CONCEPTUAL DESIGN AND ANALYSIS OF AN INDUSTRIAL TYPE VACUUM SWEEPER

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DESIGN, DEVELOPMENT AND MANUFACTURING OF AN INDUSTRIAL TYPE VACUUM SWEEPER

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ABSTRACT

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In this thesis, design and development and manufacturing processes of an industrial type vacuum sweeper is presented. Thesis is financially supported by Ministry of Industry and Trade-Turkey and Müsan A.Ş. (Makina Üretim Sanayi ve Ticaret A.Ş.) under SAN-TEZ project number 00028.STZ.2007-1. It is aimed to make innovative design changes and developments on the Müsan VSM 060 type vacuum sweeper. To achieve this aim, alternative configuration designs are prepared by using commercial 3D modeling program, Catia™ V5. Basic vehicle structure is constructed.

New Müsan VSM 060 will be a fully electrically driven vehicle. All subsystems will be activated by using electrical motors whose power is supplied by batteries.

All subsystems are mounted on the chassis which is a welded frame structure made up of 60x40x2 St37-2 grade steel tubes. Finite element analysis (FEA) of the chassis is performed by using commercial structural finite element analysis tools MSC Patran pre and post processor and MSC Nastran solver. Moment calculations are done for structural parts.

Cleaning system of the new VSM 060 vehicle is decided to be a combination of mechanical and vacuum cleaning systems. An elevator system will be integrated in addition to vacuum system to pick up coarse particles. The vacuum system will mainly be utilized for very small size particle collection. Computational fluid dynamics (CFD) analyses are done by Punto Mühendislik Ltd. Şti. for the whole cleaning system components by using CFdesign, an upfront CFD analysis tool.

Keywords: Sweeper, electrically driven sweeper, city cleaner, finite element analysis of chassis, computational fluid dynamics analysis of a sweeper

ÖZ

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Şubat 2009, 111 sayfa

Bu tezde, endüstriyel tip vakumlu süpürücü tasarımı, geliştirilmesi ve imalatı anlatılmaktadır. Tez, SAN-TEZ proje numarası 00028.STZ.2007-1 kapsamında, T.C. Sanayi ve Ticaret Bakanlığı ve Müsan A.Ş. (Makina Üretim Sanayi ve Ticaret A.Ş.) tarafından desteklenmektedir. Amaç, Müsan VSM 060 vakumlu süpürme aracı üzerinde yaratıcı tasarım değişiklikleri ve iyileştirmeler yapılmasıdır. Bu amaç doğrultusunda, ticari 3 boyutlu modelleme programı olan Catia™ V5 kullanılarak yeni araç için dış tasarım alternatifleri hazırlanmıştır. Aracın temel yapısı tasarlanmıştır.

Yeni Müsan VSM 060 aracı tamamıyla elektrikle çalışan bir araç olacaktır. Tüm alt sistemler, akülerden beslenen elektrik motorları yardımıyla çalışır hale gelecektir.

Tüm sistemler, 60x40x2 ebadında St37-2 kalitesinde çelik kutu profillerden 3 boyutlu çerçeve şeklinde imal edilecek olan şase üzerine monte edilecektir. Şase için sonlu elemanlar analizi, ticari sonlu elemanlar analiz programları olan MSC Patran ve MSC Nastran kullanılarak yapılmıştır. Yapısal parçalar için moment hesaplamaları yapılmıştır.

VSM 060 aracının temizlik sistemi, mekanik ve vakumlu temizleme sistemlerinin birleşimi şeklinde olacaktır. Büyük parçaların toplanması için, fan vakum sistemine ek olarak bir mekanik elevatör sistemi kullanılacaktır. Vakum sistemi temel olarak çok küçük parçacıkların temizliği için kullanılacaktır. Sayısal akışkanlar dinamiği analizleri tüm sistem için Punto Mühendislik Ltd. Şti. tarafından ticari bir yazılım olan CFdesign programı kullanılarak gerçekleştirilmiştir.

Anahtar kelimeler: Süpürücü, elektrikli sokak süpürücüsü, şehir süpürücüsü, şase için sonlu elemanlar analizi, süpürücü için sayısal akışkan dinamiği analizi

To My Parents

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

cc	: cubic centimeter
CFD	: Computational Fluid Dynamics
DC	: direct current
FEA	: Finite Element Analysis
g	: grams
h	: hour
hp	: horsepower
IGBT	: insulated gate bipolar transistors
kg	: kilogram
kPa	: kilopascal
kW	: kilowatt
l	: liter
m	: meter
mbar	: millibar
mm	: millimeter
MOSFET	: metal-oxide field-effect transistors
MPa	: mega pascal
MPC	: Multi Point Constraint
N	: Newton
PM	: Particulate Matter
PWM	: Pulse Width Modulation
rpm	: revolutions per minute
V	: volt

CHAPTER 1

INTRODUCTION

Today, for the cleaning of indoor and outdoor sites like factories, train stations, airports, ports, harbors, small streets and parking lots in the cities, one of the most effective, fast and low-cost methods is to utilize street sweepers.

Many companies all over the world design and manufacture different types of sweepers with various sizes and cleaning capacities. These sweepers are purchased and utilized by the municipalities, factories and firms for indoor and outdoor cleaning.

First sweeper patents were taken out at the end of 1800s [1]. With the evolution of technology and science, horse driven sweepers gave their places to autonomous robot sweepers which determine their own routes.

Most of the sweepers in the market have internal combustion engines, however electric power driven sweepers are becoming more widely used day by day. When the manufacturers' products are investigated, it is noticed that their products show many similarities. This shows that it is possible to go one step further among all other sweepers with an innovative design.

Industrial type sweepers can be classified in two ways according to their structure and their cleaning method.

There are two types of sweepers according to structure:

- Walk-behind sweepers
- Ride-on sweepers

And three types of sweepers according to the way of cleaning [2]:

- Mechanical broom sweepers
- Vacuum sweepers
- Regenerative air sweepers

Briefly, mechanical broom sweepers remove debris by sweeping material onto a conveyor system which then transports it into a debris hopper for containment [3]; vacuum sweepers suck up the loosened particles with a vacuum and send them directly to the hopper [2] and regenerative air sweepers use forced air to create a swirling knifing effect inside of a contained sweeping head and then use the negative pressure on the suction side to place the debris inside of a containment hopper. Air is then cleaned and reused to start the process [4]. These three types of sweepers are explained in more detail below [5].

1.1. Mechanical Broom Sweepers

Mechanical broom sweeping technology may be explained as cleaning with a broom and a dustpan [5]. For years, mechanical broom sweepers were the only machines that were used for road sweeping by municipalities and departments of transportation. Mechanical broom sweepers are still the primary machines in use.

Typically, these machines have a ‘main broom’ that runs transversely from one side of the sweeper to the other such that the broom bristles contact the paved surface the full width of the sweeper unit. The broom rotates in a clockwise fashion when viewed from the left side of the vehicle and collected debris is swept onto some type of a conveyor belt for transfer to a containment hopper.

Mechanical broom machines may or may not be equipped with a ‘gutter broom’ on one or both sides of the sweeper. Gutter brooms are relatively small (typically 300 to 600 mm in width), are located to the left, right, or both sides of the sweeper, and are primarily used to transfer debris into the path of the main broom. Even though mechanical sweepers are usually outfitted with a series of water spray nozzles, because they have no vacuum component, they still tend to create a substantial amount of dust in dry weather.

Mechanical sweepers give the impression of leaving a clean pavement surface. Although large debris is removed by mechanical broom sweepers, they are virtually ineffective at removing particles 60 microns and smaller. From an environmental point of view, mechanical broom sweepers may have a negative effect on the amount of micron size particle pollution. This is because the action of the broom tends to break larger particles down into smaller ones, creating more small-micron particles than there were to start with. Since, debris pick-up is via an elevator, rather than involving any type of air/suction action, large amount of these small particles are left on the pavement surface.

Advantages: Mechanical broom sweepers remain the standard for sweeping extremely heavy or packed-down material.

Disadvantages: A mechanical sweeper is a poor choice where environmental concerns exist about small particle pollution or air quality. Also, mechanical sweepers are significantly more expensive to maintain than vacuum or regenerative air sweepers, due to having so many moving parts including continuous ground contact by main broom and mechanical movement by the elevator system.

1.2. Vacuum Sweepers

Vacuum sweepers may be compared to a household vacuum system [5]. An engine powers a fan, which creates vacuum/suction. Typically, there is a suction inlet on one side of the sweeping head, and then the ‘used’ air is constantly exhausted during the sweeping process. Most vacuum sweepers do not have an air blast that transfers debris to the vacuum opening. Instead; they employ some type of broom system to brush debris toward the vacuum opening in the head. Water may or may not be used in vacuum sweeper cleaning system.

