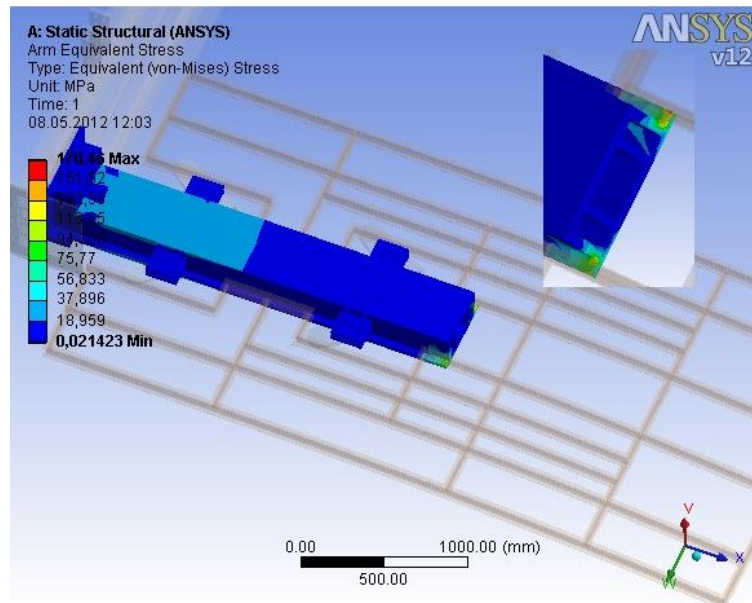


Figure IV.1.6: Equivalent stress on the arm

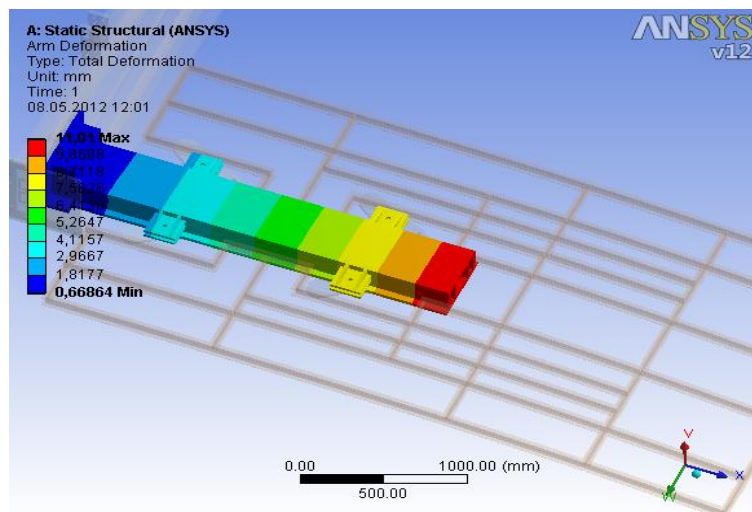


Figure IV.1.7: Total deformation on the arm

As stated above, arm has a cover on which four combined bearings are mounted and it should be analyzed also. Static analysis result for the arm cover is shown in Figure IV.1.8. Maximum equivalent stress and maximum deformation for cover are respectively 33,675 MPa and 0,992 mm. Cover is also manufactured from St 52 steel and equivalent stress occurred on the cover is extremely low in comparison to the yield strength of the St 52 steel.

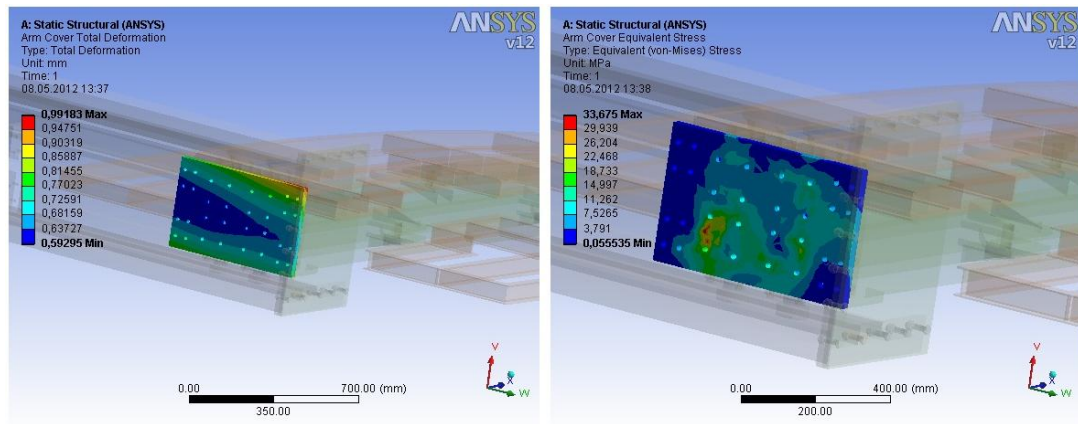


Figure IV.1.8: Static analysis results for the arm cover

Horizontal channel is the other component of the system. Similar to the arm and the arm cover, it is manufactured from St 52 grade steel. Figure IV.1.9 and Figure IV.1.10 show the equivalent stress and total deformation respectively. Maximum equivalent stress is 278,57 MPa and it occurs at the inner surface of the hole which is used to connect horizontal channel to the connection member which is located between vertical channel and the horizontal channel. 278,57 MPa is a high stress value but it is smaller than the yield strength of the St 52 steel. Maximum deformation is 2 mm and it is negligible. Total weight of the horizontal channel with the standard u channels is 1700 kg.

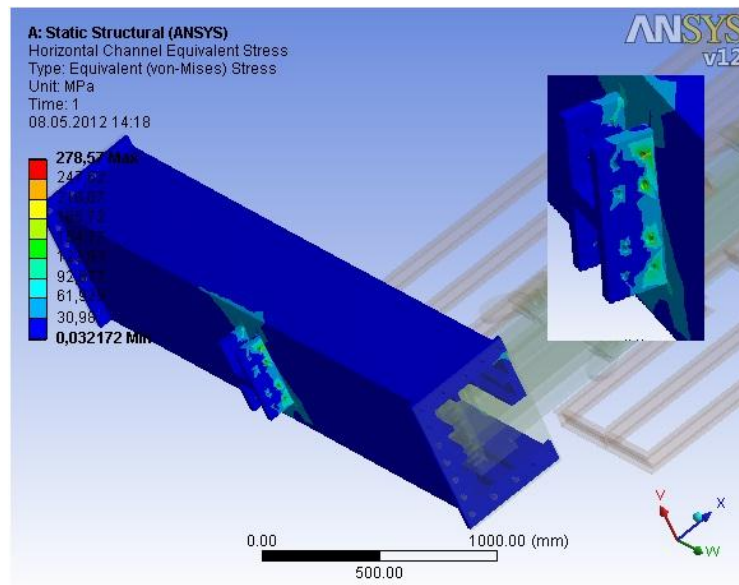


Figure IV.1.9: Equivalent stress on the horizontal channel

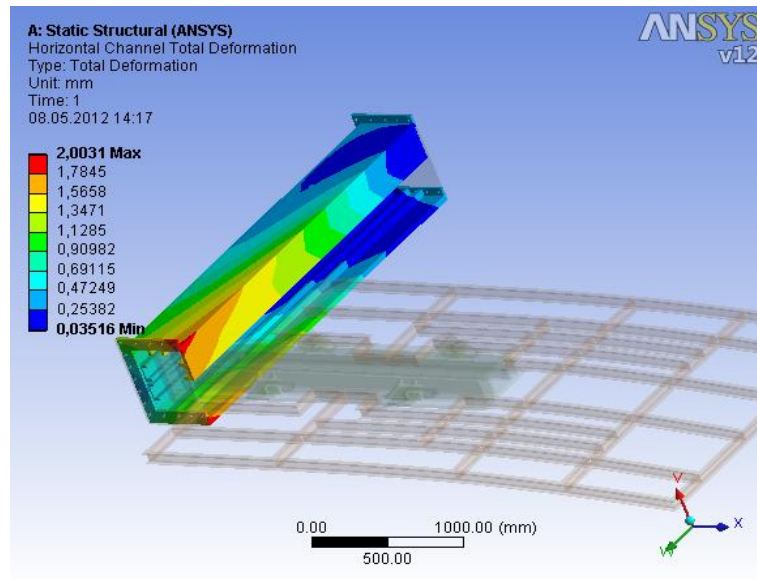


Figure IV.1.10: Total deformation on the horizontal channel

There are two covers at the both ends of the horizontal channel to prevent arm from falling when it reaches to the end, and these covers mounted to the horizontal channel with M16 bolts. Maximum equivalent stress and maximum deformation for covers are respectively 32,84 MPa and 0,32 mm as seen in Figure IV.1.11.

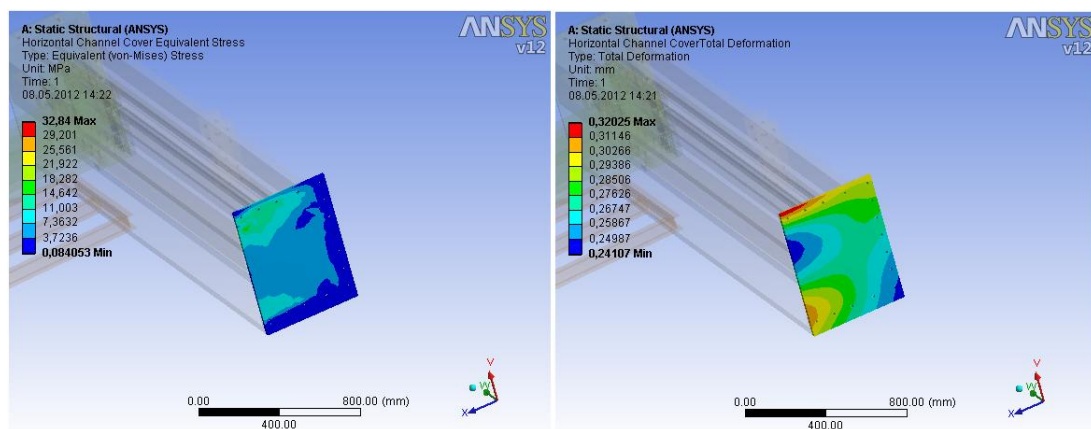


Figure IV.1.11: Static analysis results for the horizontal channel cover

As illustrated in Figure IV.1.5, there are four plates with green color and they support palette from the top. These plates belong to the locking mechanism and of course they are subjected to the some forces due to car's and palette's weights. Analysis results for these plates are shown in Figure IV.1.12 and both maximum equivalent stress and maximum deformation are low.

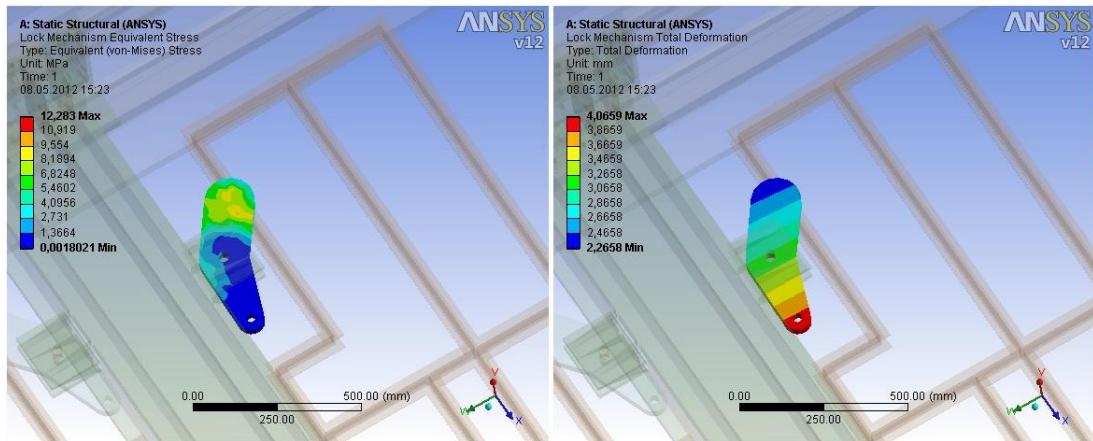


Figure IV.1.12: Static analysis results for the locking mechanism

IV.1.3 Static Analysis of the Connection Member

Connection member is used to transfer vertical motion to the horizontally moving mechanism and it connects horizontal channel and wire rope to each other. It is connected to the horizontal channel with M16 bolts as shown in Figure IV.1.13. Static analysis will be performed again to see equivalent stress and deformation on connection member. Forces are applied on the palette same as arm and the horizontal channel analysis. Four combined bearings are mounted to the connection member to reduce friction between vertical channel and connection member. Such in arm design, the same combined bearings and u channels are used in connection member.

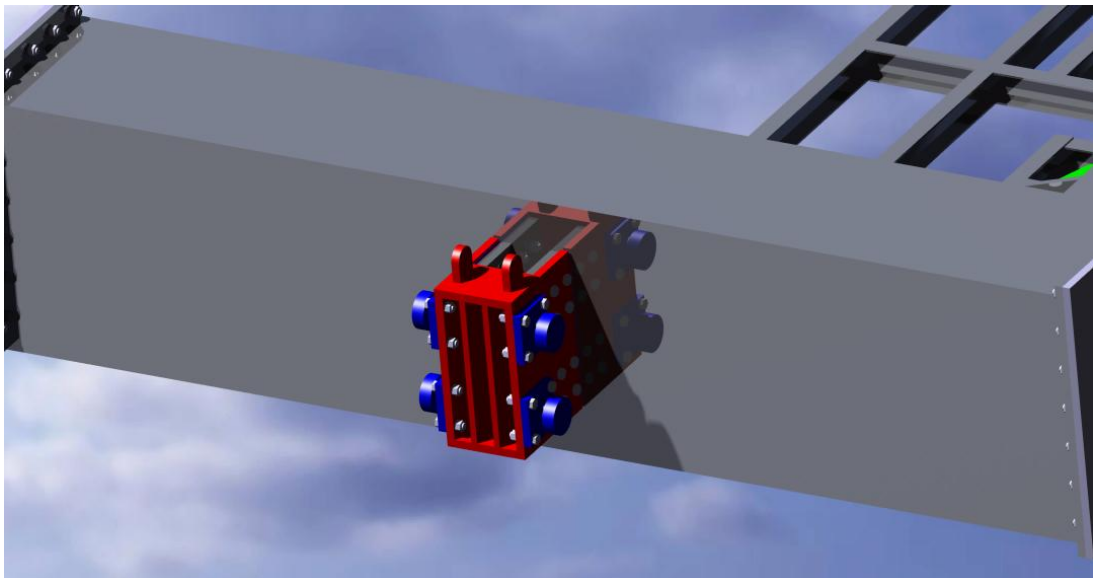


Figure IV.1.13: Connection member and the horizontal channel.

St 52 grade steel plates are welded to each other to form connection member. Static analysis results for it are shown in Figure IV.1.14 and Figure IV.1.15. Maximum equivalent stress is 159,05 MPa and it is smaller than the yield strength of the St 52 steel. Maximum deformation is 0,289 mm and occurs at the corner of the connection plates. Total weight of the connection member is 60 kg.