Nowadays, vacuum sweepers are generally equipped with a sophisticated filtration system for dust containment. With this system, sweeper can provide cleaning to a small-micron level and become preferable for any application where dangerous or toxic materials are present.

Advantages: Vacuum sweepers provide thorough cleaning near the curb line. The sweeper can clean air below PM10 if a sophisticated filtration system is used and therefore can be a good choice for industrial cleanup situations. Less dust is created when compared to mechanical broom sweepers. There are fewer moving and wear parts than mechanical sweepers.

Disadvantages: Vacuum sweepers generally cannot pick up large debris. They have relatively small intake tubes so they are more likely to become plugged with larger debris. Their brooms tend to fill pavement irregularities with debris that the suction effect isn't strong enough to remove.

1.3. Regenerative Air Sweepers

Generally speaking, regenerative air sweepers are more environmentally friendly than are vacuum or mechanical broom sweepers [5]. Regenerative air sweepers employ a closed loop, 'cyclonic effect', to clean. They are similar to vacuum sweepers, in that there is a similar vacuum inlet located on one side of the sweeping head. Unlike vacuum machines, regenerative air sweepers constantly re-circulate (regenerate) their air supply internally. To accomplish this, the re-circulating air is blasted into the sweeping head on the side opposite the pickup (inlet) tube. Essentially, the air blasts down onto the pavement on one side of the head, travels across the width of the head (gathering debris with it as it goes) and then travels up the pickup hose on the other side with the debris. Manufacturers design their sweeping heads so as to swirl the air, so it will retain the collected debris within the airstream as it moves from the blast to the intake side of the head.

Although some air is lost by the regeneration process (due to unevenness of the pavement, which allows air to escape from under the sweeping head's rubber flaps, etc.), the amount of exhausted, pollutant-laden air is low. The blast-and-pickup cycle also makes these machines more capable at picking up heavy debris, since the blast is more able to dislodge heavier materials and get them into the airflow.

Advantages: Regenerative air sweepers can clean a wide range of debris in a large variety of situations. There are fewer moving and wear parts than mechanical sweepers. They can be used to clean trapped basins by adding hand hose.

Disadvantages: Regenerative air sweepers can't handle millings and other extremely heavy-duty applications as well as can mechanical sweepers. They use water for dust suppression, which leaves some dissolved small-micron debris in pavement cracks and on the surface. They exhaust some amount of particulates into the atmosphere.

1.4. Organization of the Thesis

The outline of the thesis can be summarized as follows:

In Chapter 2, technical specifications of the former Müsan VSM 060 sweeper are presented and new sweeper design is compared with the former one and with the other sweepers in the market.

In Chapter 3, the object of the SAN-TEZ research and development project and this thesis study is explained. Work share of the project members and design requirements of the new design are clarified.

In Chapter 4, calculations done for the power requirement of the traction system are explained.

In Chapter 5, configuration design process of the new sweeper, finite element analysis of the chassis, cleaning system design studies, computational fluid dynamics analyses and electrical system design studies are explained in detail.

In Chapter 6, discussions and conclusions about the work done so far are given and in Chapter 7 future work to be done in the SAN-TEZ project is presented.

CHAPTER 2

LITERATURE SURVEY

Many sweeper products in the market are investigated. Technical specifications of these products and former and new Müsan VSM 060 sweepers are compared in this chapter.

2.1. Former Müsan VSM 060 Vacuum Sweeper

Table 1 Technical specifications of VSM 060 vacuum sweeper [6]

	One Side Brush	Two Side Brush
Sweeping Area Max. (m²/h)	12.500	15.000
Speed(Traveling) (km/h)	0-10	0-10
Sweeping Range (m)	1,35	1,55
(With Central Brush) (m)	1,05	1,05
Type Of Drive	Diesel, 2 Cylinders Air Cooled 3 Cylinders Can Be Adapted.	Diesel, 2 Cylinders Air Cooled 3 Cylinders Can Be Adapted.
Engine Power	20 hp	20 hp
Engine Starting	Electric Battery	Electric Battery
Waste Container (l)	400	400
Container Discharging (Lifting/Discharging/Closing)	Hydraulic	Hydraulic
Suction System	Hydraulic Motor With Vacuum Aspirator	Hydraulic Motor With Vacuum Aspirator
Filter Area (m²)	6	6
Filtering System	Electro-mechanic Vibrator	Electro-mechanic Vibrator
Minimum Turning Radius (m)	1,55	1,55
Brakes	Service & Parking Front	Service & Parking Front
Max. Gradeability	% 26/15°	% 26/15°
Weight (kg) With Water Tank (100l)	1.000	1.000
Discharging Height (m)	1,2	1,2
Width (m)	1,35	1,55
Length (m)	2,15	2,15
Height (m)	2,3	2,3
Fuel Consumption (l/h)	3,5	3,5

Figure 1 Müsan VSM 060 sweeper

Figure 2 Müsan VSM 060 sweeper

The cleaning system of VSM 060 sweeper is a combination of a mechanical sweeping system and a vacuum system. Debris on the path is collected and directed towards the main broom by the help of gutter brooms and impelled into the hopper by the help of the main broom. Coarse particles are collected at the lower part of the hopper. Fine particles are sucked by the suction fan through the filter and are collected at the upper part of the hopper. This system is demonstrated below in **Figure 3**.

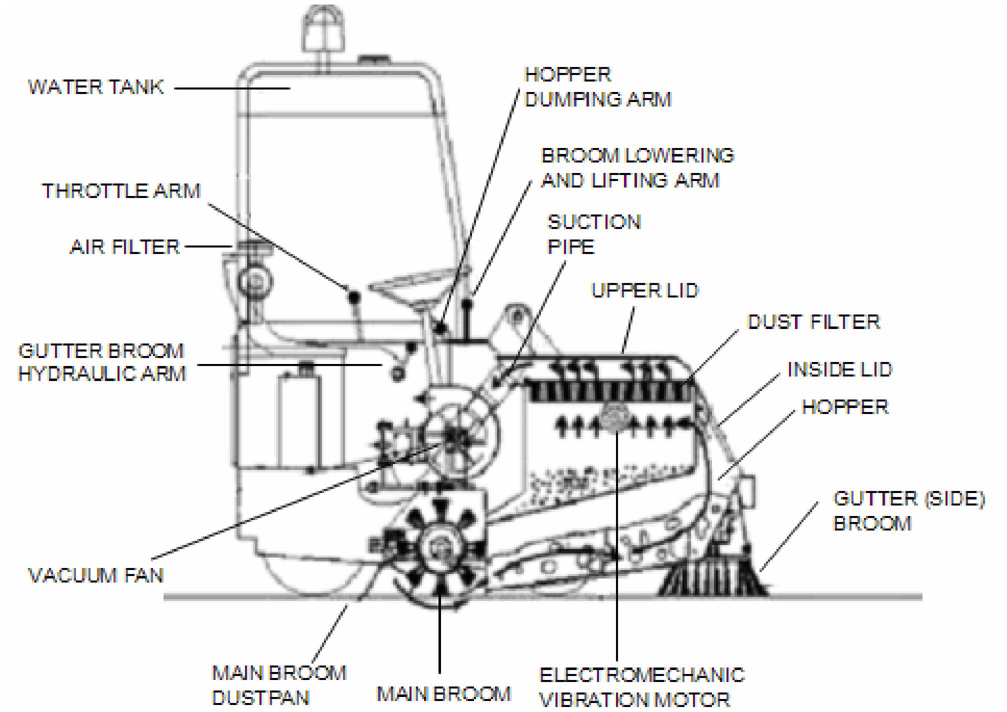

Figure 3 Cleaning principle of VSM 060 vacuum sweeper

There is a three-cylinder diesel engine on the VSM 060 vacuum sweeper. It is driven by a hydraulic motor which is connected to rear wheel. There are two wheels in the front and one at the back. Steering and speed is controlled by the foot pedal [7].

Hydraulic lever has three positions; back, middle and front. Middle is the idle position where hydraulic oil is only sent to driving systems. When the lever is pushed to forward position hydraulic oil is sent to main broom and gutter brooms and these brooms start to work. The position of the main broom is adjusted by the help of the lever at the left side of the steering wheel. When the hydraulic lever is at the rear position hydraulic oil is sent to hopper lifting cylinder.

Figure 4 Müsan VSM 060 sweeper control panel

There are two hydraulic pumps in the system:

- Piston pump which sends hydraulic oil to the driving system
- Gear pump which activates brooms, fan and hopper lifting systems

Steering wheel controls the rear wheel. Mechanical brakes are mounted at the front wheels. Vacuum fan is driven by a high speed hydraulic motor and starts to work automatically when the main broom is activated. An electro-mechanic vibrator is utilized for filter cleaning. Filtered air is used as oil cooler in the system. Total hopper volume is 400 l. Operator manually checks out the debris level by the help of the cover at the front side.