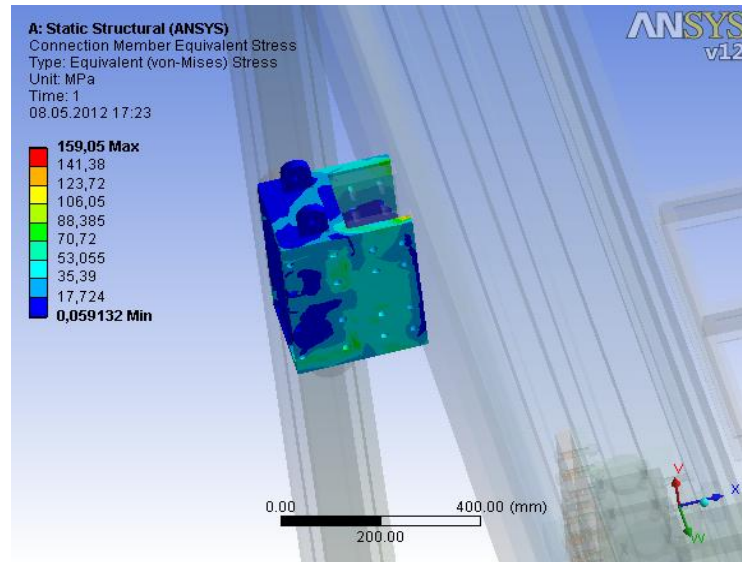


Figure IV.1.14: Equivalent stress on the connection member

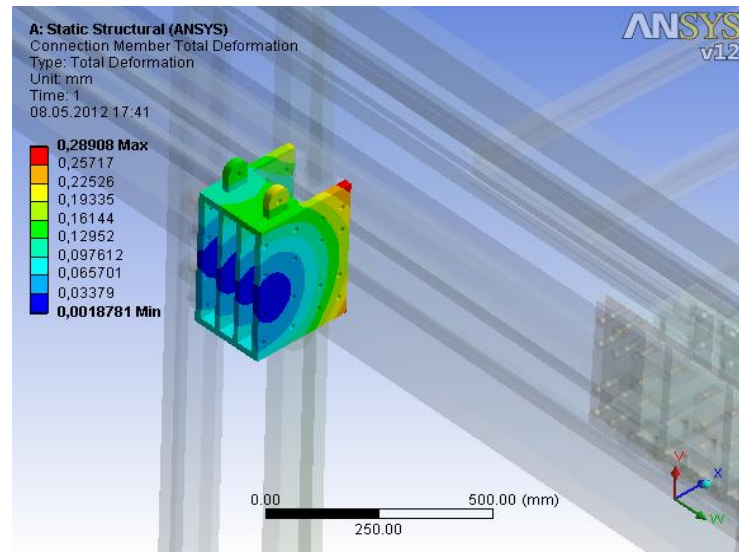


Figure IV.1.15: Total deformation on the connection member

IV.1.4 Static Analysis of the Vertical Channel

Palette, arm, horizontal channel and connection member have been analyzed and now vertical channel will be analyzed. Figure IV.1.16 shows the total system with the vertical channel. Forces are applied to the palette and loads due to weights

of the all components are considered. During analysis, both ends of the vertical channel are assumed as fixed.

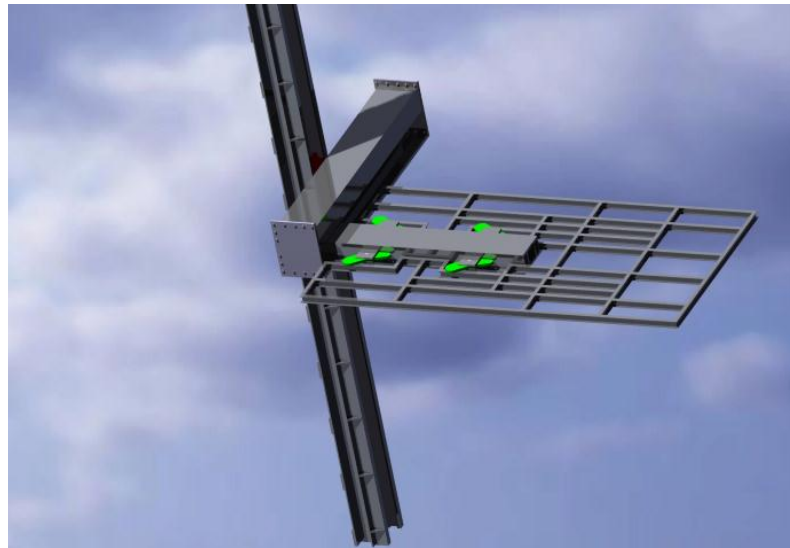


Figure IV.1.16: System with the vertical channel

Results achieved from the static analysis are shown in Figure IV.1.17 and Figure IV.1.18. Bearing in mind the results of the analysis, it can be said that the vertical channel is considerably strong. It is constructed from I beams and steel plates used to connect two I beams to each other. Material grades of I beams and steel plates are respectively St 44-2 and St 52. Maximum equivalent stress is 28,472 MPa and it is well below of the yield strenghts of the St 44-2 and St 52. Maximum stress occurred at the near of the midpoint of the channel. As seen from Figure IV.1.18 total deformation is 0,427 mm. Total weight of the vertical channel is 2380 kg.

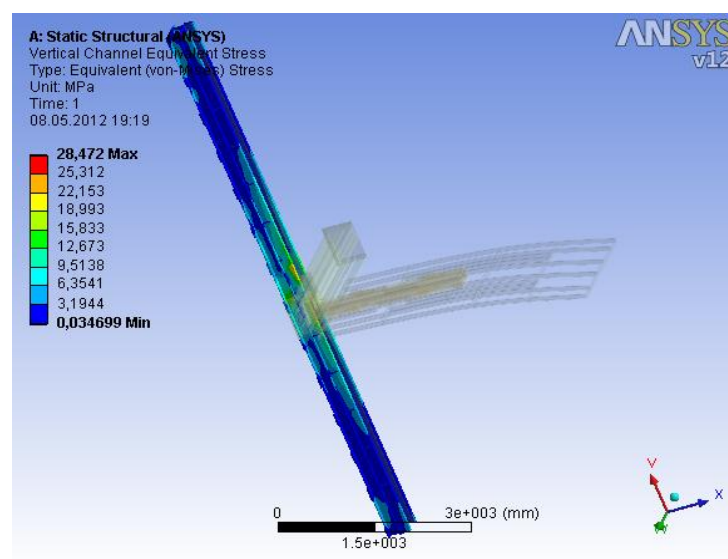


Figure IV.1.17: Equivalent stress on the vertical channel

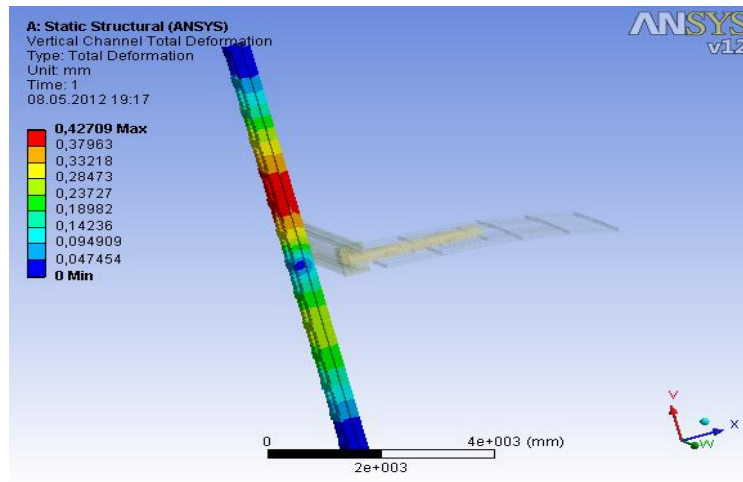


Figure IV.1.18: Total deformation on the vertical channel

IV.1.5 Static Analysis of the Frame Cells

As it is indicated in DP₁₁ there are cells on the frame to put cars on. These cells have platforms and palette, on which there will be car, will be put on these platforms. As a result of the palette's and car's weight, some forces such in palette analysis will act on the frame. Analysis results for the platform are seen in Figure IV.1.19 and Figure IV.1.20. Maximum equivalent stress is 67,85 MPa and maximum deformation is 12,41 mm. Platform are made from St44-2 grade steel and its total weight is 640 kg.

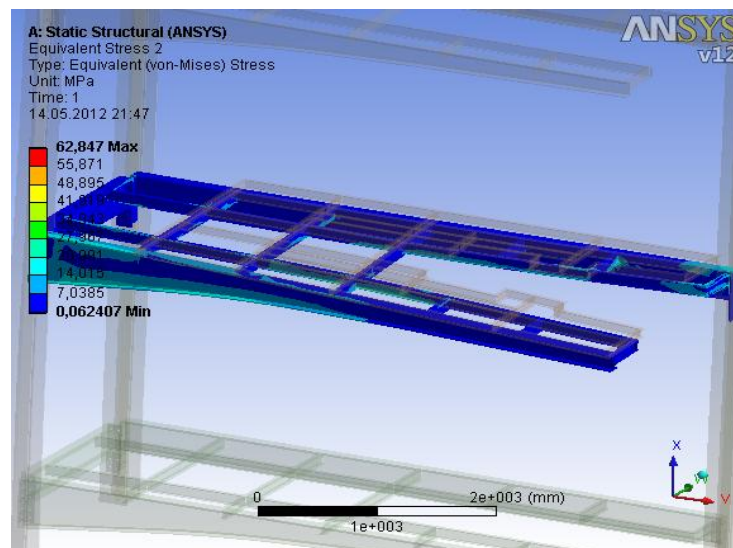


Figure IV.1.19: Equivalent stress on the cell platform

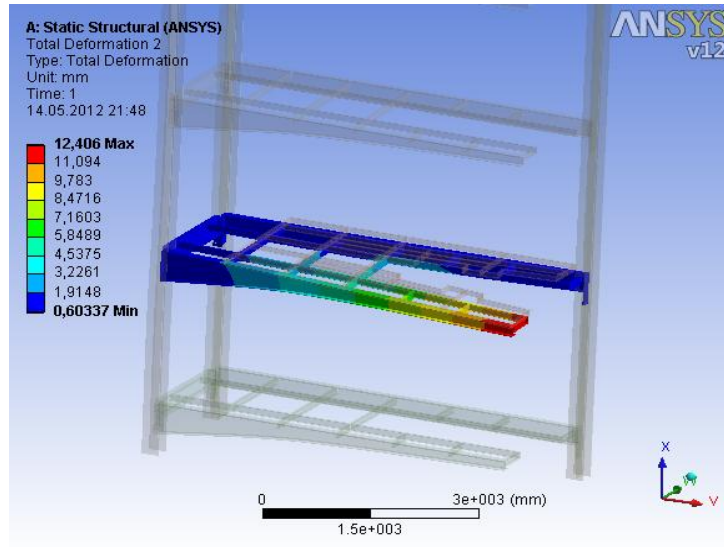


Figure IV.1.20: Total deformation on the cell platform

IV.2 CALCULATIONS AND SELECTIONS OF THE MECHANICAL COMPONENTS

IV.2.1 Vertically Moving Mechanism Calculations

In this part, wire rope, drum, electric motor for vertical movement and reducer calculations and selection will be performed.

IV.2.1.1 Wire Rope and Drum Calculations

Firstly diameter and properties of wire rope will be determined and then using these information, dimensions of the drum will be determined. Equation (IV.2.1) is used to determine wire rope diameter.

$$d_{Ha} \geq k\sqrt{F_{Ha}} \text{ (mm)} \quad (\text{IV.2.1})$$

where k is a factor according to drive system and wire rope type, F_{Ha} is force acting on the each wire rope. k factor is selected from Table IV.2.1.

Table IV.2.1: k factor selection table [Cürgül, 1995]

Drive system	Round cordon wire rope	Elliptical or triangular cordon wire rope
1B _m	0,265	0,280
1A _m	0,280	0,300
2 _m	0,300	0,335
3 _m	0,335	0,375
4 _m	0,375	0,425
5 _m	0,425	0,475

In Table IV.2.1, there is a term as drive system and to determine drive system a new table is used. Table IV.2.2 gives information about the drive systems. Working hour per day is selected between 2 and 4 hours for the mechanical car parking system and load distribution is chosen as normal. Using these information, drive system is determined as 2_m, and from Table IV.2.1, k factor is selected as 0,300, because round cordon wire rope is used.

Table IV.2.2: Drive system selection table

Operating time class	Symbol			V ₀₀₆	V ₀₁₂	V ₀₂₅	V ₀₅	V ₁	V ₂	V ₃	V ₄	V ₅
	Average working hour per day considering in a year			≤0,125	>0,125 ≤0, 25	>0,25 ≤0, 5	>0,5 ≤1	>1 ≤2	>2 ≤4	>4 ≤8	>8 ≤16	>16
Load distributions	No	Specification	Description	Drive class								
	1	Light	Rarely maximum load	1E _m	1E _m	1D _m	1C _m	1B _m	1A _m	2 _m	3 _m	4 _m
	2	Normal	Maximum load is equal to light and normal loads	1E _m	1D _m	1C _m	1B _m	1A _m	2_m	3 _m	4 _m	5 _m
	3	Heavy	Always nearly maximum loads	1D _m	1C _m	1B _m	1A _m	2 _m	3 _m	4 _m	5 _m	5 _m

F_{Ha} value is required to be able to calculate wire rope diameter. Formula for finding F_{Ha} is like below.

$$F_{Ha} = \frac{Q+W}{Z} \quad (IV.2.2)$$

where Q is capacity of the lifting system, W is the total weights of the palette, arm, and horizontal channel and Z is number of wire ropes. Units of Q and W are kg. Lifting capacity of the vertical moving mechanism is 2000 kg and W is 3000 kg. Two wire ropes will be used in the system. So, F_{Ha} is calculated as

$$F_{Ha} = \frac{2000 + 3000}{2} = 2500kg$$

Putting F_{Ha} in the Equation (IV.2.1)

$$d_{Ha} \geq 0.300\sqrt{2500} = 15mm$$

Wire rope diameter is calculated as 15 mm but it is chosen as 16mm, and drum dimensions will be determined according to this diameter. Some figures and tables that are used during calculations are given below. D_{Ta} in Figure IV.2.2 is drum diameter and formula to calculate it is

$$D_{Ta} \geq h_1 h_2 d_{Ha} \quad (mm) \quad (IV.2.3)$$

where h_1 and h_2 are constants and their values are respectively 14 and 1. Putting into these values in Equation (IV.2.3), drum diameter is calculated as

$$D_{Ta} \geq 14.1.16 = 224 \text{ mm}$$

Drum diameter must be greater than or equal to 224 mm and it is chosen as 225 mm. As seen in Figure IV.2.1 there are grooves on the drum and dimensions of these grooves are given below.

$$a = 6 \text{ mm} \quad (\text{from Figure IV.2.1 and Table IV.2.3})$$

$$h = 9 \text{ mm} \quad (\text{from Figure IV.2.2 and Table IV.2.4})$$

$$R_{Yi} = 8,5 \text{ mm} \quad (\text{from Figure IV.2.1 and Table IV.2.3})$$

$$p_{Yi} = 18 \text{ mm} \quad (\text{from Figure IV.2.1 and Table IV.2.3})$$

$$R_1 = 0,8 \text{ mm} \quad (\text{from Figure IV.2.1 and Table IV.2.3})$$

Clamp screw: 3XM12 screws (from Figure IV.2.2 and Table IV.2.5)

$$u = 1,5p_{Yi} = 1,5.18 = 27 \text{ mm} \quad (IV.2.4)$$

where u is distance between first wire rope and side disc. (from Figure IV.2.2 and Table IV.2.5)

$$x = p_{Yi} + Mx + 2mm = 18 + 12 + 2 = 32 \text{ mm} \quad (IV.2.5)$$

where x is distance between two wire ropes tighten by plate. (from Figure IV.2.2 and Table IV.2.5).

$$u_1 = u + v + 2p_{Yi} = 27 + 32 + 2.18 = 95 \text{ mm} \quad (\text{IV.2.6})$$

where u_1 is distance between side disc and last idle wire rope. (from Figure IV.2.2 and Table IV.2.5).

$$a_p \geq M_x = 12 \text{ mm} \quad (\text{IV.2.7})$$

(from Figure IV.2.2 and Table IV.2.5)

$$b_p \geq v + d_{Ha} + 2 = 32 + 16 + 2 = 50 \text{ mm} \quad (\text{IV.2.8})$$

where b_p is width of the tighten plate. Its length is also 48 mm. (from Figure IV.2.2 and Table IV.2.5).

$$a_{top} = a_p + a = 12 + 6 = 18 \text{ mm} \quad (\text{IV.2.9})$$

where a_{top} is thickness of the tighten plate. (from Figure IV.2.2 and Table IV.2.5)

$$s \geq 2d_{Ha} = 2.16 = 32 \text{ mm} \quad (\text{IV.2.10})$$

Using this value, diameter of the side disc is calculated as

$$D_{disc} = D_{Ta} + 2m = 225 + 2.32 = 289 \text{ mm} \quad (\text{IV.2.11})$$

$w \approx d_{Ha} = 16 \text{ mm}$, where w is thickness of the side disc and it is selected as 15 mm

Required grooves number is calculated using following formula

$$n_{Yi} = \frac{H}{\pi D_{Ta}} \quad (\text{IV.2.12})$$

where H is distance between ground level and the drum. H is 10 m and D_{Ta} is 0,225 m. Putting these values in Equation (IV.2.12)

$$n_{Yi} = \frac{10}{\pi \cdot 0.225} = 14,15 \text{ } n_{Yi} \text{ must be an integer number and it is 15.}$$

Distance between two wire ropes is calculated using following formula

$$L_{He} = 0,5d = 0,5 * 225 = 112.5 \text{ mm} \quad (\text{IV.2.13})$$

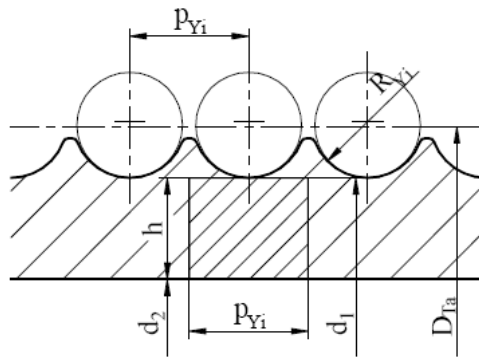


Figure IV.2.1: Recommended dimensions for drum [Kutay, 2011]

Table IV.2.3: Recommended dimensions for drum [Kutay, 2011]

d_{Ha}	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
R_{Yi}	1,6	2,2	2,7	3,2	3,7	4,2	4,8	5,3	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5
ΔR_{Yi}	+0,1								+0,2									
p_{Yi}	4	5	6	7	8	9,5	10,5	11,5	13	14	15	16	17	18	19	20	21	22
$a^{*)1}$	1,2	1,5	1,9	2,3	2,7	3,0	3,5	4	4,5	4,5	5	5,5	6	6	6,5	7	7,5	7,5
$R1$	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8

$*)1 \quad "a \geq 0,375 \cdot d_{Ha} "$

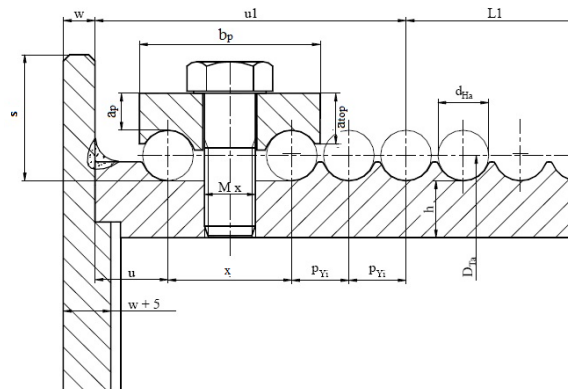


Figure IV.2.2: Drum dimensions [Kutay, 2011]

Table IV.2.4: Recommended dimensions for drum wall thickness “h” [Kutay, 2011]

F_{Hb} kN	d_{Hb} mm	p_{Yi} mm	D_{Ta} mm					
			250	300 (315)	400	500	600 (630)	700 (710)
≤ 5	≤ 8	9,5	4 (6)	4 (6)				
≤ 10	≤ 10	12	6 (9)	6 (9)				
≤ 15	≤ 13	15		8 (12)	7 (12)			
≤ 20	≤ 16	18		9 (14)	8 (13)			
≤ 25	≤ 16	18			10 (15)	10 (12)		
≤ 30	≤ 19	22			11 (16)	11 (16)		
≤ 40	≤ 22	25				12 (18)	14 (20)	
≤ 50	≤ 24	27				14 (20)	15 (22)	
≤ 60	≤ 27	31					16 (24)	14 (22)
≤ 70	≤ 29	33						16 (24)
≤ 80	≤ 31	35						17 (26)
≤ 90	≤ 31	35						19 (27)
≤ 100	≤ 33	37						19 (27)

Table IV.2.5: Recommended dimensions for clamp screw [Kutay, 2011]

D_{Ta} mm	250	280 315	355 400	450 500	560 630	710	800
Mx	3xM12	3xM12	3xM12	3xM16	3xM16	3xM16	3xM20
$v = p_{Yi} + Mx + 2mm$							
$u \geq 1,5 \cdot p_{Yi}$							
$u_1 = u + v + 2 \cdot p_{Yi}$							
$a \geq d_{Ha}$							
$b = v + d_{Ha} + 2mm$							

Final design for the drum is seen in Figure IV.2.3. Drum is manufactured from St 37 grade steel.

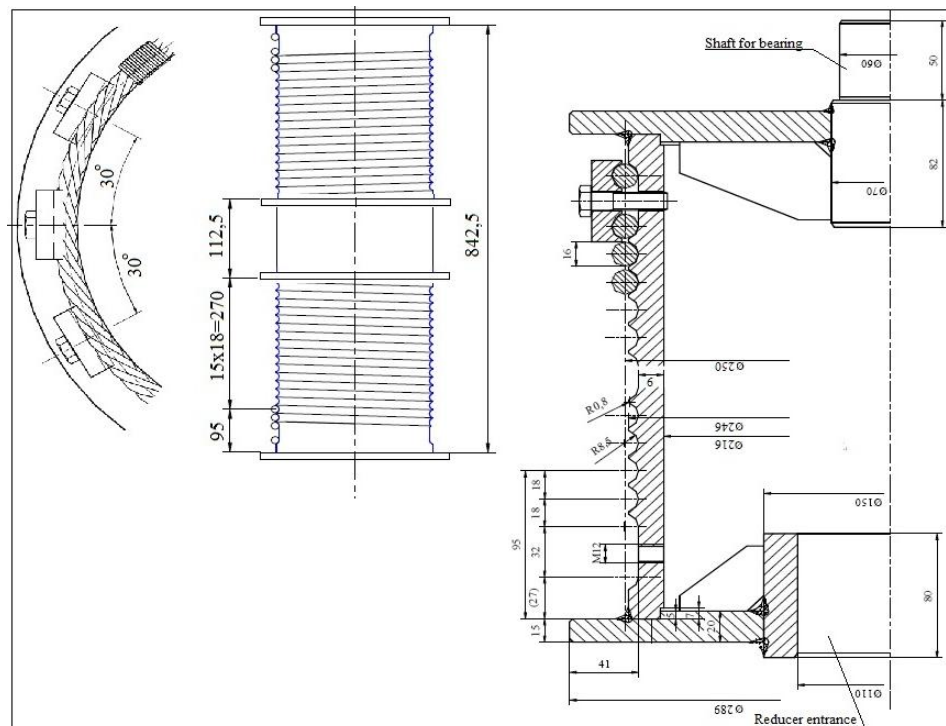


Figure IV.2.3: Final design for the drum

One end of the drum will be mounted to the bearing and the other end will be mounted to the reducer. To select bearing, firstly, dynamic load rating will be calculated and then a bearing will be selected using this rating. Formula to calculate dynamic load rating is

$$C = \frac{q}{\sqrt{\frac{L_{10}h60nP^q}{10^6}}} \quad (\text{IV.2.14})$$

where n is rotational speed (r/min), L_{10h} is basic rated life (millions of revolutions), q is exponent of the life equation and P is equivalent dynamic bearing load (N). L_{10h} is taken between 20000 and 30000 hours for cranes and lifting machines. Upper limit,

30000 hour that is to say, of the L_{10h} is selected for the system. p value for ball bearings and roller bearings are respectively 3 and 3,3 and P is 50000 N. To calculate n value, lifting speed of the system should be determined. Lifting speed for mechanical car parking system is generally between 6 m/min and 7 m/min and it is selected as 6,5 m/min for our system. n is calculated with following formula

$$n = \frac{V}{C_{Ta}} \quad (\text{IV.2.15})$$

where V is lifting speed of the system (m/min) and C_{Ta} is circumference of the drum.

n is calculated as $n = \frac{6,5}{\pi 0,25} = 8,3 \text{ r/min}$. So now, C can be calculated.

$$C = \sqrt[3,3]{\frac{30000 \cdot 60 \cdot 8,3 \cdot 50000^{3,3}}{10^6}} = 113457 \text{ N}$$

To provide easy assembly, a bearing unit will be selected from catalogue. FAG-SNV110 bearing unit is selected and it contains FAG-22212E1 spherical roller bearing with 160000 N dynamic load rating. Drawings and properties of the bearing unit and bearing are given in Figure IV.2.4.

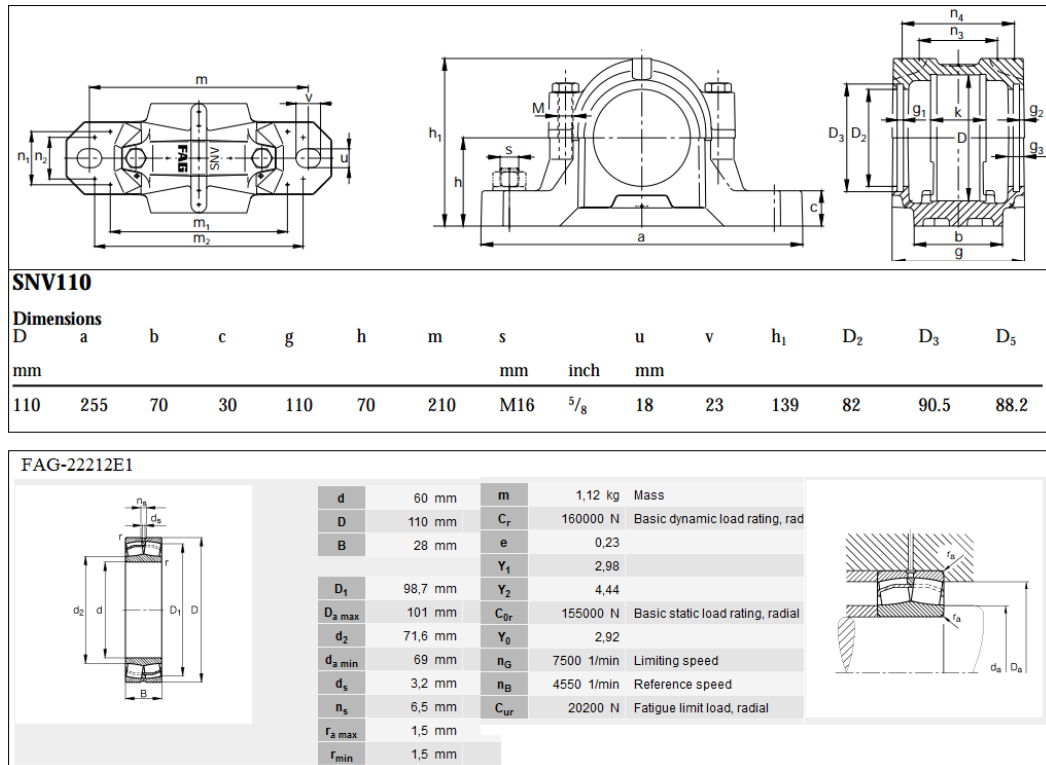


Figure IV.2.4: Bearing and bearing unit for drum.

IV.2.1.2 Electric Motor and Reducer Calculations and Selections for Wire Rope System

To determine properties of the electric motor, it should be calculated that how much power it must generate. Following formula is used to calculate power requirement.

$$P_m = \frac{Q_{total}V}{6120h_{eff.}} \quad (kW) \quad (IV.2.16)$$

where Q_{total} is the total weight includes weights of car, palette, arm and horizontal channel, V is lifting velocity and in m/min, $h_{eff.}$ is efficiency of the electric motor and it is taken 0,95 for rolling bearings. For our system Q_{total} is 5000kg and V is selected as 6,5 m/min. Using these values P_m is calculated as

$$P_m = \frac{5000.6,5}{6120.0,95} = 5,6 \text{ kW}$$

From catalogue 7,5kW, 1000 r/min, NM 160M-6 type electric motor is selected. Table shows the properties of the electric motor.

Table IV.2.6: Properties of the electric motor for wire rope system [Emtaş, 2011]

NM 132M-6	5,5	7,5	12,7 Δ	952	0,80	82	55,2	6,7	2,4	3,0	0,0420	80
NM 160M-6	7,5	10	15,8 Δ	964	0,84	86	74,3	6,8	2,6	2,8	0,0776	115
NM 160L-6	11	15	22,6 Δ	957	0,86	86	109,8	6,0	2,4	2,9	0,1085	140
NM 180L-6	15	20	29,4 Δ	967	0,86	90	148,1	6,8	2,3	3,4	0,1636	192
NM 200L-6	18,5	25	38,0 Δ	972	0,84	88	181,8	6,0	2,0	3,4	0,2291	242
Motor type	P			Rated speed								

Rotational speed of the drum is calculated as 8,3 r/min, but rated speed of the electric motor is 964 r/min. So, a reducer will be used with a reduction ratio of $964/8,3=116,14$. From catalogue KH3200 reducer is selected. Its properties and dimensions are given in Figure IV.2.5.

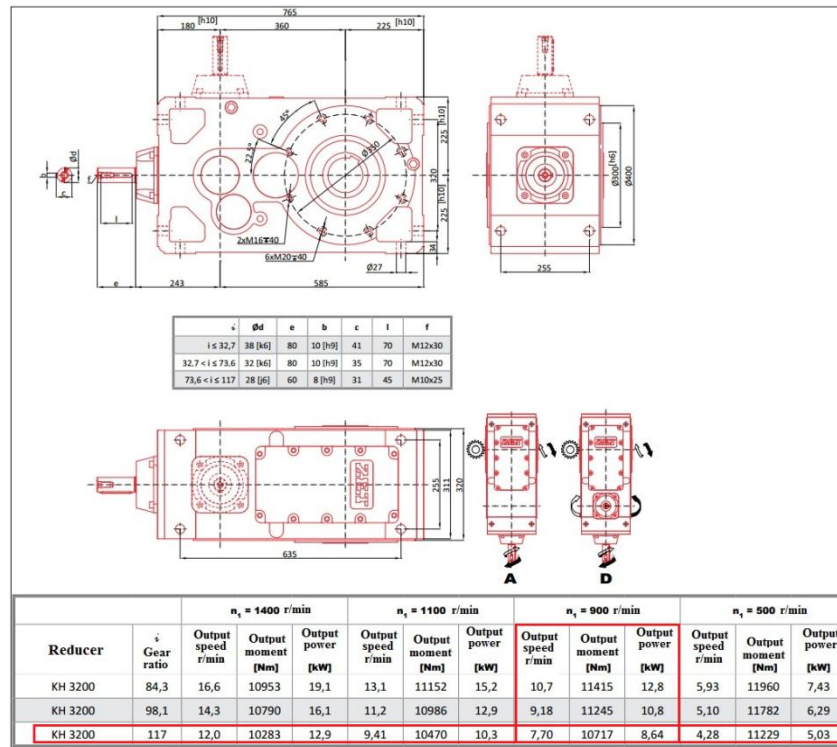


Figure IV.2.5: Properties and dimension of the reducer for wire rope system [Zet, 2012]

IV.2.2 Slewing Unit Calculations

Slewing unit includes pinion, internal gear, electric motor and reducer.

IV.2.2.1 Internal Gear and Pinion Selection

Velocity ratio for internal gear and pinion set is $\frac{N_p}{N_G}$, where N_p is teeth number of the pinion and N_G is teeth number of the gear. Velocity ratio is wanted to be $1/2$ and as pinion, a gear is selected with 20 teeth and 5 gear module. Since velocity ratio will be $1/2$, internal gear will have 40 teeth. Dimensions of the pinion and internal gear are given in Figure IV.2.6. E value is 50 mm in Figure IV.2.6.

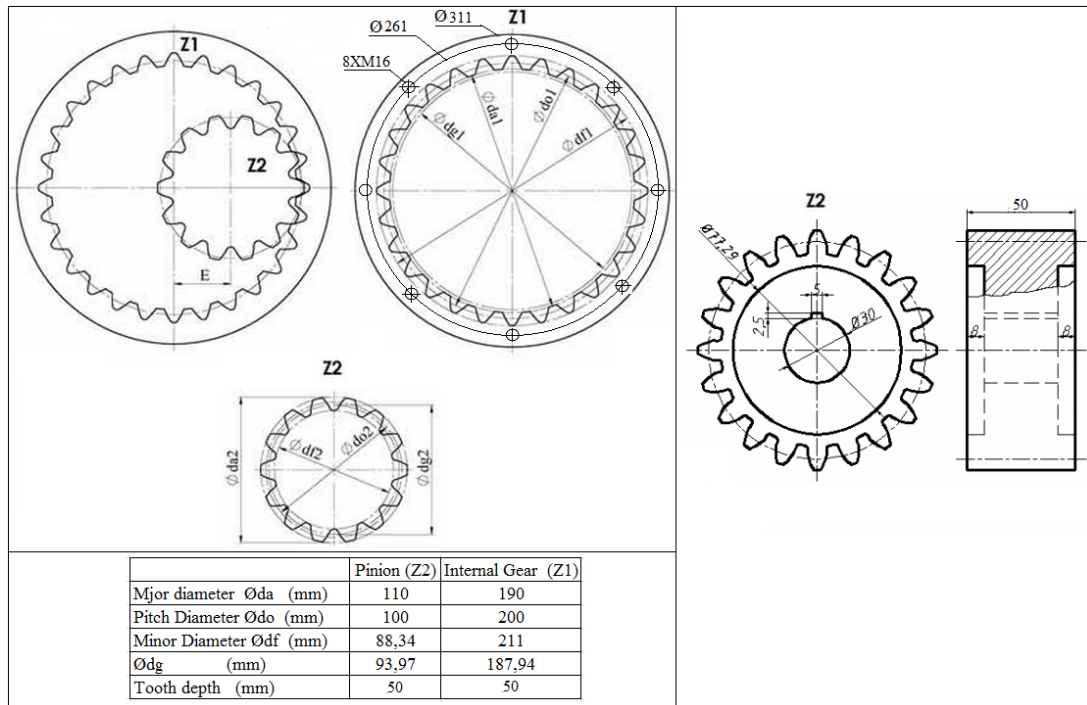


Figure IV.2.6: Pinion and internal gear for slewing unit

IV.2.2.2 Electric Motor and Reducer Selections for Slewing Unit

Vertical channel will be rotated 180° and when it rotates there will not palette and any car on it. This situation will reduce moment torque requirement. So, it is not necessary to select a powerful electric motor such in wire rope system. From catalogue *4kW, 1000 r/min, NM 132M-6 type electric motor* is selected.