2.2. Comparison with the Other Products

New Müsan VSM 060 sweeper is compared with the former one and the other sweepers in the market according to its determined properties. The vehicles that will be compared are listed as follows:

- Karcher ICC 1D
- Karcher ICC 2 Adv
- Tennant 8300
- Tennant 8210
- Grünig Sweeping Fox 2000
- Nilfisk Advance RS 501
- Dulevo 100 EH
- Dulevo 120 EH

Figure 5 Karcher ICC 1D sweeper [8]

Figure 6 Karcher ICC 2 Adv [8]

Figure 7 Tennant 8300 battery sweeper-scrubber [9]

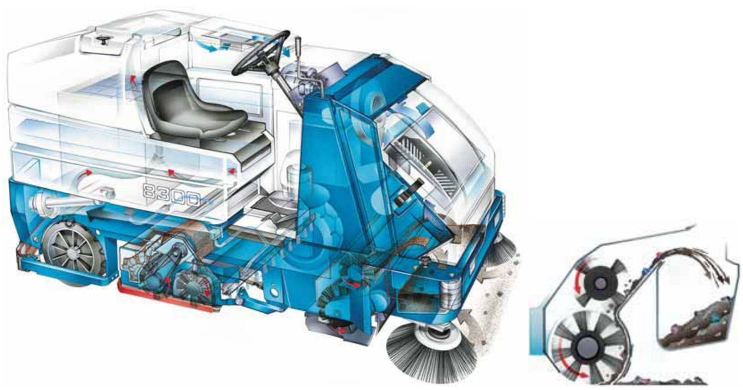

Figure 8 Tennant 8300 battery sweeper-scrubber sweeping system [9]

Figure 9 Tennant 8210 [10]

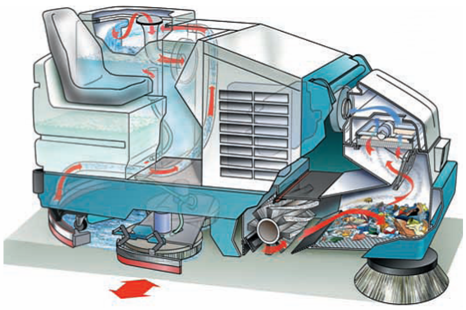

Figure 10 Tennant 8210 sweeping system [10]

Figure 11 Grünig Sweeping Fox 2000 [11]

Figure 12 Dulevo 100 EH [12]

Figure 13 Dulevo 120 EH [13]

Figure 14 Nilfisk Advance RS 501 [14]

Table 2 Comparison Table

TECHNICAL SPECIFICATIONS	New Müsan VSM 060	Former Müsan VSM 060	Karcher ICC 1 D	Karcher ICC 2D ADV	Tennant 8300	Tennant 8210	Nilfisk Advance RS 501	Grünig SF 2000	Dulevo 100 EH	Dulevo 120 EH
Propulsion	Electrical	3 Cyl. Diesel (Kubota)	3 Cyl. Diesel (Kubota)	4 Cyl. Diesel	Electrical	3 Cyl. Diesel (Kubota)	3 Cylinder Diesel	3 Cylinder Diesel	Electrical	Electrical
Traction Power	48 V - 10 kW (13.4 hp)	20 hp (14.9 kW)	14 kW (19 hp)	27 kW (50 hp)	36 V - 3.5 kW (5.7 hp)	28 kW (37.5 hp)	34 hp (25.4 kW)	14 kW (19 hp)	36 V-4 kW (5.4 hp)	48 V-10 kW (13.4 hp)
Speed (km/h)	12	12	16	40			20	10	10,5	12
Operation Speed	10	10	9	16	9	10	12			
Fuel Cons. (l/h)	N/A	3	2	4	N/A		5		N/A	N/A
Hopper Vol. (l)	1000	400	550	1500	85	220	500	305	400	450
Gradeability (%)	% 26/15°	% 26/15°	20	18	8°/%14, 6°/%10.5	8°/%14, 6°/%10.5	22			
Dumping Height (mm)	1200	1200	1350	1550	1524	1445	1460	1400	1500	1500
Cleaning Width (mm)	1350	1050-1550	900-1400	1500 - 2350	1270-1625	1270	1600	2000-2700	1700	1800
Turning Radius (mm)	0	1550	2900	3100	2870	2970	4600	2350	2200	2600

Table 2 (Continued)

TECHNICAL SPECIFICATIONS	New Müsan VSM 060	Former Müsan VSM 060	Karcher ICC 1 D	Karcher ICC 2D ADV	Tennant 8300	Tennant 8210	Nilfisk Advance RS 501	Grünig SF 2000	Dulevo 100 EH	Dulevo 120 EH
Filter Area (m^2)		6			4,9	6			7,5	10
Vacuum Fan Speed (rpm)		5747			4500	14000				
Vacuum Fan Diameter (mm)		250			230					
Theoretical Cleaning Perf. (m^2/h)		15000	12500	37600	9700		19000	20000		
Main Broom Length (mm)	1300	1057			915	915				
Main Broom Speed (rpm)		440			480					
Gutter Broom Diameter (mm)	500	460			480	585	650		600	600
Gutter Broom Speed (rpm)		140			75	90	80		90	110
Water Tank Capacity (l)	N/A	100	150	300			240			
Weight (kg)	2000	1000	1150	1880	1895 (battery included)	1385	2230	1200	2000	1450

Table 2 (Continued)

TECHNICAL SPECIFICATIONS	New Müsan VSM 060	Former Müsan VSM 060	Karcher ICC 1 D	Karcher ICC 2D ADV	Tennant 8300	Tennant 8210	Nilfisk Advance RS 501	Grünig SF 2000	Dulevo 100 EH	Dulevo 120 EH
Length (mm)	3540	2150	2850	4150	1445	1475	3070	1970	2315	
Width (mm)	1310	1350	980	1130	1145	1204	1320	2490	1480	
Height (mm)	2295	2300	1920	1900	2640	2550	1990	2800	2300	
Battery (V)	48	12	12		36				36	48
Battery Capacity (Ah)	1000	60	44							
Front Wheel	Ø500 mm	Ø400X100 mm	2 x 4.80/4.00 -8	185/75/R 16						5.00/8''
Rear Wheel	Ø500 mm	Ø450x120 mm	2 x 165/65/R 13	185/75/R 16						Cushion

In Table 2, new Müsan VSM 060 sweeper is compared with the former VSM 060 sweeper and the other sweepers in the market according to their technical specifications.

The cleaning system design of the new sweeper is not completed yet therefore the vehicle can only be compared according to its structural and mechanical specifications.

New VSM 060 has some advantages due to utilizing electrical propulsion system. The turning radius of the vehicle is zero as the sweeper is capable of making sideward movement with independent wheel hub motors. The operation speed of the vehicle is 10 km/h and it can climb to a terrain which has gradient of 26 % with this speed.

CHAPTER 3

OBJECT OF THE PRESENT INVESTIGATION

Müsan A.Ş. manufactures VSM 060 hydraulic vacuum sweepers for 20 years. The purpose of this thesis is to develop a vacuum sweeper which works efficiently with low noise level, low price and aesthetic design, meeting international environmental standards.

For this reason, during the SAN-TEZ research and development project, the following subjects will be investigated:

- Redesign of VSM 060 vacuum sweeper with aesthetic approach.
- Redesign of traction and motion control system
- Redesign of cleaning system according to the CFD analysis, test results and environmental criteria to provide efficient cleaning.

Sweepers that are driven with internal combustion engines are not suitable for indoor usage due to exhaust emission and noise. Municipality equipment drivers generally suffer from lung diseases and there are many ongoing researches in the world on this subject [15, 16].

In Turkey, there are some projects and regulations to increase the air quality like *EU Twinning Project Air Quality*, 96/62/EC, 99/30/EC regulations [17]. According to these regulations, SO_2, NO_x, PM10, CO, Pb and ozone levels have to be kept below defined limits.

Directive 2000/14/EC of the European Parliament and of the Council of 8 May 2000 on the approximation of the laws of the Member States relating to the noise emission in the environment by equipment for use outdoors which is valid in Turkey states that marking of equipment for use outdoors with its guaranteed sound power level is essential in order to enable consumers and users to make an informed choice of equipment and as a basis for regulation on use or economic instruments to be adopted at the local or national level. Manufacturing companies need to perform their measurements according to this standard to qualify for meeting the EC/2000/14 directive.

Taking these factors into consideration, it is decided to use electrical system instead of internal combustion engine for Müsan VSM 060 sweeper. In electrically driven sweepers, each subsystem can either be actuated by individual electric motors or by a hydraulic system driven by central electric motor. Electric motors are controlled by microcontrollers. Rechargeable batteries supply power to electric motors.