Table IV.2.7: Properties of the electric motor for slewing unit [Emtaş, 2011]

NM 132S-6	3	4	6,9 Δ	952	0,80	82	30,1	6,4	2,4	2,6	0,0299	65
NM 132M-6	4	5,5	8,7 Δ	956	0,84	83	40,0	6,7	2,4	3,0	0,0356	73
NM 132M-6/	5,5	7,5	12,7 Δ	952	0,80	82	55,2	6,7	2,4	3,0	0,0420	80
NM 160M-6	7,5	10	15,8 Δ	964	0,84	86	74,3	6,8	2,6	2,8	0,0776	115
NM 160L-6	11	15	22,6 Δ	957	0,86	86	109,8	6,0	2,4	2,9	0,1085	140
Motor type	P											

Vertical channel is wanted to complete its rotation in 10 seconds. It means that rotational speed of the internal gear is $60/10=6$ r/min. Velocity ratio for pinion and internal gear is $\frac{1}{2}$. So, rotational speed of the pinion is $2 \times 6=12$ r/min. Rated speed of the electric motor is 958 r/min. For this reason, a reducer will be used with a reduction ratio of $958/12=79,83$. From catalogue *KH3160 reducer* is selected.

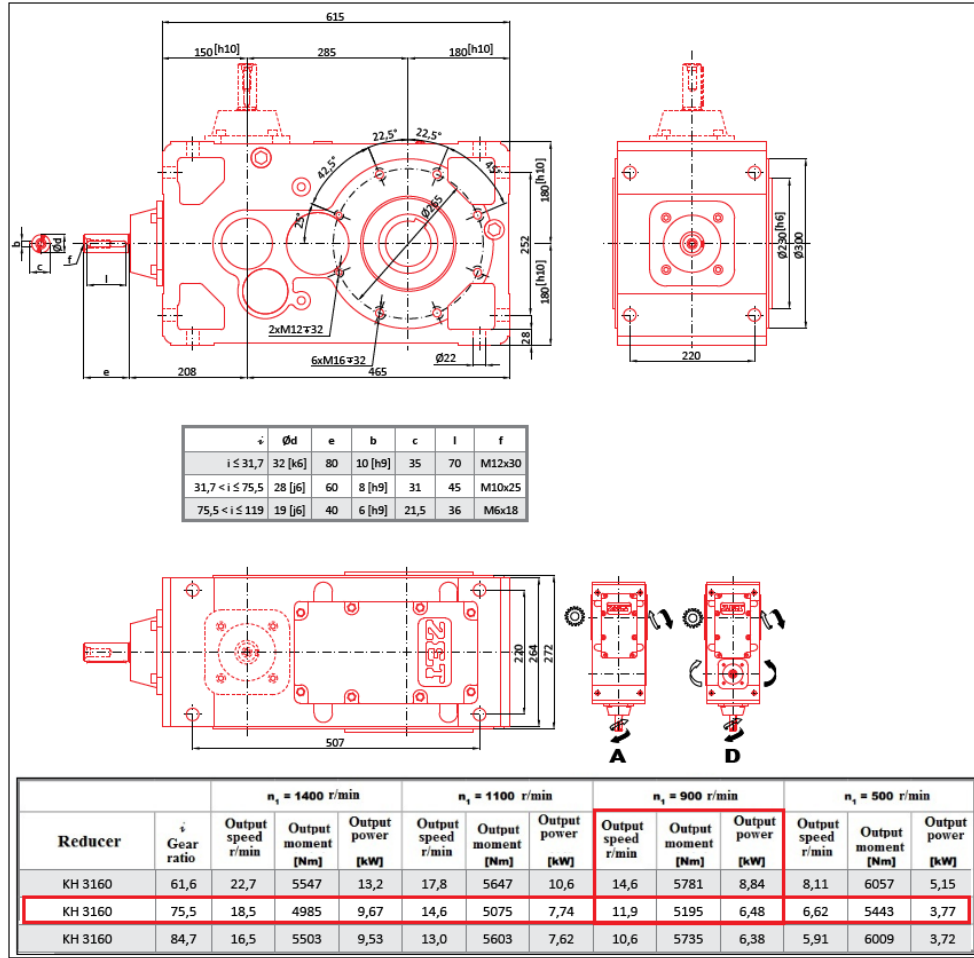


Figure IV.2.7: Properties and dimension of the reducer for the slewing unit [Zet, 2012]

IV.2.2.3 Bearing Calculations for Vertical Channel

There will be bearings at both ends of the vertical channel as indicated in DP₂₂₁₄₂₄. These bearings will be subjected to radial and axial loadings. Figure IV.2.8 shows the loading condition for the vertical channel. F_1 is total weight of the car, palette, arm and horizontal channel and F_2 is weight of the vertical channel. A and B points are where bearings are located. Calculations will be performed for only A point and same bearing will be used at B point also. F_1 is 50000 N and x will be taken as 2 m. L is total length of the vertical channel and it is 10 m. Radial load acting at point A is calculated using following formula.

$$R_A = \left[\left(\frac{F_1 x}{L} \right)^2 + \left(\frac{F_2}{2} \right)^2 \right]^{1/2} \quad (\text{IV.2.17})$$

$$R_A = \left[\left(\frac{50000 \cdot 2}{10} \right)^2 + \left(\frac{F_2}{2} \right)^2 \right]^{1/2} = 10000 \text{ N}$$

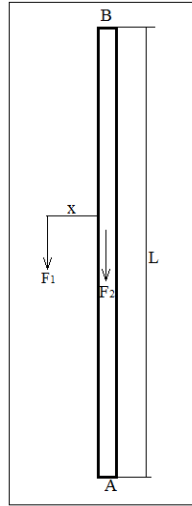


Figure IV.2.8: Loading condition for the vertical channel

Table IV.2.8: Dynamic equivalent radial load equations for P

Thrust Condition	Equivalent Radial Load
$\frac{0.5R_A}{Y_A} < \frac{0.5R_B}{Y_B} + (F_a)_A$	$P_A = 0.4R_A + Y_A \left(\frac{0.5R_B}{Y_B} + (F_a)_A \right)$ $P_B = R_B$
$\frac{0.5R_A}{Y_A} > \frac{0.5R_B}{Y_B} + (F_a)_A$	$P_A = R_A$ $P_B = 0.4R_B + Y_B \left(\frac{0.5R_A}{Y_A} - (F_a)_A \right)$

where P_A =equivalent radial load on bearing A

P_B =equivalent radial load on bearing B

R_A = applied radial load on bearing A

R_B = applied radial load on bearing B

$(F_a)_A$ = thrust load on bearing A

Y_A = thrust factor for bearing A from catalogue

Y_B = thrust factor for bearing B from catalogue

Formulas used to select appropriate bearing are given in Table IV.2.8. R_A is calculated as 10000 N and R_B is equal to R_A . $(F_a)_A$ is total weight of the system includes weight of the vertical channel and its value is 70000 N. Shaft diameter will be 120 mm and desired life will be taken as 30000 hours such in drum bearing. The shaft speed is equal to pinion speed and it is 12r/min. Let's use $Y_A = Y_B = 1,91$.

$$\frac{0,5R_A}{Y_A} <? > \frac{0,5R_B}{Y_B} + F_{aA}$$

$$\frac{0,5.10000}{1,91} <? > \frac{0,5.10000}{1,91} + 70000$$

2617 < 72617 the top row of Table IV.2.8 applies.

$$P_A = 0,4.10000 + 1,91 \left(\frac{0,5.10000}{1,91} + 70000 \right) = 142698N$$

Now dynamic load rating should be calculated using Equation (IV.2.14)

$$C = \sqrt[3,33]{\frac{30000.60.12.142698^{3,33}}{10^6}} = 358873N$$

From catalogue we can choose FAG-32224A tapered roller bearing for both A and B points, with $d=120$ mm, $D=215$ mm, $C=490000$ N and $Y=1,38$.

Now we will recompute the equivalent loads and dynamic load rating to check if the selected bearing is satisfactory or not.

$$P_A = 0,4.10000 + 1,38 \left(\frac{0,5.10000}{1,38} + 70000 \right) = 105600N$$

$$C = \sqrt[3,33]{\frac{30000.60.12.105600^{3,33}}{10^6}} = 265705N$$

New value of C is still satisfactory for selected bearing. So, *FAG-32224A tapered roller bearing* will be used for both ends.

IV.2.3 Horizontally Moving Mechanism Calculations

Horizontally moving mechanism contains rack and pinion, electric motor and reducer. Calculations and selection about these components are performed in this section.

IV.2.3.1 Rack and Pinion Calculations and Selections

Rack and pinion system will carry palette, car and arm. Therefore, total weight that system should be able to carry is 3500 kg. Following formulas are used for calculations.

$$a = \frac{v}{t_b} \quad (\text{m/s}^2) \quad (\text{IV.2.18})$$

$$F_u = \frac{mg\mu + ma}{1000} \quad (\text{kN}) \quad (\text{IV.2.19})$$

$$F_{u \text{ perm.}} = \frac{F_u T_{ab}}{K_A S_B f_n L_{KHB}} \quad (\text{kN}) \quad (\text{IV.2.20})$$

$$F_u < F_{u \text{ perm.}} \text{ must be fulfilled} \quad (\text{IV.2.21})$$

where F_u = Tangential force

m = mass to be moved (kg)

v = speed (m/s)

t_b = acceleration time (s)

g = acceleration due to gravity (m/s^2)

μ = coefficient of friction

K_A = Load factor

F_n = life time factor

S_f = safety coefficient

L_{KHB} = Linear load distribution factor

Speed and acceleration time will be selected respectively 0,1m/s and 1s. Load factor for uniform drive and medium shock is selected as 1,25 from Table IV.2.9. Safety coefficient is 1,3 and life time factor is 0,95 from Table IV.2.10. Linear load distribution factor and friction coefficient are respectively 1,5 and 0,1. Using these values F_u will be calculated and from catalogue a pinion will be selected to determine $F_u T_{ab}$. Then, $F_{u \text{ perm.}}$ will be calculated to check whether it violates Equation (IV.2.21) or not.

Table IV.2.9: Load factor selection table [Atlanta, 2012]

Drive	Type of load from the machines to be driven		
	Uniform	Medium Shocks	Heavy Shocks
Uniform	1.00	1.25	1.75
Light Shocks	1.25	1.50	2.00
Medium Shocks	1.50	1.75	2.25

Table IV.2.10: Life time factor selection table [Atlanta, 2012]

Lubrication		Continuous	Daily	Monthly
Peripheral Speed of Gearing				
m/sec	m/min			
0.5	30	0.85	0.95	from 3 to 10
1.0	60	0.95	1.10	
1.5	90	1.00	1.20	
2.0	120	1.05	1.30	
3.0	180	1.10	1.50	
5.0	300	1.25	1.90	

$$a = \frac{0,1}{1} = 0,1 \text{ m/s}^2$$

$$F_u = \frac{3500.9,81.0,1 + 3500.0,1}{1000} = 3,78 \text{ kN}$$

Table IV.2.11: Rack and pinion selection table [Atlanta, 2012]

Rack		UHPR	HPR			PR			BR			
Quality		5	6		7	8			9		10	
Rack	Material	16MnCr5	16MnCr5	C45	C45	C45	42CrMo4		C45		C45	
	Heat Treatment	Case Hardened	Induction Hardened		Ind. Hardened	Ind. Hardened	Quenched + Tempered		Soft		Induction Hardened	
Pinion	Material	16MnCr5	16MnCr5	16MnCr5	16MnCr5	16MnCr5	16MnCr5	C45	16MnCr5	C45	16MnCr5	C45
	Heat Treatment	Case Hardened	Case Hardened	Case Hardened	Case Hardened	Case Hardened	Case Hardened	Ind. Hardened	Case Hardened	Soft	Case Hardened	Ind. Hardened
No. of Pinion Teeth ¹⁾	Pitch Circle Dia.	Maximum Feed Force										
12	36 mm	6.5 kN	6.5 kN	6.5 kN	6.5 kN	6.0 kN	2.5 kN	2.5 kN	1.5 kN	0.7 kN	5.5 kN	3.5 kN
13	39 mm	7.5 kN	7.5 kN	7.5 kN	7.5 kN	7.0 kN	3.0 kN	2.5 kN	1.5 kN	0.9 kN	6.5 kN	4.0 kN
14	42 mm	9.5 kN	9.5 kN	9.5 kN	9.5 kN	8.5 kN	3.5 kN	3.0 kN	2.0 kN	1.0 kN	8.0 kN	4.5 kN
15	45 mm	11.0 kN	11.0 kN	10.5 kN	10.5 kN	9.5 kN	4.0 kN	3.0 kN	2.0 kN	1.0 kN	8.5 kN	5.5 kN
16	48 mm	12.5 kN	12.5 kN	12.0 kN	11.5 kN	10.5 kN	4.0 kN	3.5 kN	2.0 kN	1.0 kN	9.5 kN	6.0 kN
17	51 mm	14.5 kN	14.5 kN	13.5 kN	13.5 kN	12.0 kN	5.0 kN	4.0 kN	2.5 kN	1.5 kN	10.0 kN	6.5 kN
18	54 mm	16.0 kN	16.0 kN	14.0 kN	14.0 kN	13.0 kN	5.0 kN	4.5 kN	2.5 kN	1.5 kN	10.5 kN	7.0 kN
19	57 mm	17.5 kN	17.5 kN	15.0 kN	15.0 kN	13.5 kN	5.5 kN	4.5 kN	3.0 kN	1.5 kN	11.0 kN	8.0 kN
20	60 mm	18.5 kN	18.5 kN	16.0 kN	16.0 kN	14.5 kN	5.5 kN	5.0 kN	3.0 kN	2.0 kN	11.5 kN	8.5 kN

From Table IV.2.11, a straight tooth pinion with 5 module and made from 16MnCr5 material is selected and its $F_{u \text{ Tab}}$ is 18,5kN. $F_{u \text{ perm.}}$ is calculated as

$$F_{u \text{ perm.}} = \frac{18,5}{1,25.1,3.0,95.1,5} = 7,99 \text{ kN}$$

$F_u < F_{u \text{ perm.}}$ condition is satisfied. Properties and dimensions of the selected rack and pinion are given in Figure IV.2.9.

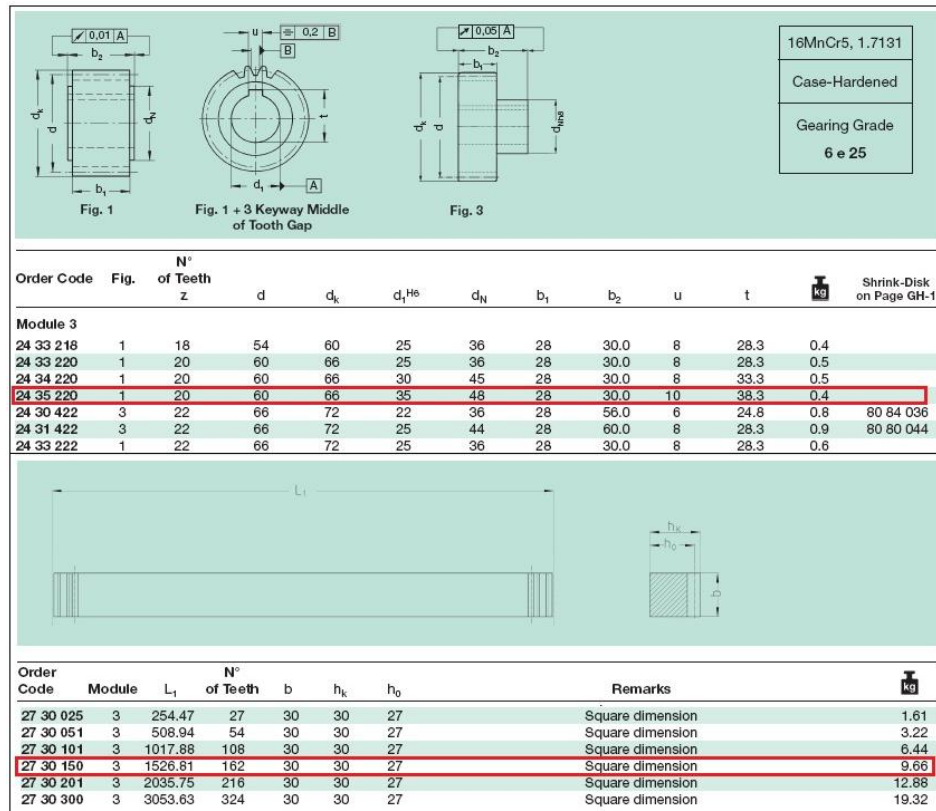


Figure IV.2.9: Properties of selected rack and pinion [Atlanta, 2012]

IV.2.3.2 Electric Motor and Reducer Selections for Horizontally Moving Mechanism

For horizontally moving mechanism tangential force has been calculated as 3,78kN. An electric motor with 1000 rpm and 2 kW power will be suitable for moving cars horizontally.