Advantages of electrical systems:

- No exhaust emission
- Lower risk of suffering from diseases due to exhaust emissions
- No noise emission
- No fuel cost
- Cost reduction with rechargeable batteries
- Increase in maneuverability

Disadvantage:

- Limited operation time due to batteries
- Battery compartment weight

The responsibilities of SAN-TEZ 00028.STZ.2007-1 project are shared among the project members.

The work that is investigated throughout this thesis can be summarized as follows:

- The configuration design of the new vehicle
- Design of subsystems and components to be manufactured
- Assembling the detailed designs on the vehicle body
- Finite element analysis of the structure
- Power calculations

Concurrent research that will conduct to another thesis study is about the cleaning system of the vehicle which includes fan design, fan tests and elevator system design.

Punto Mühendislik Ltd. Şti. is responsible for the computational fluid dynamics (CFD) analyses of the cleaning system and system components of the former and new vehicle.

Emsa Otomasyon A.Ş. is responsible for all electrical subsystems, driver and firmware designs. Component procurements and integration of electrical systems to the vehicle will also be done by the firm.

Müsan A.Ş. is responsible for the detailed design of some subsystems and components, drafting for the designed parts and manufacturing.

Initial design requirements are defined at the beginning of the project by the project members and a preliminary vehicle design is constructed by using Catia™, thereon this preliminary design is improved with additional requirements and encountered constraints.

Design requirements for the new sweeper can be listed as follows:

- Length will be in the range of 2150-3150 mm
- Width will be approximately 1350 mm
- The height of the sweeper must be kept as low as possible
- For traction, electric motor driven system will be used instead of internal combustion engine driven system
- For the control of the vehicle a joystick and a steering wheel will be used. Joystick will be utilized for forward-backward movement and steering wheel for steering of the vehicle.
- There will be four wheels on the vehicle
- Wheels will have independent electric motors for traction and rotation around their vertical axis
- Driver circuits will be designed to run the electric motors

- Firmware will be developed for the motion control of the sweeper
- Cabin will be made from lightweight material
- There will be one driver seat in the cabin
- Driver seat is at the right side of the cabin to provide better vision
- Joystick, steering wheel and their equipments will be placed on a control panel
- Control panel will be mounted in front of the driver seat
- Ergonomic issues will be taken into consideration for the cabin and interior design
- There will a 3-dimensional chassis made up of steel tubes
- Tires will be at least 500 mm in diameter
- It will be preferred to supply off-the-shelf equipments from domestic market
- Cleaning system will be a combination of vacuum system and mechanical broom system
- The volume will be approximately 1 m^3
- Linear actuators will be used for the dumping mechanism of the hopper and vertical movement of the gutter brooms.

CHAPTER 4

POWER CALCULATION

In order to calculate the power requirement of the traction electric motors, total force that has to be applied by the vehicle must be calculated. This force is the summation of rolling resistance force, gradient resistance force, air resistance force and inertial force.

$$F_T = F_r + F_g + F_a + m \times a_{\max} \tag{4.1}$$

F_T : Total force that can be applied by the vehicle

F_r : Rolling resistance force

F_g : Gradient resistance force

F_a : Air resistance force

M : Mass of the vehicle [kg]

$a_{\max}$: Maximum acceleration of the vehicle

$V_{\max}$: Maximum operation speed of the vehicle

W : Weight of the vehicle

Mass of the vehicle is assumed to be 2200 kg when it is fully loaded and maximum operation speed is 10 km/h.

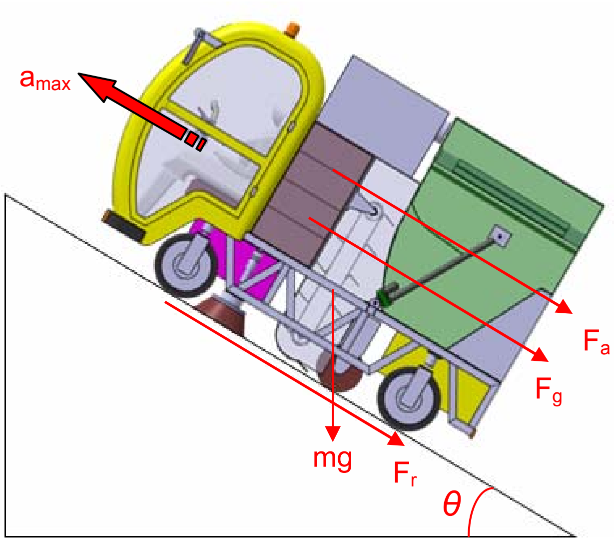

Figure 15 Force representation

4.1. Rolling Resistance

$$F_r = f_r \times W \tag{4.2}$$

f_r : Coefficient of rolling resistance

Coefficient of rolling resistance is taken to be 0.018 for average tarmac road condition.

F_r = 388.5 N

Table 3 Coefficients of rolling resistance for different road conditions [18]

Road Surface	f_r
Very good concrete	0.008-0.010
Average concrete	0.010-0.015
Concrete in poor condition	0.020
Very good tarmac	0.010-0.0125
Average tarmac	**0.018**
Tarmac in poor condition	0.023
Very good macadam	0.013-0.016
Average macadam	0.018-0.023
Dusty macadam	0.023-0.028
Good Stone paving	0.033-0.055
Stone paving in poor condition	0.033-0.055
Snow(50mm layer)	0.025
Snow(100mm layer)	0.037
Unmaintained natural road	0.080-0.160
Sand	0.150-0.300

4.2. Gradient Resistance

$$F_g = W \times \sin\theta \tag{4.3}$$

θ : Angle of the climbed hill with respect to horizontal plane

Gradient can be defined as tangent of the angle of inclination (θ) multiplied by 100 to obtain percentage. Gradient resistance is calculated for 15 degrees (26.8% gradient).

F_g = 5585.8 N (15 degrees)

Table 4 Angle-Gradient correspondence

Angle	Gradient (%)
5	8,8
10	17,6
15	**26,8**
20	36,4

4.3. Air Resistance

$$F_a = 1/2 \times \rho \times C_d \times A_f \times V_{air}{}^2 \tag{4.4}$$

ρ : Air density [kg/m3]

C_d : Drag coefficient

A_f : Frontal area of the vehicle

V_{air} : Velocity of the vehicle with respect to the air [m/s]

V_{air} it is assumed to be equal to the maximum velocity of the car and for the maximum power calculation which is 10 km/h.

Air density is assumed to be 1,169 kg/m3 [19] for 25°C and 100 kPa and drag coefficient is assumed to be 0.3 [20].

F_a = 2.5 N

Although this value is negligible, it is still added into the calculation.

4.4. Force Due To Inertial Acceleration

$$F = m \times a_{\max} \tag{4.5}$$

a_{max} is assumed to be approximately 0.5 m/s^2

F = 1100 N

4.5. Total Force

$$F_T = F_r + F_g + F_a + m \times a_{\max} \tag{4.1}$$

F_T = 7076.8 N

4.6. Power

Power required is calculated as:

$$P_e = F_T \times V_{\max} \tag{4.6}$$

P_e = 19673.6 Watt

This power value is calculated for the extreme case scenario where the sweeper is cleaning a terrain which has a gradient of %26.8 and is also accelerating meanwhile. In reality this situation may last only for a few seconds. For these situations, DC motors reach maximum power level instantaneously which is nearly %150 of its nominal power.

DC motors that will be used for the sweeper are chosen according to average power consumption which is approximately 10 kW. Four 2.5 kW car hub motors are ordered from a DC motor manufacturer company in China. Motor details will be given in Chapter 5.

Table 5 Traction power table

Angle (deg)	Grad.	Rolling Res. [N]	Grad. Res. [N]	Air Res. [N]	Inertial Force [N]	Total Force [N]	Power [W]
0	0,000	388,48	0,00	2,52	1100,00	611,12	4144,97
1	0,017	388,48	376,66	2,52	1100,00	987,78	5192,08
2	0,035	388,48	753,20	2,52	1100,00	1364,32	6238,87
3	0,052	388,48	1129,51	2,52	1100,00	1740,64	7285,02
4	0,070	388,48	1505,48	2,52	1100,00	2116,61	8330,22
5	0,087	388,48	1881,00	2,52	1100,00	2492,12	9374,14
6	0,105	388,48	2255,93	2,52	1100,00	2867,05	10416,47
7	0,123	388,48	2630,18	2,52	1100,00	3241,31	11456,88
8	0,141	388,48	3003,63	2,52	1100,00	3614,76	12495,07
9	0,158	388,48	3376,17	2,52	1100,00	3987,29	13530,72
10	0,176	388,48	3747,67	2,52	1100,00	4358,80	14563,51
11	0,194	388,48	4118,04	2,52	1100,00	4729,16	15593,12
12	0,213	388,48	4487,15	2,52	1100,00	5098,27	16619,25
13	0,231	388,48	4854,89	2,52	1100,00	5466,02	17641,57
14	0,249	388,48	5221,16	2,52	1100,00	5832,28	18659,79
15	**0,268**	**388,48**	**5585,83**	**2,52**	**1100,00**	**6196,95**	**19673,59**
16	0,287	388,48	5948,81	2,52	1100,00	6559,93	20682,65
17	0,306	388,48	6309,97	2,52	1100,00	6921,09	21686,68
18	0,325	388,48	6669,20	2,52	1100,00	7280,33	22685,36
19	0,344	388,48	7026,41	2,52	1100,00	7637,53	23678,40
20	0,364	388,48	7381,48	2,52	1100,00	7992,60	24665,48

CHAPTER 5

VEHICLE DESIGN

For the design of the Müsan VSM 060 sweeper under SAN-TEZ program, commercial 3D modeling tool Catia™ V5 is used. Technical drawings of parts and assemblies are given in Appendix.

5.1. System Configuration Design

To build a preliminary design, current VSM 060 vacuum sweeper dimensions are taken as the basis for dimensioning. The current sweeper's width is 1.35 m and length is 2.15 m; in the new design it is decided to keep the width same but to have a length in the range of 2.15-3.15 m.

The current vehicle has three wheels, two at the front and one at the rear side. In the new design, to increase the maneuverability of the sweeper, it is decided to have four wheels which have independent motors instead of three wheels. A joystick will be used for the steering and rotation of the wheels. Cabin, brooms, wheels, battery compartment, hopper and motor controller compartment are drawn and assembled. The first models are shown in the following figures.

Figure 16 Initial VSM 060 design study

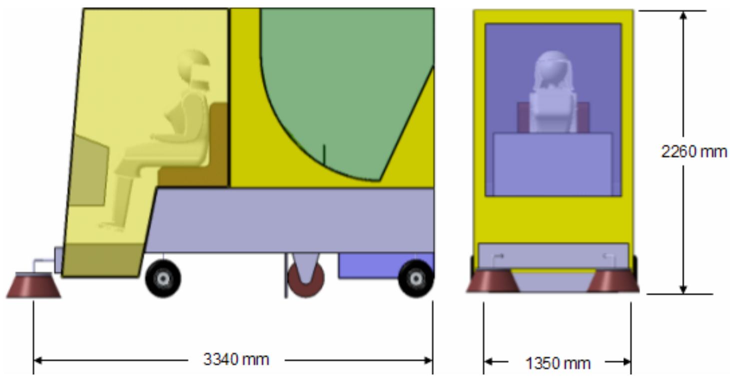

Figure 17 Initial VSM 060 design outer dimensions

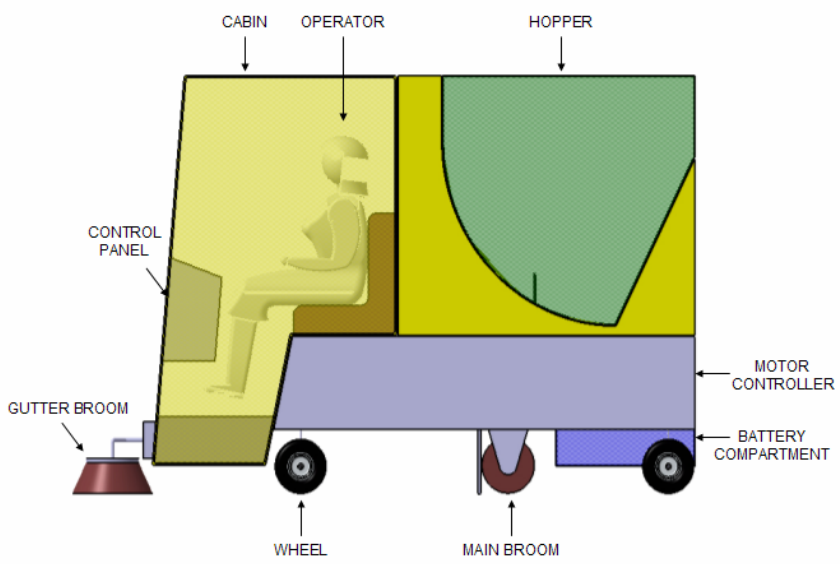

Figure 18 Initial VSM 060 design subsystems

Figure 19 Second VSM 060 design study

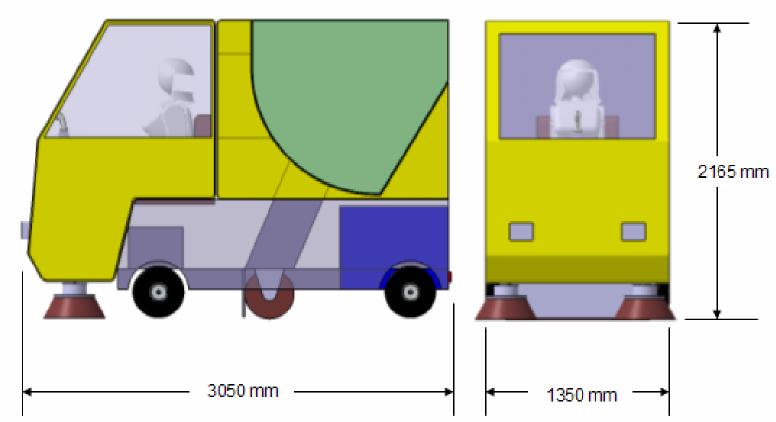

Figure 20 Second VSM 060 design outer dimensions

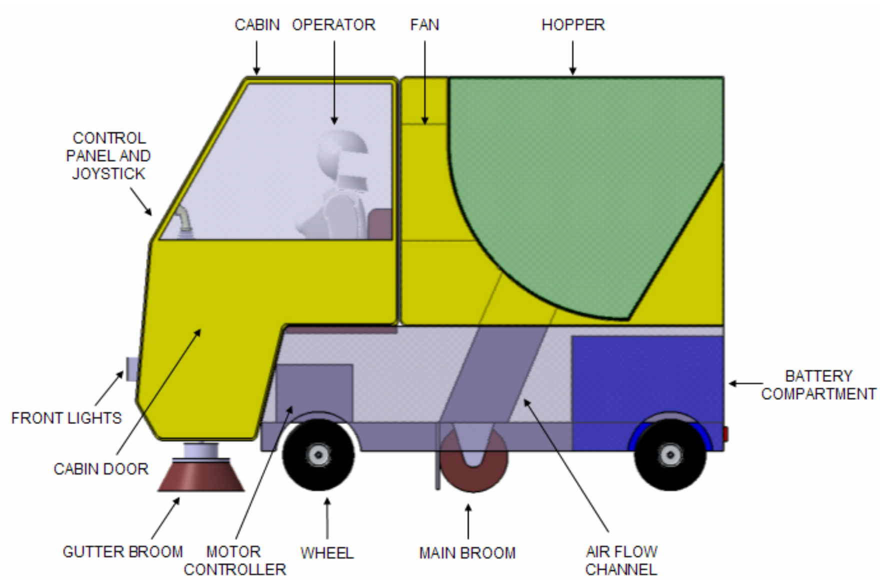

Figure 21 Second VSM 060 design subsystems

These basic system configuration models are developed with new design requirements and parameters.

Ergonomic issues are taken into consideration for the cabin and panel designs. Driver seat and control panel are shifted to the right side to have a more clear vision. It is intended to leave enough clearance for the comfort of the driver. Left side of the driver is left free for additional equipments that may be needed in the detailed design phase. A convex front window from floor level to ceiling of the cabin is added to the model.

A 2D chassis is constructed from welded rectangular profile steel tubes. The total battery weight must be distributed on the chassis in order to avoid uneven loading on the chassis therefore battery casings are located in the front and rear sides of the vehicle.

Tires are claimed to be 500 mm in diameter and to be easily procurable in the market for maintenance purposes.

To improve the cleaning system, it is decided to use a mechanical elevator system beside the vacuum system. Linear actuators are used for the vertical movement of the gutter brooms and for the dumping mechanism of the hopper. The hopper volume is 1 m^3.