Table IV.2.12: Properties of the electric motor for horizontally moving mechanism [Emtaş, 2011]

NM 90L-6	1,1	1,5	3,1	907	0,77	70	11,6	3,8	1,8	1,9	0,0045	21
NM 100L-6	1,5	2	3,9	940	0,77	76	15,2	4,8	2,3	2,3	0,0094	30
NM 112M-6	2,2	3	5,6	940	0,78	77	22,4	5,3	2,5	2,6	0,0161	44
NM 132S-6	3	4	6,9	952	0,80	82	30,1	6,4	2,4	2,6	0,0299	65

Output speed of the electric motor is 940 rpm and it should be reduced to the desired value. Total length of the horizontal channel is 2500 m and numbers of teeth of the rack in 1526 mm length are 162. It means that, there are 265 teeth in 2500 mm length. Revolution number of the pinion to travel 2500 mm distance is calculated as *number of rack/number of pinion*=13,25 and it should take this distance in 20 seconds. So, speed of the pinion is 13,25x3=39,75 rpm. Output speed of the electric

motor must be reduced to 39,75 rpm and this process will be done by a reducer with 24,64 reduction ratio. *KH 2080 reducer* is selected from catalogue. Properties and dimensions of the reducer are given in Figure IV.2.10.

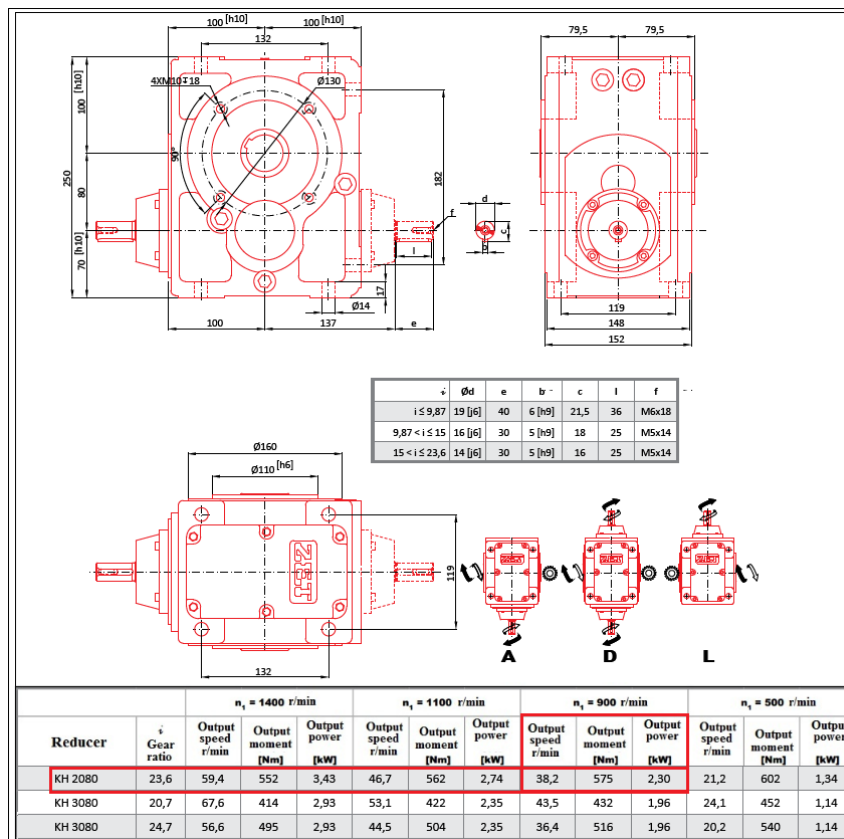


Figure IV.2.10: Properties and dimension of the reducer for the horizontally moving mechanism [Zet, 2012]

IV.2.4 Locking Mechanism Calculations

Servo motor, reducer and lead screw mechanism calculations will be performed in this section.

IV.2.4.1 Servo Motor and Reducer Selection

Servo motor will not be exposed to any moment or force, because as it seen from Figure III.2.33, it will just lock and unlock the four steel plates. From Anaheim Automation catalogue, 200 W, *EMJ-02APA22 servo motor* with 3000 rpm speed and 0.64 Nm output torque is selected. 3000 rpm speed must be reduced to a lower speed value and Table IV.2.13 shows the properties of the reducer chosen for this purpose. Reduction ratio of the reducer is 100 and it means that output speed will be $3000/100=30$ rpm.

Table IV.2.13: Properties of the reducer for the locking mechanism [Apex, 2012]

Model No.	Stages	Ratio	PE050	PE070	PE090	PE120	PE155
Nominal Output Torque T_{2N}	1	3	14	39	104	215	423
		4	12	31	85	176	364
		5	14	39	104	215	423
		7	12	33	91	195	358
		10	9	26	65	150	293
		15	14	39	104	215	423
		16	12	31	85	176	364
		20	12	31	85	176	364
		25	14	39	104	215	423
	2	30	14	39	104	215	423
		35	12	33	91	195	358
		40	12	31	85	176	364
		50	14	39	104	215	423
		70	12	33	91	195	358
		100	9	26	65	150	293
Emergency Stop Torque T_{2NOT}^2	Nm	1,2	3~100	3 times of Nominal Output Torque			
Nominal Input Speed n_{1N}	rpm	1,2	3~100	4,500	4,000	3,600	2,500
Max. Input Speed n_{1B}	rpm	1,2	3~100	8,000	6,000	6,000	4,800
Backlash*	arcmin	1	3~10	≤ 8	≤ 8	≤ 6	≤ 6
		2	15~100	≤ 10	≤ 10	≤ 8	≤ 8
Torsional Rigidity	Nm/arcmin	1,2	3~100	2	4,4	13,5	35,6
Max. Radial Load F_{2R}^3	N	1,2	3~100	820	1,910	2,060	4,160
Max. Axial Load F_{2a}^4	N	1,2	3~100	410	955	1,030	2,080
Service Life	hr	1,2	3~100	20,000*			
Efficiency η	%	1	3~10	≥ 97%			
		2	15~100	≥ 94%			
Weight	kg	1	3~10	0,8	1,9	3,8	8,9
		2	15~100	1,1	2,7	5,2	12,2
Operating Temp	°C	1,2	3~100	0°C~+90°C			
Lubrication		1,2	3~100	Synthetic lubrication grease			
Degree of Gearbox Protection		1,2	3~100	IP64			
Mounting Position		1,2	3~100	all directions			
Noise Level ($n_1=3000$ rpm, No Load)	dB(A)	1,2	3~100	≤ 68	≤ 70	≤ 72	≤ 74

IV.2.4.2 Lead Screw Mechanism Selection

Properties of the used lead screw are given in Table IV.2.14

Table IV.2.14: Properties of lead screw for locking mechanism [LMS, 2011]

ACME Thread - inch dimensions (nominal)						Trapezoidal Thread - mm dimensions (nominal)					
Order No.	A	TPI	R	Length - feet		Order No.	A	P	R	Length - metres	
				Standard	Maximum*					Standard	Maximum*
05010	0.500	10	0.40	3	9	1203	12	3	9	1	3
06258	0.625	8	0.50	5	9	1604	16	4	12	1.5	3
07508	0.750	8	0.63	5	15	2004	20	4	16	1.5	5
10005	1.000	5	0.80	8	15	2505	25	5	20	2.5	5
12504	1.250	4	1.00	8	15	3206	32	6	26	2.5	5
15004	1.500	4	1.25	10	15	4006	40	6	34	3	5
20003	2.000	3	1.67	10	15	5008	50	8	42	3	5
25002	2.500	2	2.00	12	15	6010	60	10	50	3.5	5

*Normal maximum length. For longer lengths, seamless joined screws or special materials contact our Technical Staff



A - Thread diameter
TPI - Threads per inch
R - Root diameter
P - Pitch
L - Length

Ordering:- Examples
 12 off 20003RH x 3 foot long
 6 off 4006LH x 4.5 metres long

NB: Right hand thread and standard length screws will be supplied unless specified otherwise

Full range of **Power Nuts** to suit overleaf

CHAPTER V

CONCLUSION

This thesis can show a methodology and example for the applications of axiomatic design to analyze an existing design and develop a new product for the researchers who works in the field of design engineering. Using axiomatic design principle is important to determine expectations from the system at the beginning. As a result of the analysis of the rotary type mechanical car parking system using axiomatic design approach, it has been seen that the system is not applicable to a surface area having 7900 mm width. This deficiency has been determined at the beginning of the design process and a constraint, which states that width of the developed system must be less or equal to 2,5m, has chosen. This constraint has been kept in mind during design process and a system with 2308 mm width has been developed. Hence, proposed system can be built parallel to the road line.

To develop proposed system with eight cars capacity, a surface area having 12722 mm length and 2038 mm with is required as seen in Appendix D. This area is smaller than required space given in Figure II.2.1 to park two cars. It means that proposed system makes possible to park eight cars to a certain space instead of two cars. That was one of the expectations of this thesis.

Cost analysis for the proposed system is given in Appendix C and it is seen that total cost to develop a system with eight cars capacity is 73.925,531 TL. Comparing to rotary and puzzle type mechanical car parking systems, this cost is considerably low. As it has been stated in Chapter II, for rotary and puzzle type mechanical car parking systems with eight cars capacity, investment costs are respectively 161.770 TL and 369.760 TL. In the proposed system, parking cars to cells in all rows along two columns with only one mechanism decreases investment cost. This property of the proposed system has been determined by DP₂ at the beginning of the design process and next level FRs and DPs have been chosen according to necessities of it. For this reason axiomatic design approach is important. Because, designers know what they expect from the system at the beginning of the design process and they detail the system at each level of the decomposition process. Decomposition process is one of the most critical and

important process of axiomatic design approach. Everybody who doesn't have any idea about the system can solve and understand the system easily by investigating decomposition process. So, axiomatic design approach makes the design simpler and understandable.

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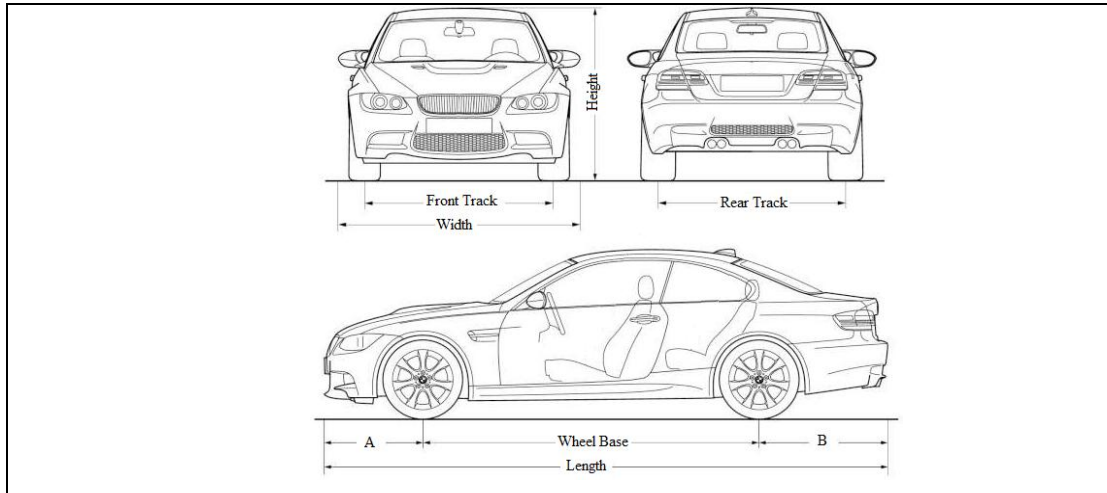
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APPENDICES

Appendix A. Physical Properties of the Cars



Car Name	Length (mm)	Width (mm)	Height (mm)	Wheel Base (mm)	Front Track (mm)	Rear Track (mm)	Weight (kg)	Tires	A and B (mm)
Ford Mondeo	4850	2092	1550	2850		1605	1569		965/1030
Ford Focus (Station Wagon)	4550	2010	1505	2648			1367		
Ford Fiesta	3950	1973	1481	2489			1118		
Toyota Avensis	4695	1810	1480	2700			1580	215/55/R17	
Toyota Corolla	4545	1760	1470	2600	1760		1290	215/55/R16	935/1010
Toyota Auris	4245	1760	1515	2600	1515		1310	205/55/R16	905/740
Honda Civic	4545	1755	1435	2675	1505	1530	1220	195/65/r15	
Honda Accord	4725	1840	1440	2705	1585	1590	1490	225/55/R17	
Honda Jazz	3900	1695	1525	2500	1492	1475	1079	175/65/R15	
Fiat Linea	4560	1728	1494	2603	1467	1482	1290	195/55/R16	
Fiat Albea	4180	1703	1490	2439	1414	1438	1085		
Fiat Punto	4065	1686	1490	2510	1473	1466	1145	185/65/R15	
Hyundai Accent	4370	1700	1457	2570	1470	1465	1210	155/50/R16	
Hyundai Elantra	4530	1775	1445	2700			1228	195/65/R15	
Hyundai i20	3940	1710	1490	2525	1493		1301	185/60/R15	785/630
Opel Astra Sedan	4587	2033	1458	2703	1488	1779	1308	205/55/R16	
Opel Insignia	4830	1856	1498	2737	1585	1587	1438		
Opel Corsa	3999	1737	1488	2511	1485	1478	1088		
VW Passat	4769	1820	1472		1552	1551	1560		
VW Jetta	4644	1778	1492	2651			1412		
VW Polo	3970	1682	1462	2470	1463	1456	1179		
Audi A6	4915	1875	1455				1660		
Audi A3	4238	2025	1421	2578	1534	1507	1530	225/40/R18	881/779
BMW 5 Series	4899	2094	1464	2968	1600	1627	1725		832/1099
BMW 7 Series	5072	2134	1479	3070	1611	1650	1840		
Chevrolet Cruze	4597	1797	1477	2685	1544	1558	1285		
Citroen C5	4779	2096	1458	2815	1584	1560			1054/950
Peugeot 508	4792	2068	1456	2817	1576	1548			985/990
Kia Rio Sedan	4365	1720	1455	2570	1521	1525	1173	195/55/R16	

Appendix B. Combined Bearing, U Channel and Flange Plate Properties

Abdichtung 2 RS | Sealings 2 RS

Typ	Artikel-Nr.	D mm	T mm	d -0.05 mm	H mm	h mm	B mm	A mm	S mm	r mm	F _r kN	F _a kN	C kN	C ₀ kN	C _a kN	C _{0a} kN
Type	Article no.	D mm	T mm	d -0.05 mm	H mm	h mm	B mm	A mm	S mm	r mm	F _r kN	F _a kN	C kN	C ₀ kN	C _a kN	C _{0a} kN
4.053	200.024.000	52,5	40	30	33,0	27,0	17	5,0	15	2	5,23	1,68	24,0	32,0	7	7
4.054	200.001.000	62,5	42	30	37,5	30,5	20	2,5	20	3	9,40	3,10	31,0	35,5	11	11
4.055	200.002.000	70,1	48	35	44,0	36,0	23	2,5	22	4	11,30	3,73	45,5	51,0	13	14
4.056	200.003.000	77,7	54	40	48,0	36,5	23	3,0	26	4	11,72	3,87	48,0	56,8	18	18
4.057	200.004.002	77,7	53	40	40,0	29,0	23	3,0	26	4	11,72	3,87	48,0	56,8	18	18
4.058	200.005.000	88,4	59	45	57,0	44,0	30	3,5	26	3	20,47	6,76	68,0	72,0	23	23
4.059	200.006.000	101,2	67	50	46,0	33,0	28	3,0	30	3	20,11	6,70	73,0	82,0	25	27
4.060	200.007.000	107,7	71	55	53,0	39,0	31	3,0	34	5	21,68	7,16	81,0	95,0	31	36
4.061	200.008.000	107,7	71	60	69,0	55,0	31	4,0	34	5	21,68	7,16	81,0	95,0	31	36
4.062	200.009.000	123,0	80	60	72,3	56,0	37	5,0	40	5	30,92 (24,70)	10,20	110,0	132,0	43	50
4.063	200.010.000	149,0	103	60	78,5	58,5	43	5,5	50	3	54,02	17,80	151,0	192,0	68	71

C = Dynamic load capacity radial bearing (ISO 281/1), C₀ = Static load capacity radial bearing (ISO 76),
C_a = Dynamic load capacity axial bearing (ISO 281/1), C_{0a} = Static load capacity axial bearing (ISO 76),
F_r = Load capacity radial bearing max. allowable force between bearing and profile,
F_a = Load capacity axial bearing max. allowable force between bearing and profile

Standard 3 Nb

Artikel-Nr. 113.013.000
Article no.

m	28,6	kg/m
A	36,4	cm ²
I _x	864,1	cm ⁴
W _x	127,6	cm ³
I _y	89,5	cm ⁴
W _y	27,1	cm ³
e _y	2,0	cm

L_{max} = 12 m

AP 3-Q

Artikel-Nr. 212.006.000
Article no.