Figure 22 Third VSM 060 design study

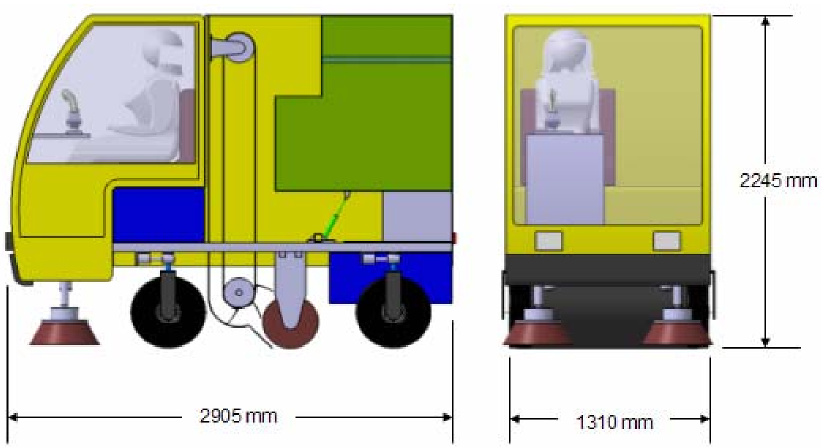

Figure 23 Third VSM 060 design outer dimensions

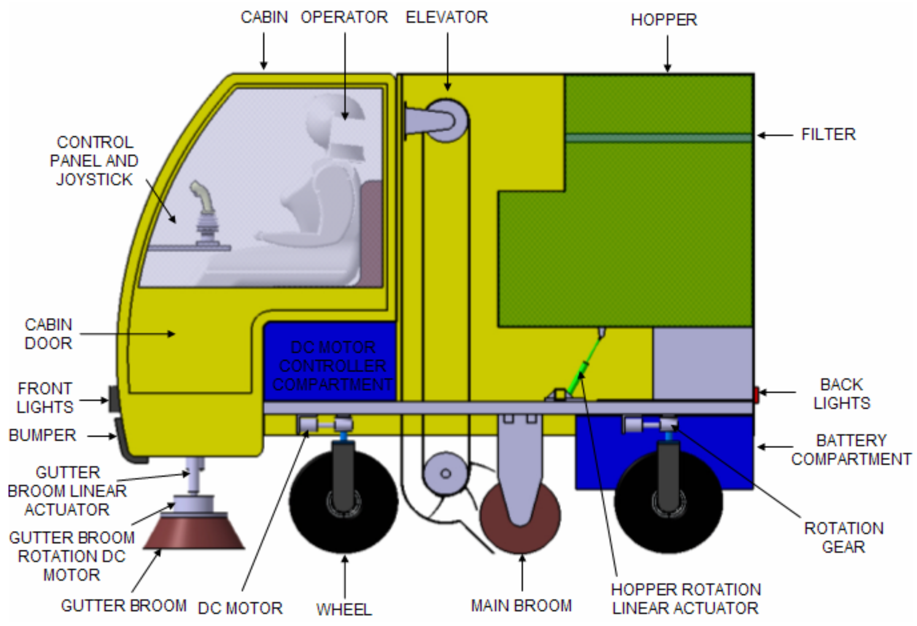

Figure 24 Third VSM 060 design subsystems

The elevator system is modified by shortening the system length, lowering it to the ground and by making the dustpan at the tip of the collector panel a little bit shorter. The motor controller casing is relocated to a more appropriate place instead of bottom of the hopper. With this relocation the hopper comes closer to the chassis.

The gutter brooms and vehicles front wheels are replaced. Gutter brooms are repositioned just before the elevator to increase the efficiency of the debris collection and to avoid scattering of dust and debris before main broom.

It is important to protect delicate parts like DC motors and actuators from damage therefore the linear actuators of the gutter brooms and DC motors that enable the rotation of the wheels around its own axis are kept within the frame of the chassis.

The hopper actuators and controllers are put into a triangular casing at the rear side of the chassis which is also used for the hinges of the hopper enabling rotation for dumping.

Some aesthetic features like warning light on top of the cabin, door frames, handles and hinges are added to the design.

Figure 25 Fourth VSM 060 design

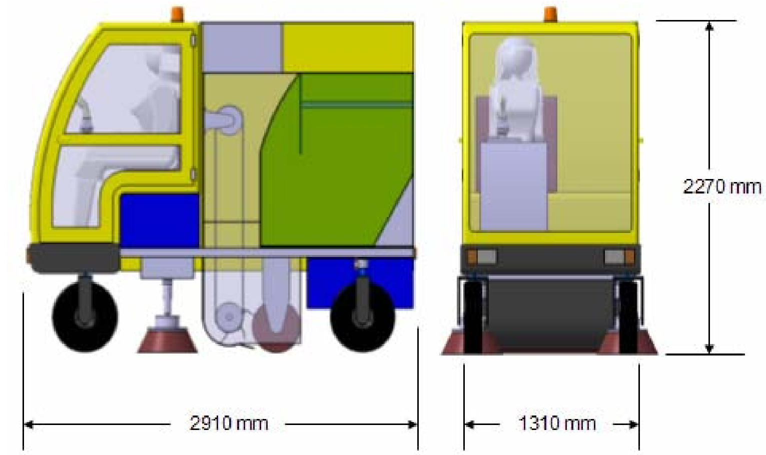

Figure 26 Fourth VSM 060 design outer dimensions

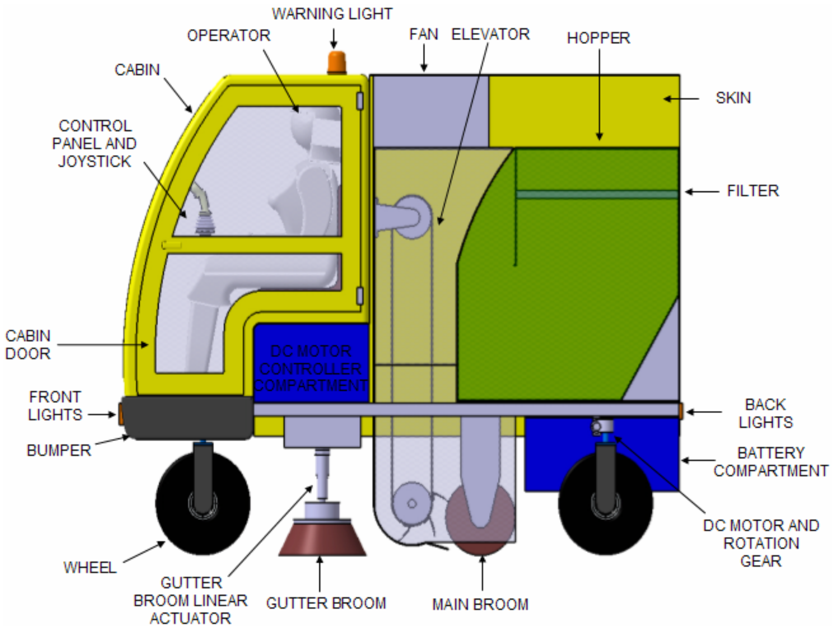

Figure 27 Fourth VSM 060 design subsystems

Chassis design is modified from 2D to 3D construction to provide structural rigidity and to reduce total height of the sweeper. It is a welded construction from 60x40x3 [mm] steel tubes. The bottom level of the chassis corresponds to the center level of the wheel. Wheels are placed so that there is no clash with the 3D chassis at any angle of rotation. All subsystems are relocated according to the new chassis construction. Cabin is modified by changing the curvature of the front window.

The conveyor system is shortened a little bit more for efficiency of the debris collection. Fan module is placed on top of the conveyor system. Two fan suction pipes are placed between the fan and the hopper.

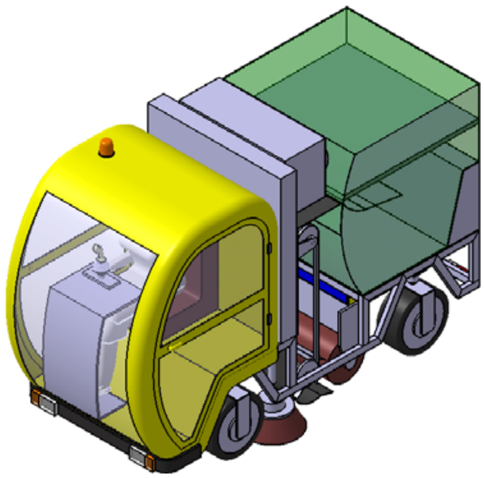

Figure 28 Fifth VSM 060 design

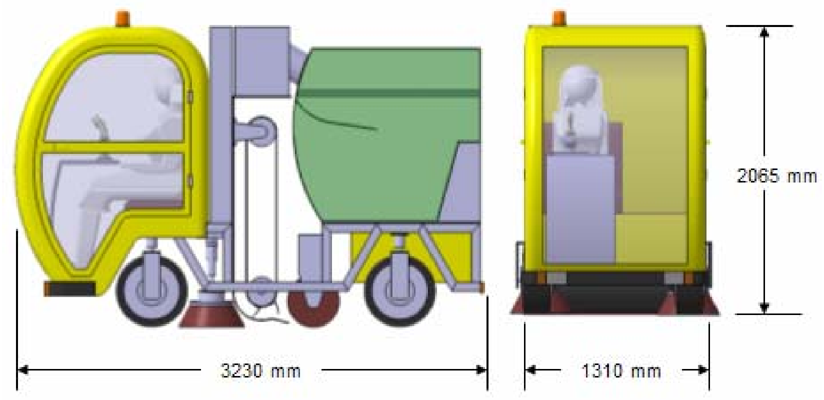

Figure 29 Fifth VSM 060 design outer dimensions

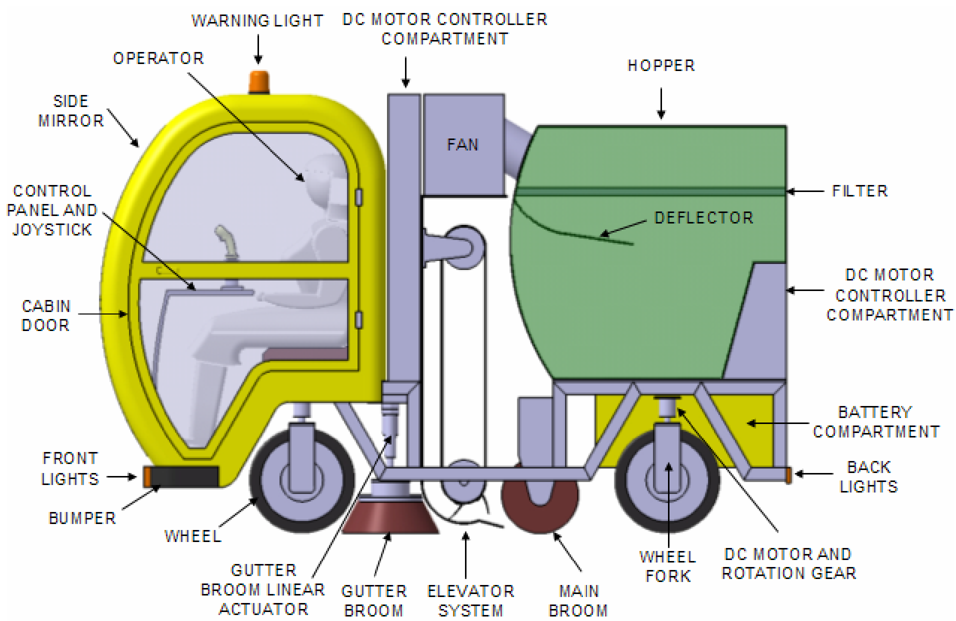

Figure 30 Fifth VSM 060 design subsystems

Chassis is elongated and strengthened at the middle section. Support frames are added to the chassis where necessary. To provide balanced loading on the chassis, battery compartment is placed in the middle section. Battery compartment dimensions are defined such that it accommodates sixteen batteries inside.

Cabin length is shortened and control console is touched up. Besides the joystick, a steering wheel is added. Joystick will be used for forward-backward movement and steering wheel will be used for steering of the vehicle.

Fan is placed on top of the battery compartment and conveyor system. Fan suction pipe is made as short as possible. The curvature of the hopper and the angle of the fan suction pipes are modified so that at its normal position, hopper makes pressure on the seals of the inlet of the fan suction pipes.

The hopper is divided into two. Upper and lower parts are connected by the help of four electrical actuators. Filter is shifted upwards and secured with L-profile sheet metals that are fixed from inside to the upper part. A protective perforated sheet metal is placed under the filter and above the deflector inside to protect the filter from the sharp objects during bumping. The filter must be cleaned during operation to avoid clogging. Filter cleaning will be done with mechanical vibration created by an eccentric electric motor that will be mounted on the filter. This motor will be activated by the operator. Before the electromechanic vibration, four electric actuators will elongate detaching the upper part of the hopper from the lower part. After the filter cleaning these actuators will come back to their original position.

Hopper dumping mechanism is designed. Hopper will be rotated around its hinges by the help of linear actuators on both sides. Linear actuators are supported from the chassis. Hopper lid is between the filter and hinge of the hopper having a height of 230 mm. Lid is opened and closed by the command of operator from control panel. When it is opened the bottom of the lid is at least 1280 mm above the ground level assuming that the container height is 1200 mm.

The conveyor system components are modified. One wide polyester belt from one pulley to the other will be used instead of two separate belts. Bucket shaped pendants become wing shaped.

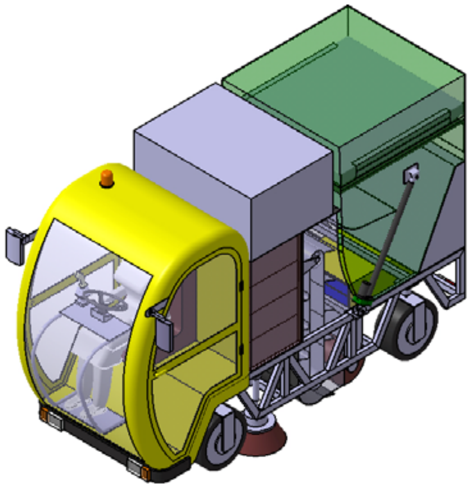

Figure 31 Sixth VSM 060 design

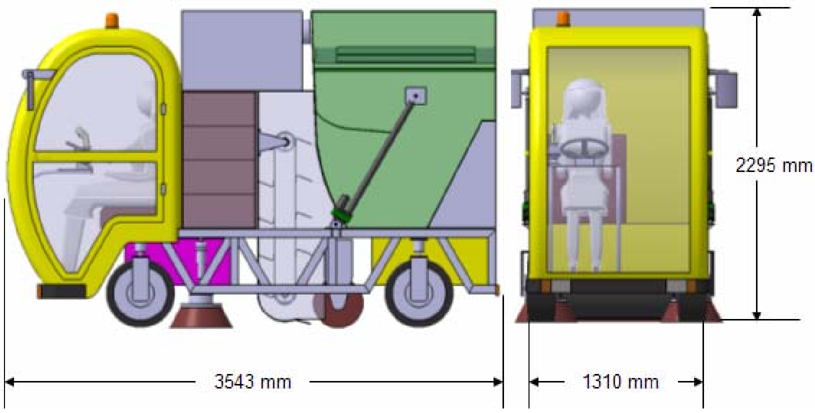

Figure 32 Sixth VSM 060 design outer dimensions

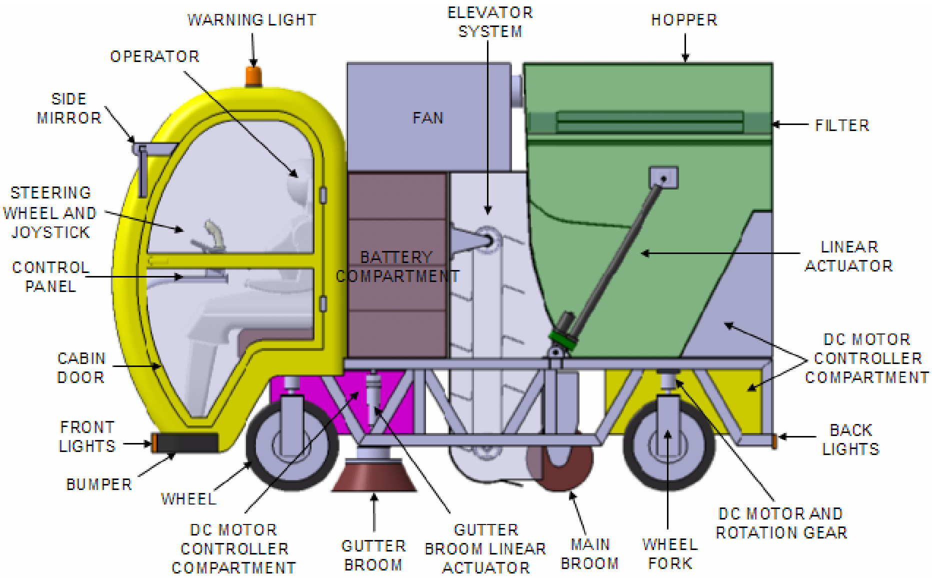

Figure 33 Sixth VSM 060 design subsystems

The sweeper will climb to the pavements for cleaning. To ease the climbing and to avoid tipping over and hitting the bottom part of the chassis to the curbs, the chassis is shortened and strengthened with ribs on both sides.

For the mounting of the wheels, two sheet metal parts are used instead of support steel tubes chassis.