Appendix C. Cost Analysis For an Eight Cars Capacity System

Steel Structure							
Name	Unit Weight (kg)	Quantity	Total Weight (kg)	Material Cost (TL/kg)	Manufacturing Cost (TL/kg)	Assembly Cost (TL/kg) (Including Shipping)	Total Cost (TL)
Vertical Channel	2380	1	2380	1,35	0,8	0,5	6307
Arm	1000	1	1000	1,35	0,8	0,5	2650
Arm Cover	52,54	1	52,54	1,35	0,8	0,5	139,231
Horizontal Channel	1700	1	1700	1,35	0,8	0,5	4505
Horizontal Channel Cover	54	2	108	1,35	0,8	0,5	286,2
Palette	500	8	4000	1,35	0,8	0,5	10600
Connection Member	60	1	60	1,35	0,8	0,5	159
Frame Cell	640	8	5120	1,35	0,8	0,5	13568
Column	970	6	5820	1,35	0,8	0,5	15423
Slewing Unit Support	340	1	340	1,35	0,8	0,5	901
Beam	54	5	270	1,35	0,8	0,5	715,5

Standard and Machined Parts							
Part Name	Unit Cost (TL)	Quantity					Total Cost (TL)
NM 160M-6 Electric Motor	1465	1					1465
NM 132M-6 Electric Motor	1150	1					1150
NM 112M-6 Electric Motor	805	1					805
KH 3200 Reducer	7000	1					7000
KH 3160 Reducer	3500	1					3500
KH 2080 Reducer	1250	1					1250
EMJ-02APA22 Servo Motor	478	1					478
PE 050 Reducer	363,6	1					363,6
FAG-32224A Bearing	630	2					1260
FAG-SNV110 Bearing Unit	200	1					200
Gears and gear Components							300
Bolt and Nuts							200
Machined parts							600
Wire rope	5TL/m	20 m					100
Total Cost=73.925,531 TL							

Appendix D. Drawings of the Main Components of the Proposed System

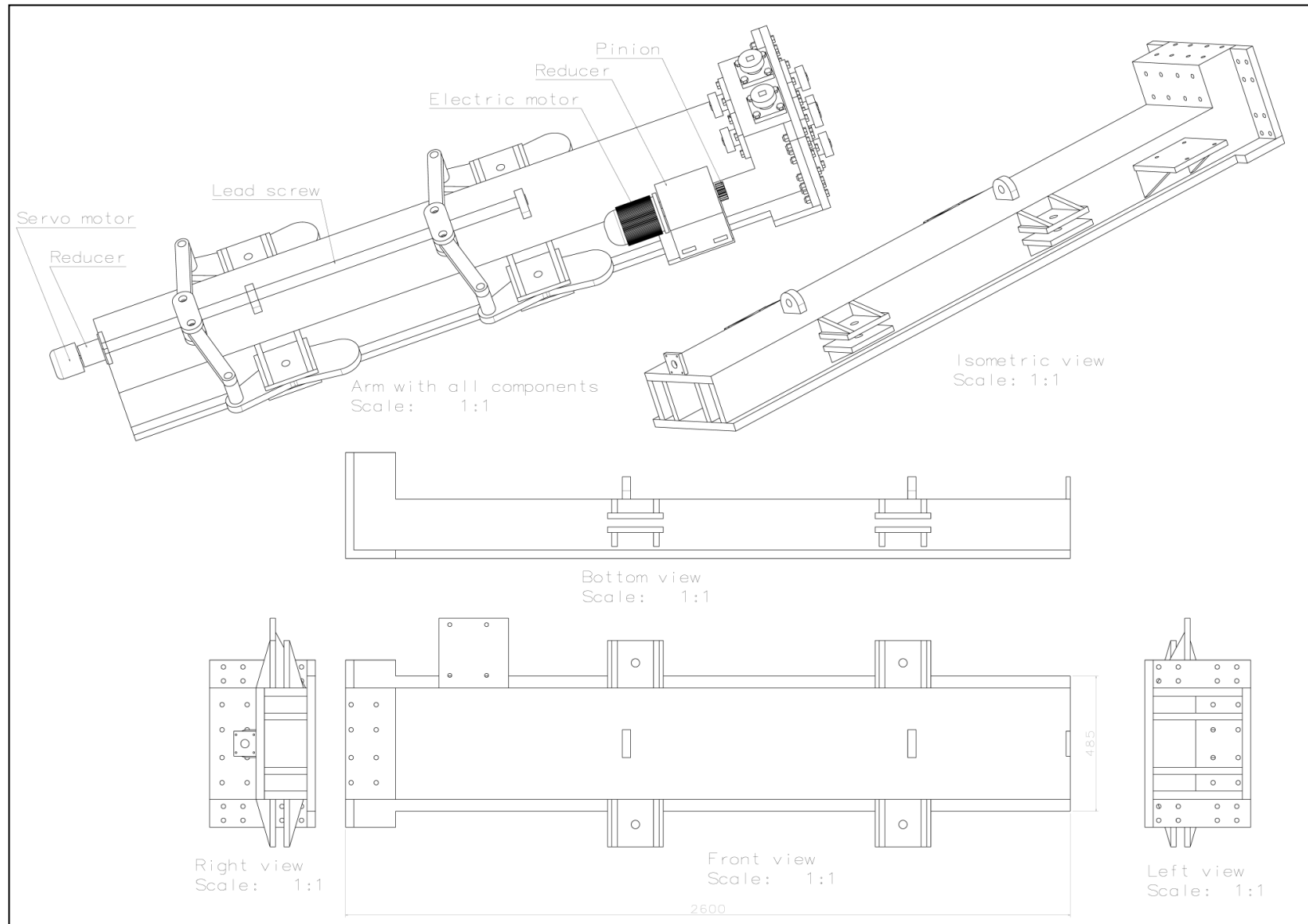


Figure D.1: Drawings of the arm with all components

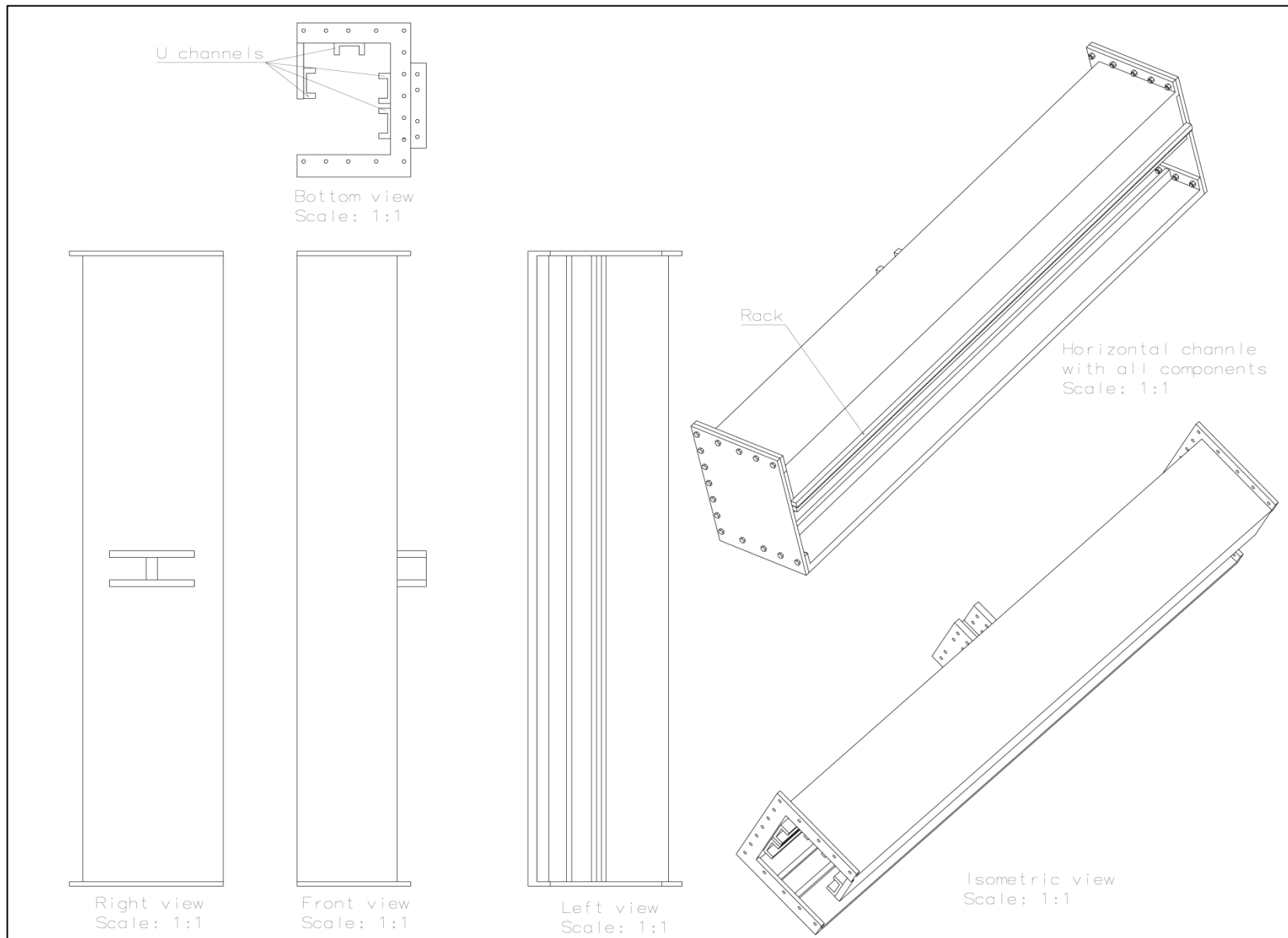


Figure D.2: Drawings of the horizontal channel with all components

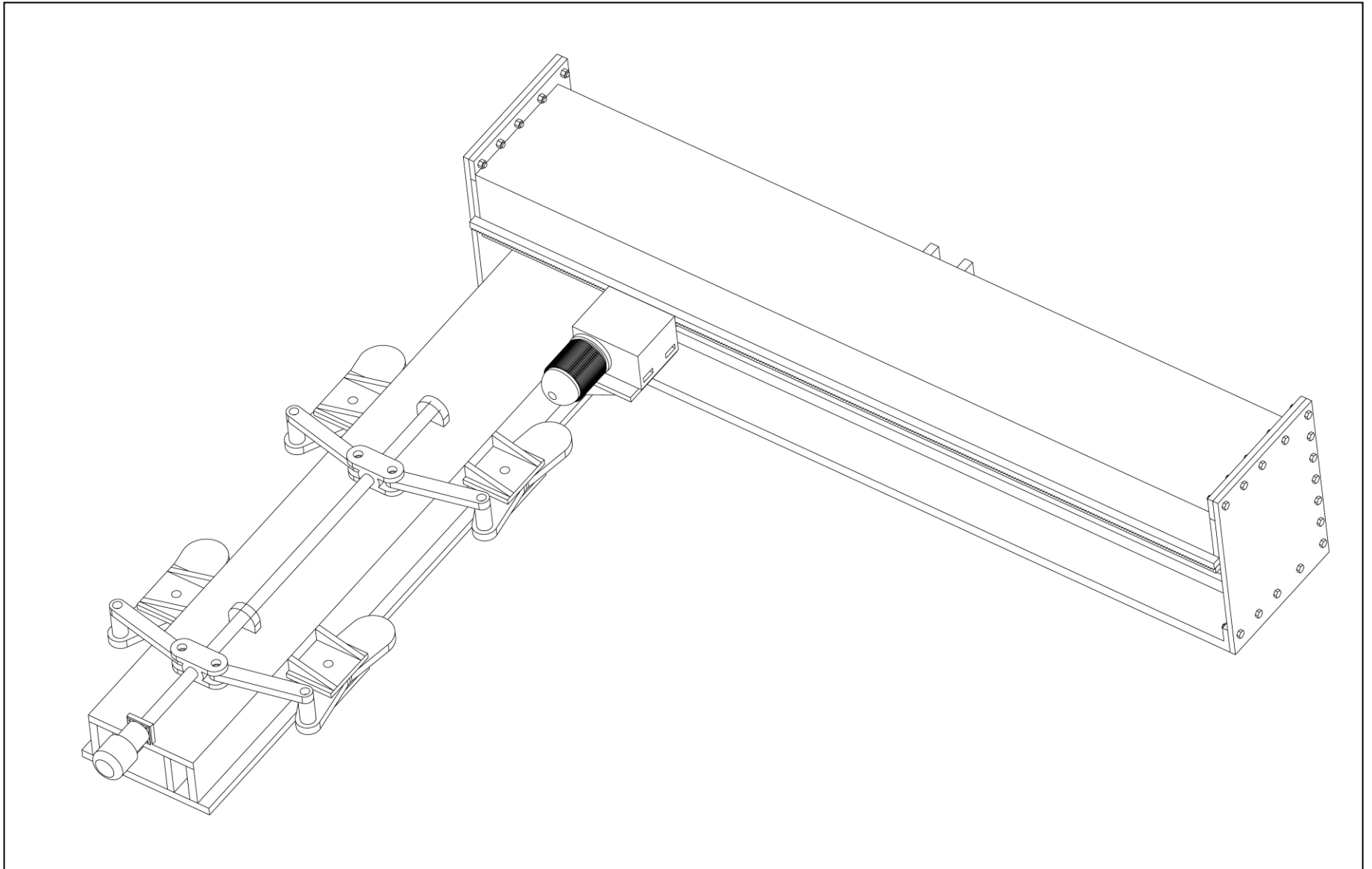


Figure D.3: Drawing of the horizontal channel and arm together

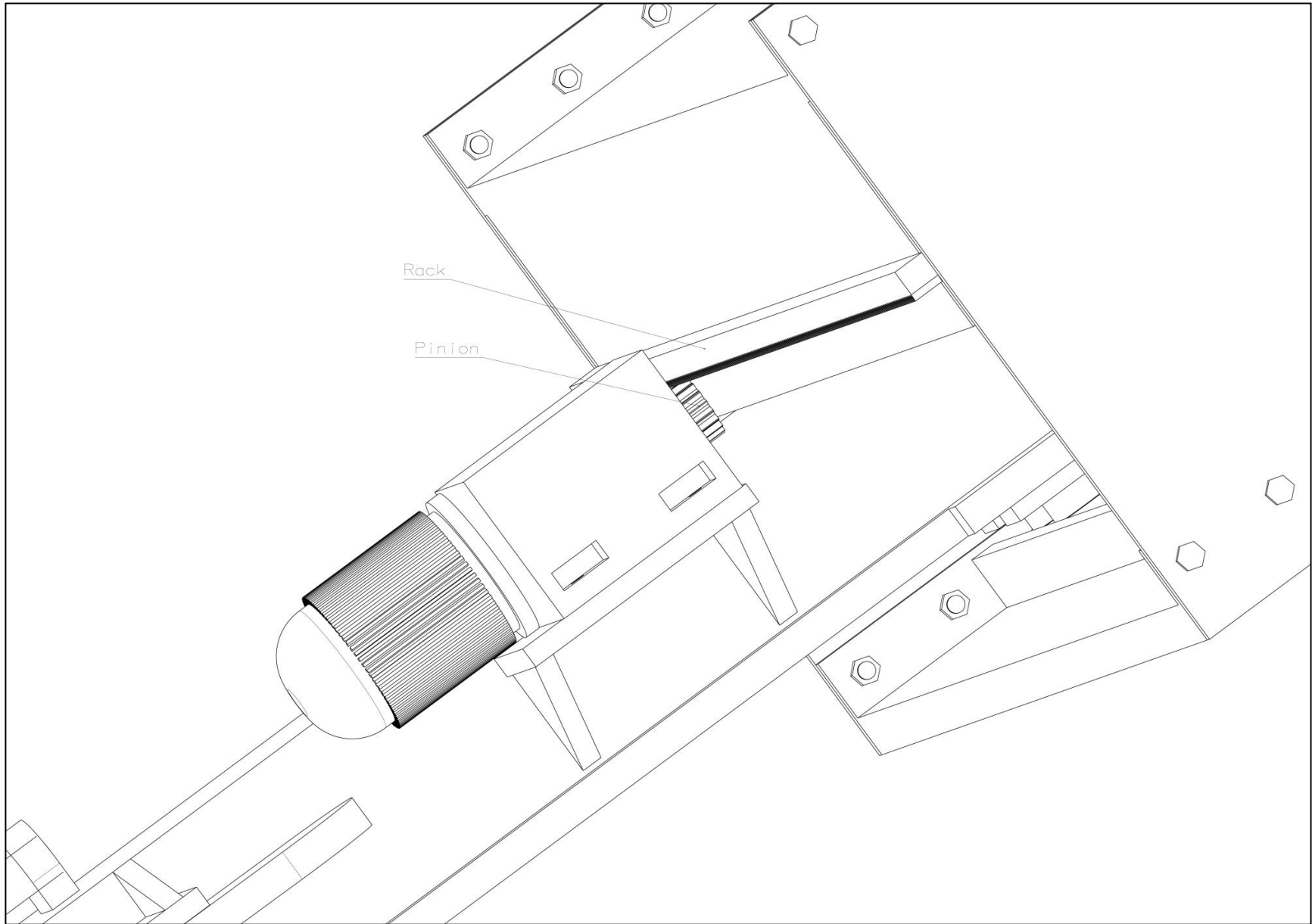


Figure D.4: Major portion extracted from Figure D.3

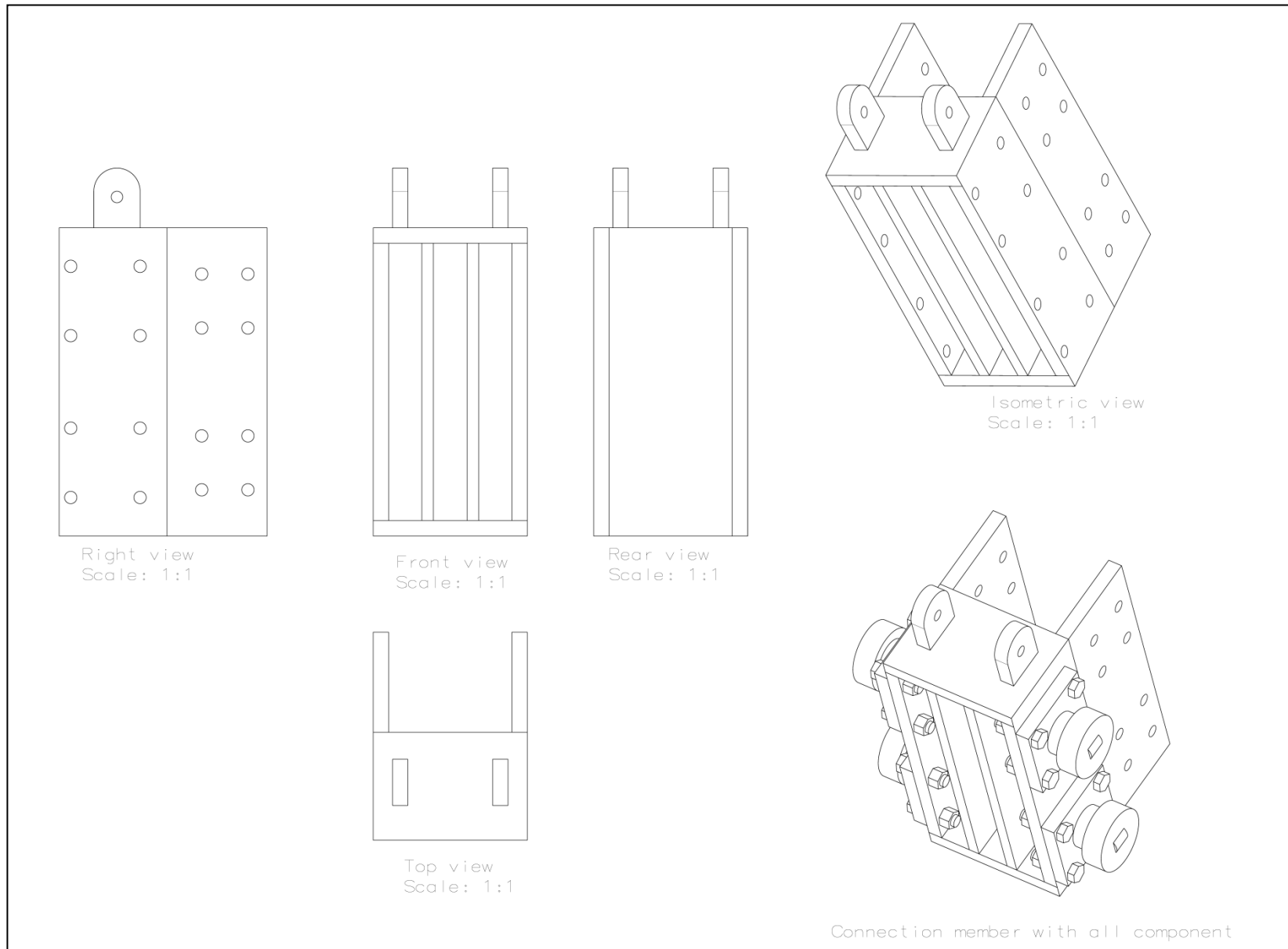


Figure D.5: Drawings of the connection member with all components

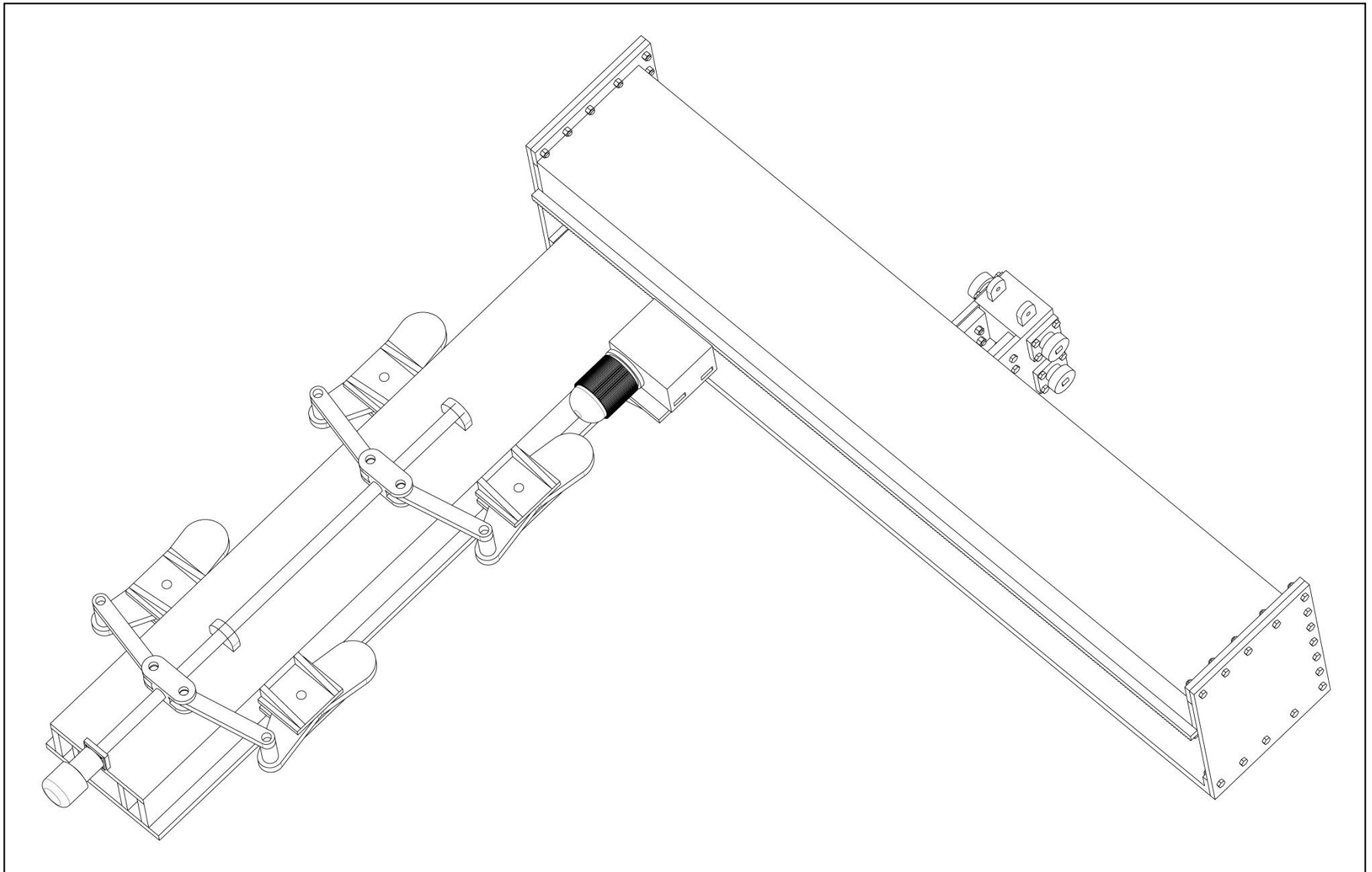


Figure D.6: Drawing of the horizontal channel, arm and connection member together

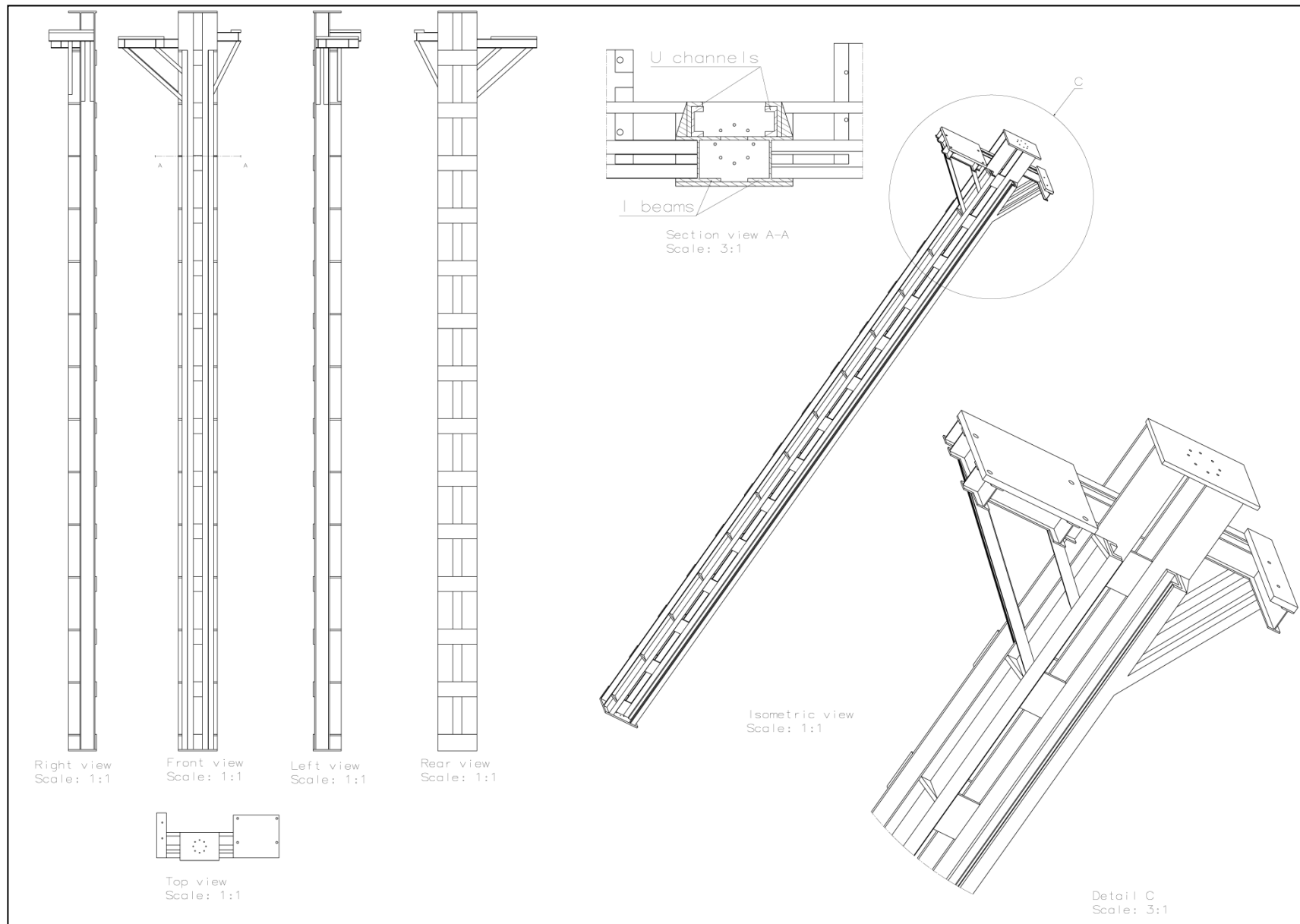


Figure D.7: Drawings of the vertical channel

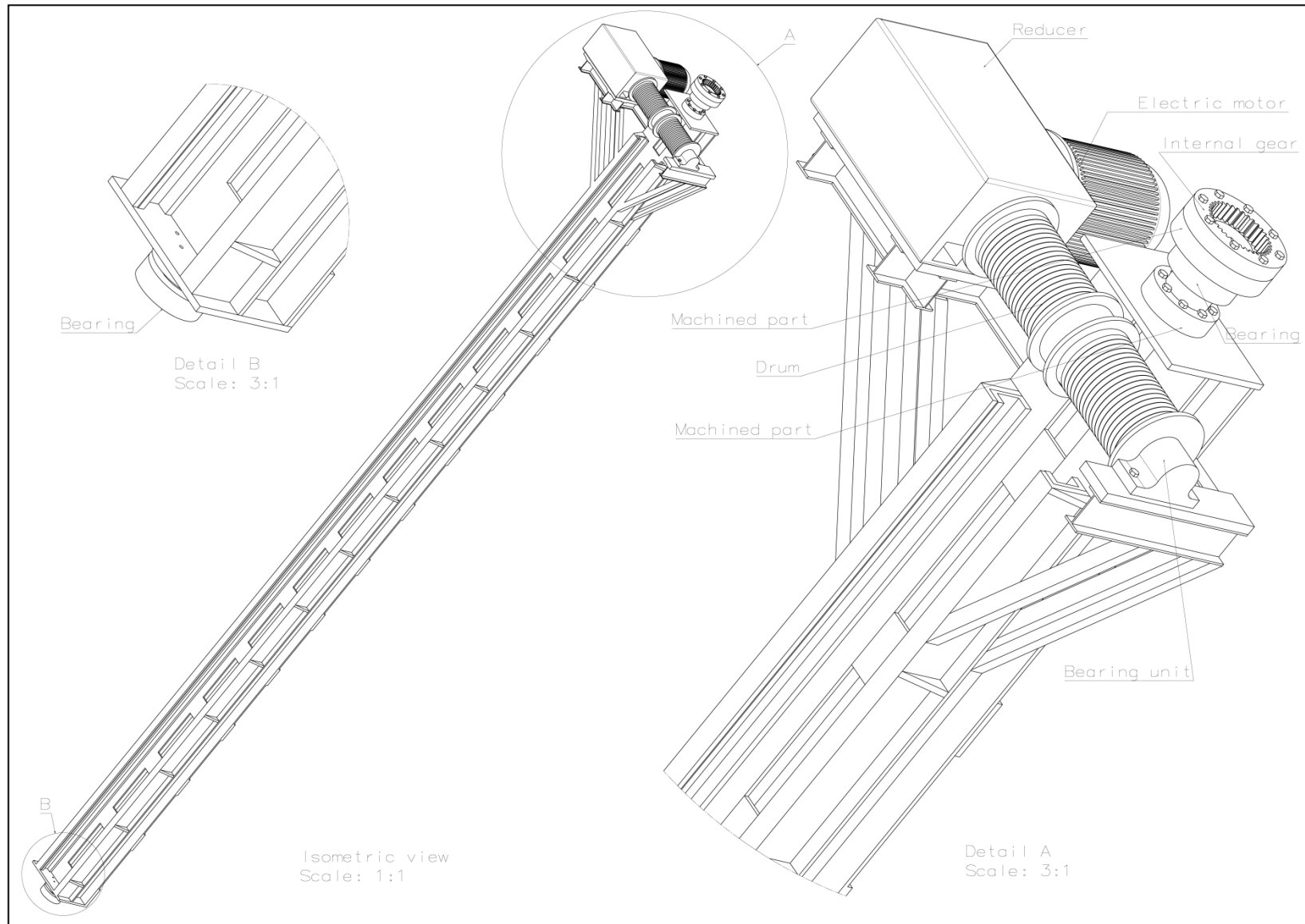


Figure D.8: Drawings of the vertical channel with all components

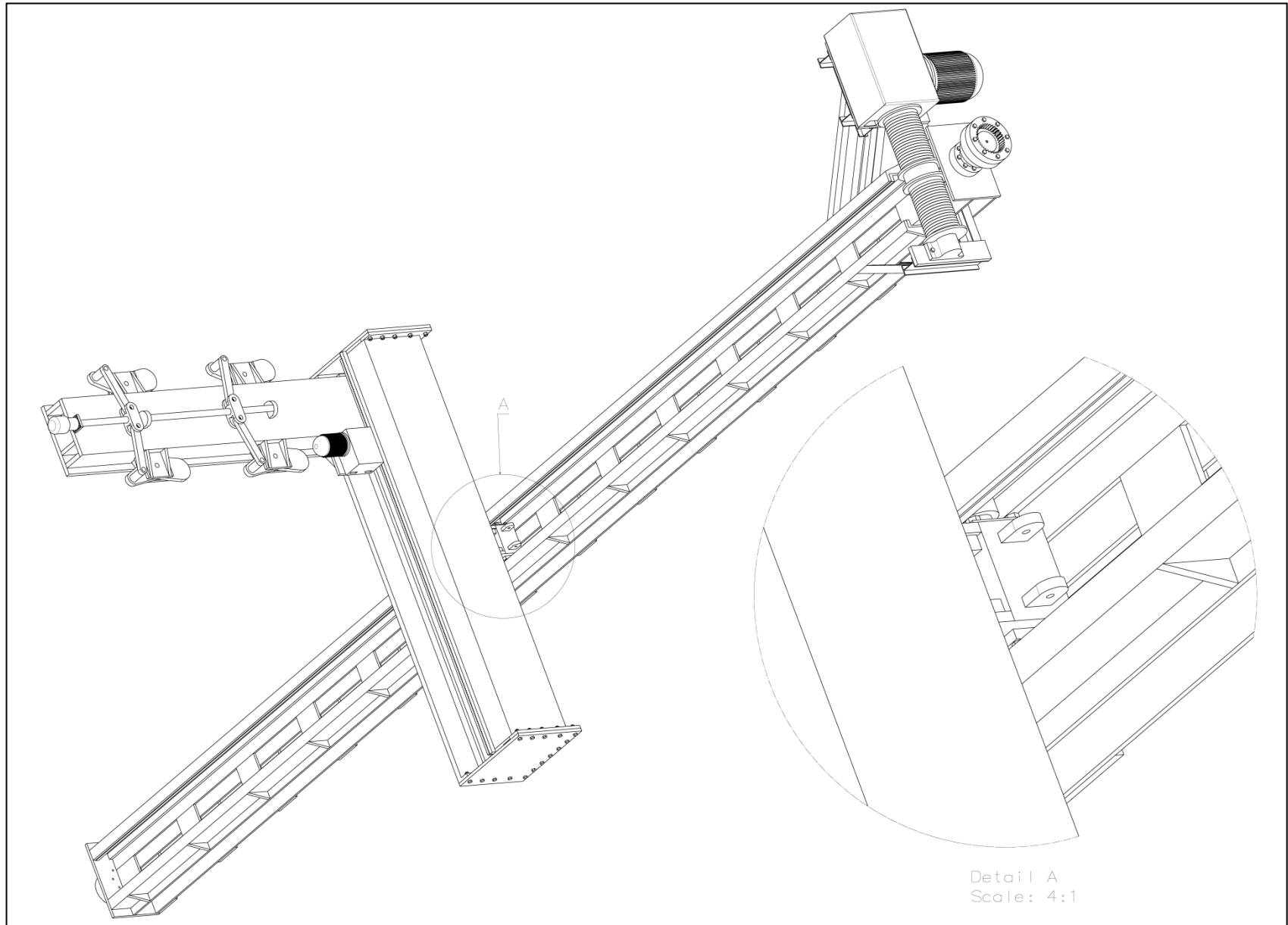


Figure D.9: Drawing of the horizontal channel, arm, connection member and vertical channel together

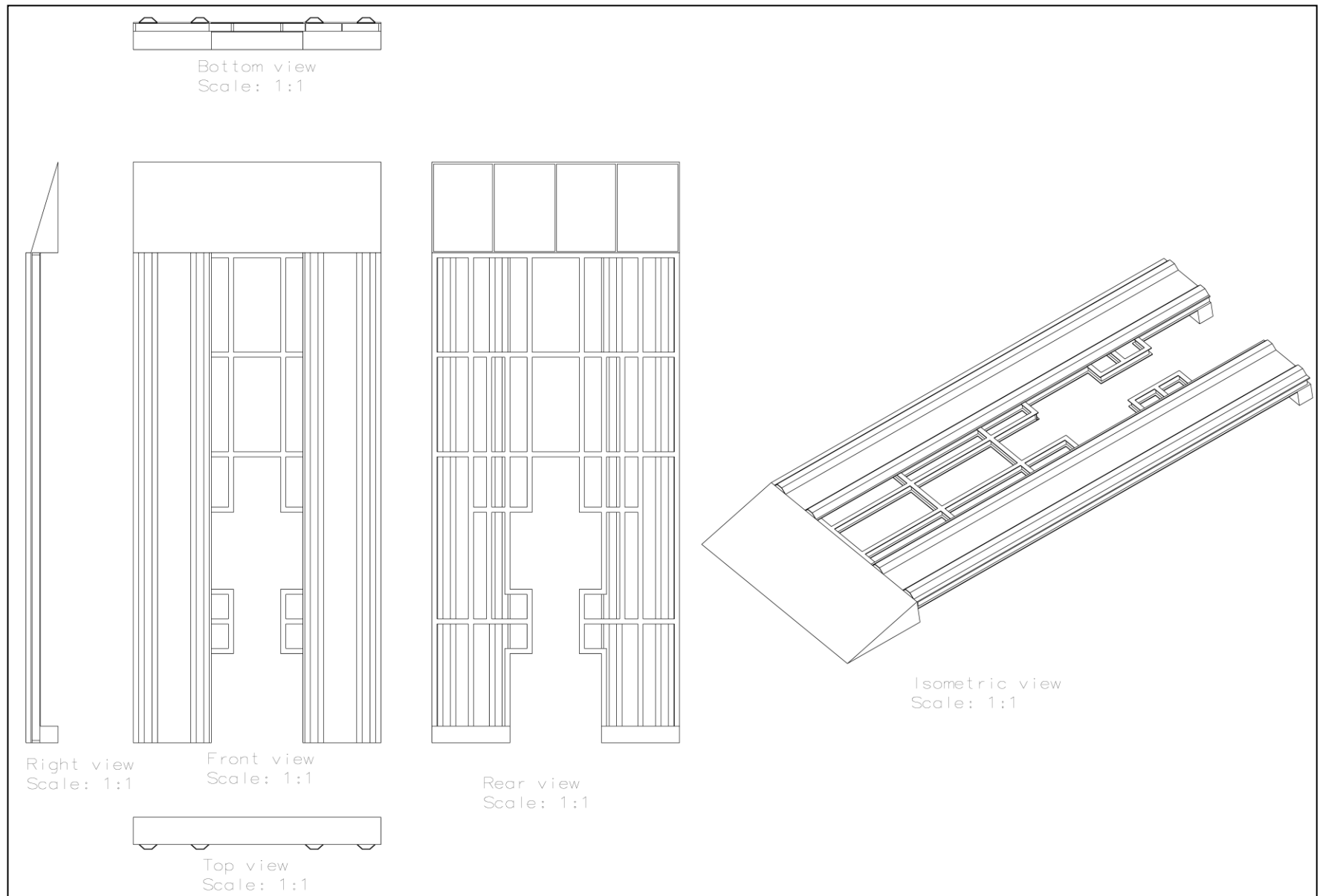


Figure D.10: Drawing of the pallet

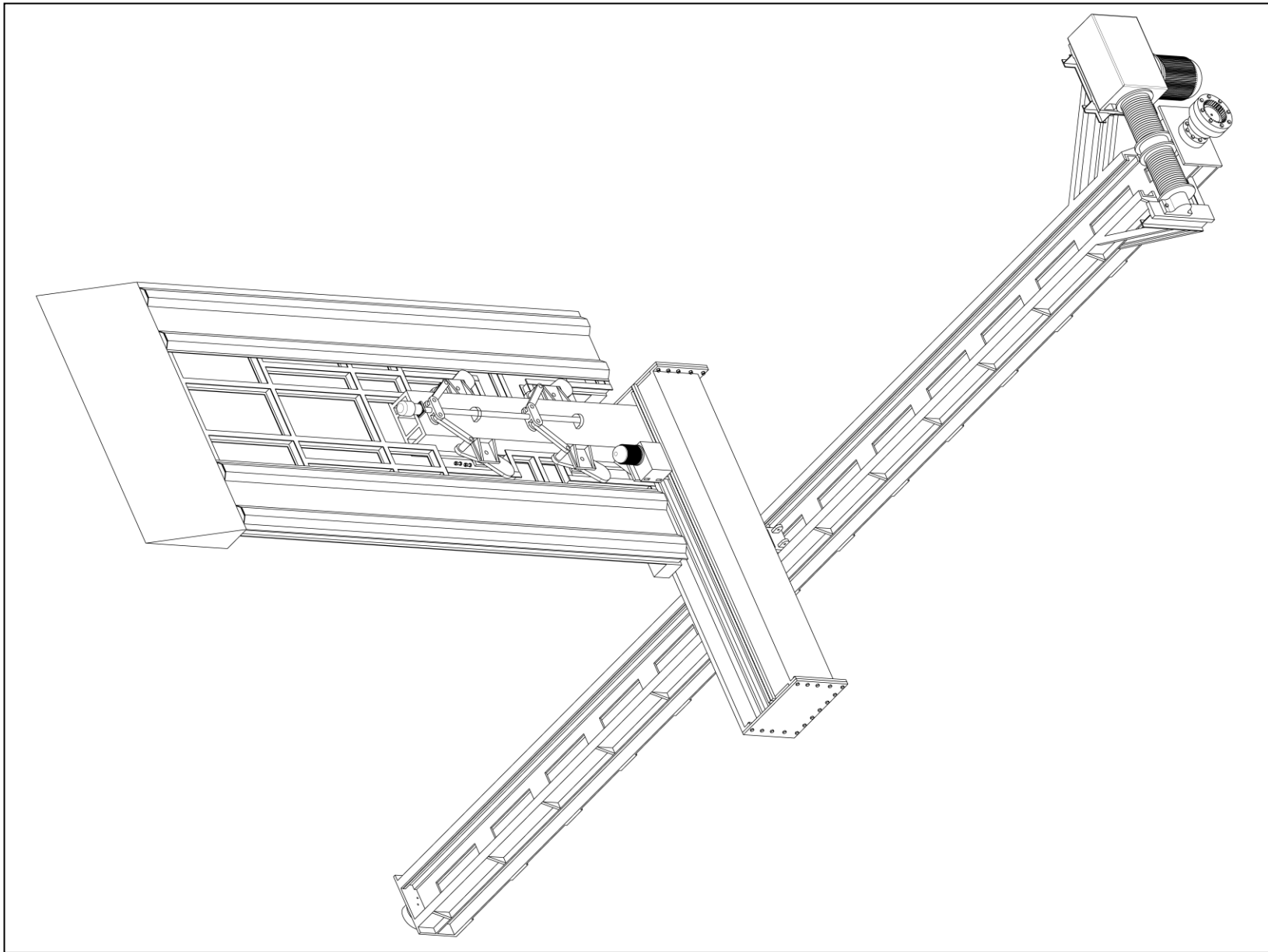


Figure D.11: Drawing of the horizontal channel, arm, connection member, vertical channel and palette together

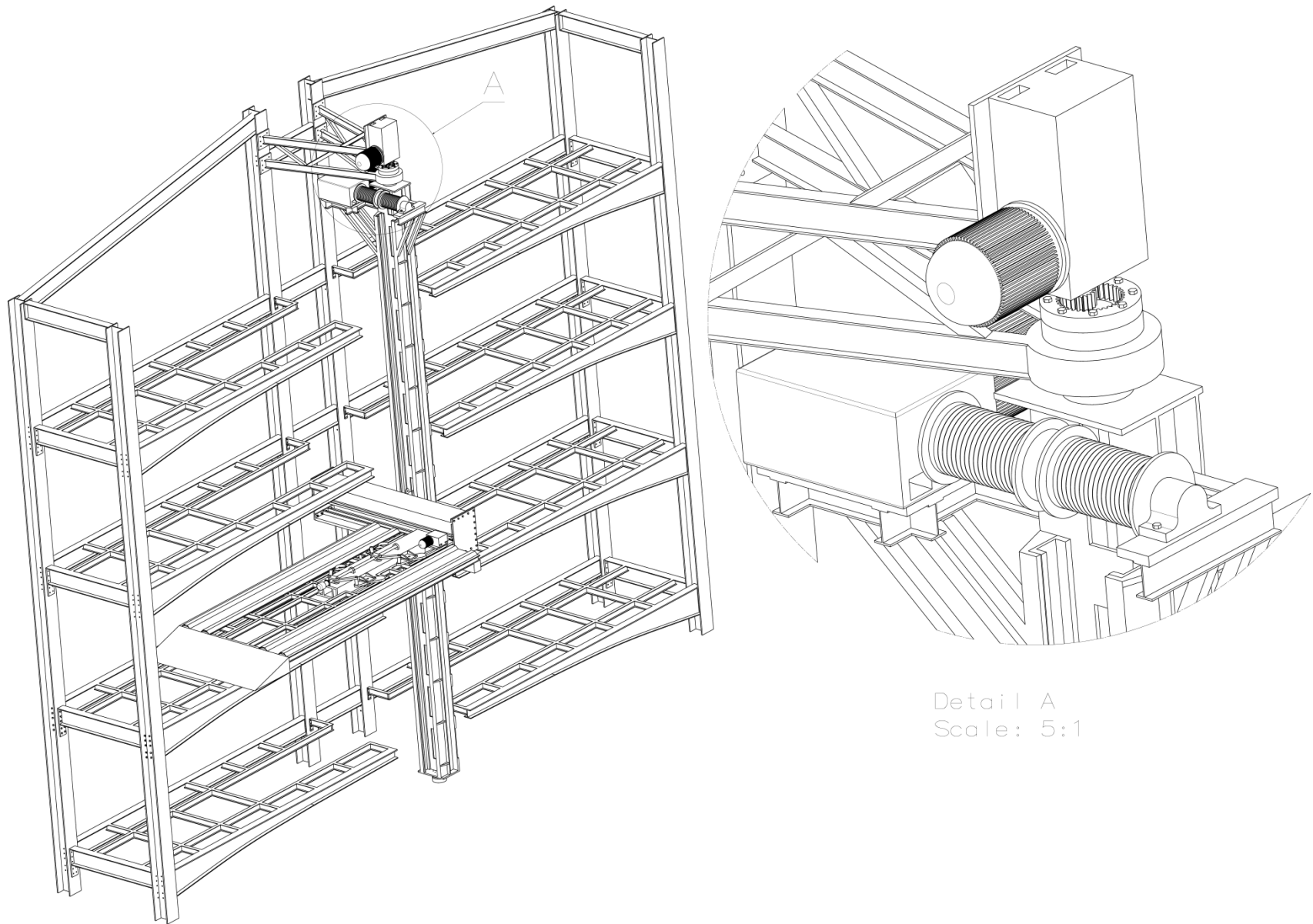


Figure D.12: Drawing of the total system

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