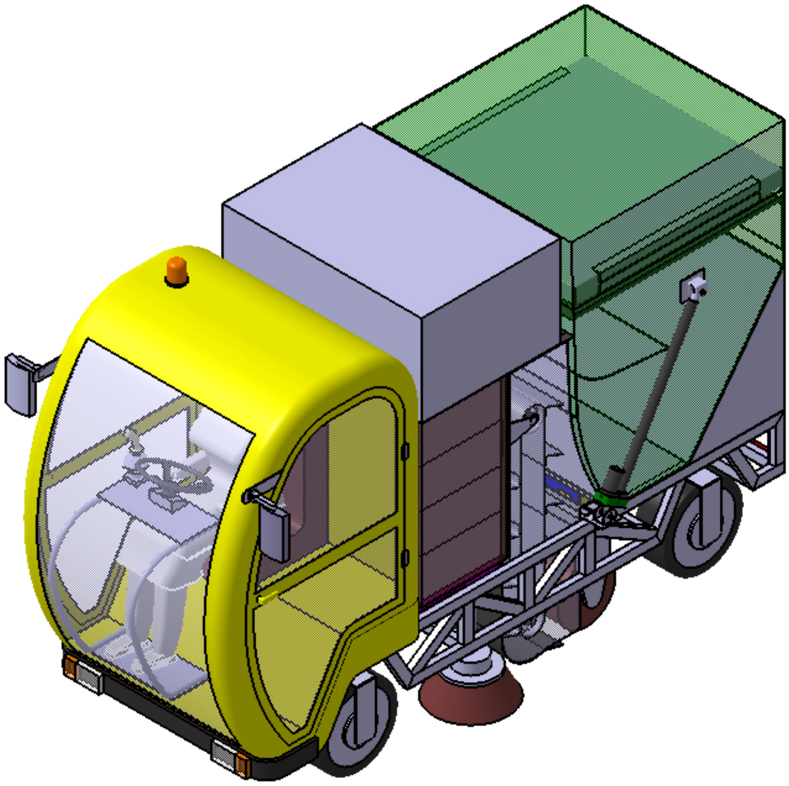

Figure 34 Seventh VSM 060 design

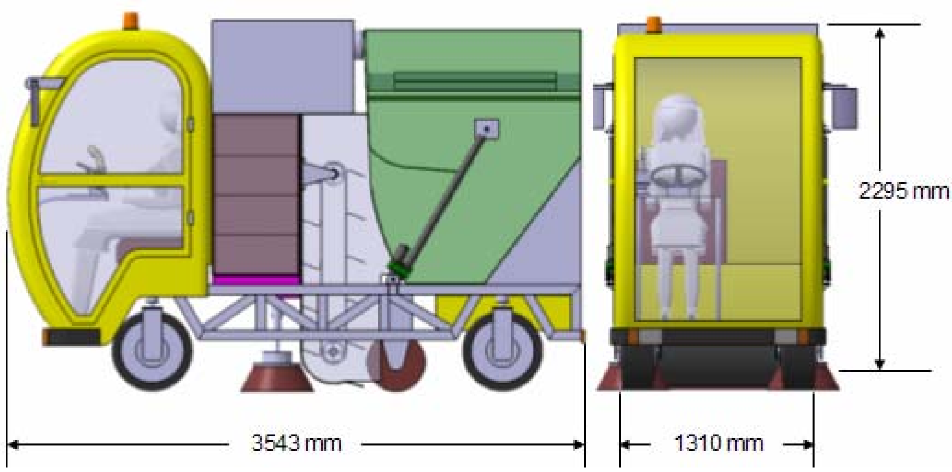

Figure 35 Seventh VSM 060 design outer dimensions

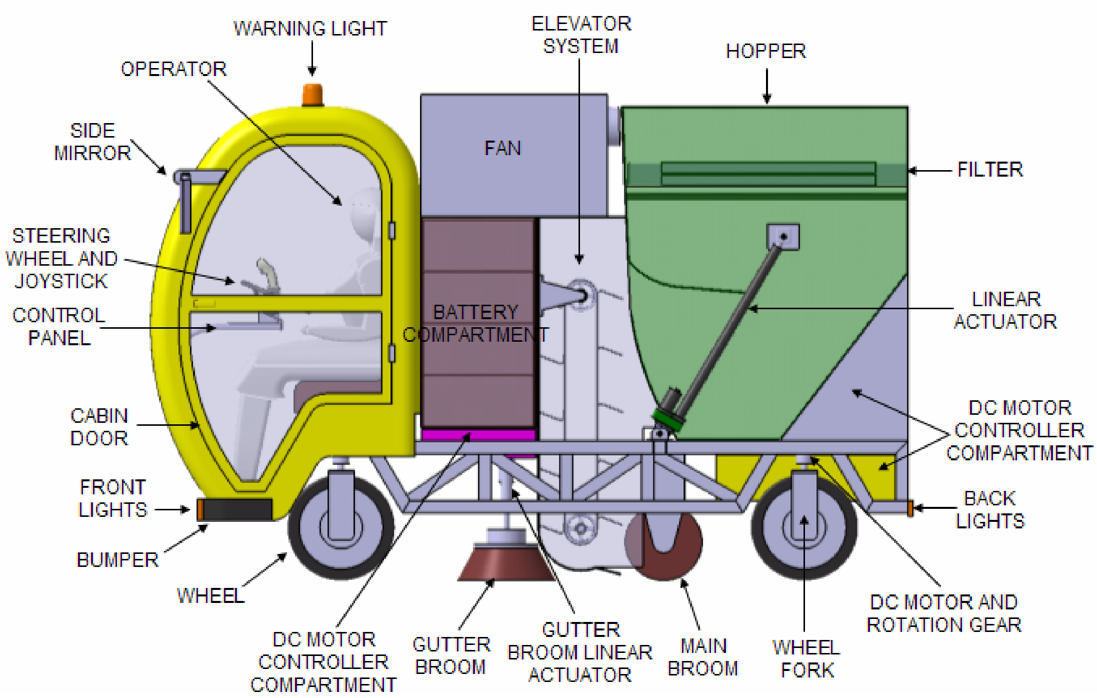

Figure 36 Seventh VSM 060 design subsystems

Vehicle design is not finished yet. Except the chassis and wheels, all the subsystems and components are still subject to change during the detailed design phase. A cover panel will be mounted to the vehicle body to secure the delicate parts and to avoid dust emission to the surround.

Chassis is manufactured. Wheels and their DC motors for rotation are mounted on the chassis which can be seen in the following **Figure 37**.

Figure 37 Chassis

5.1.1. Center of Gravity Locations

Center of gravity locations in the horizontal direction for empty, fully loaded and dumping conditions are found at the end of configuration design study.

Center of gravity locations vary slightly due to weight and rotation of the hopper. As the design is not finished, the masses of the components can only be estimated and according to these estimations a rough calculation is made to guess the center of gravity locations for three conditions.

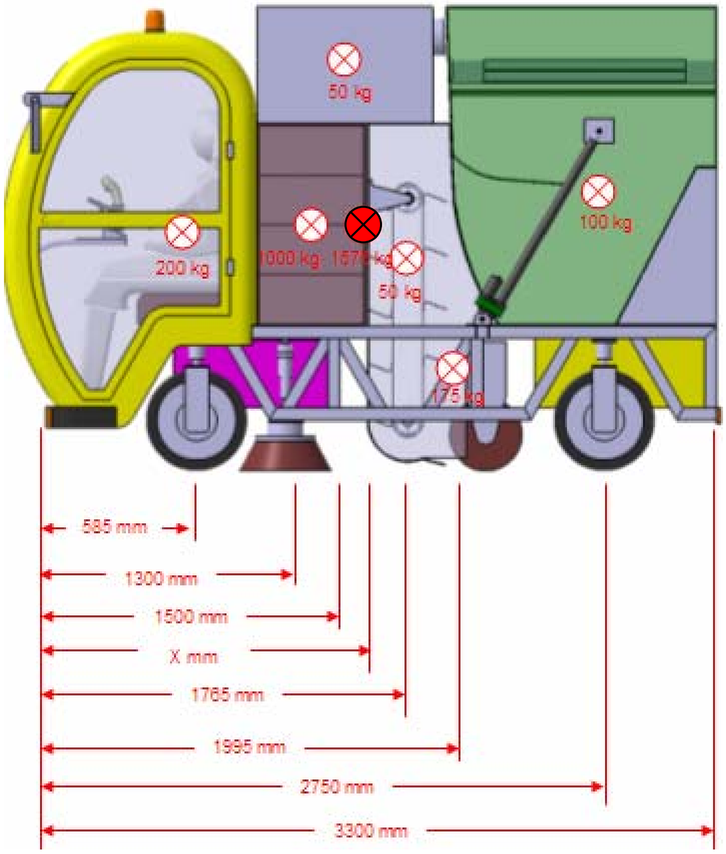

Figure 38 Empty condition

$$(200kg*585mm)+(1000kg*1300mm)+(50kg*1500mm)+(50kg*1765mm)+$$
$$(175kg*1995mm)+(100kg*2750mm)=(1575*X)$$
$$X=1400mm$$

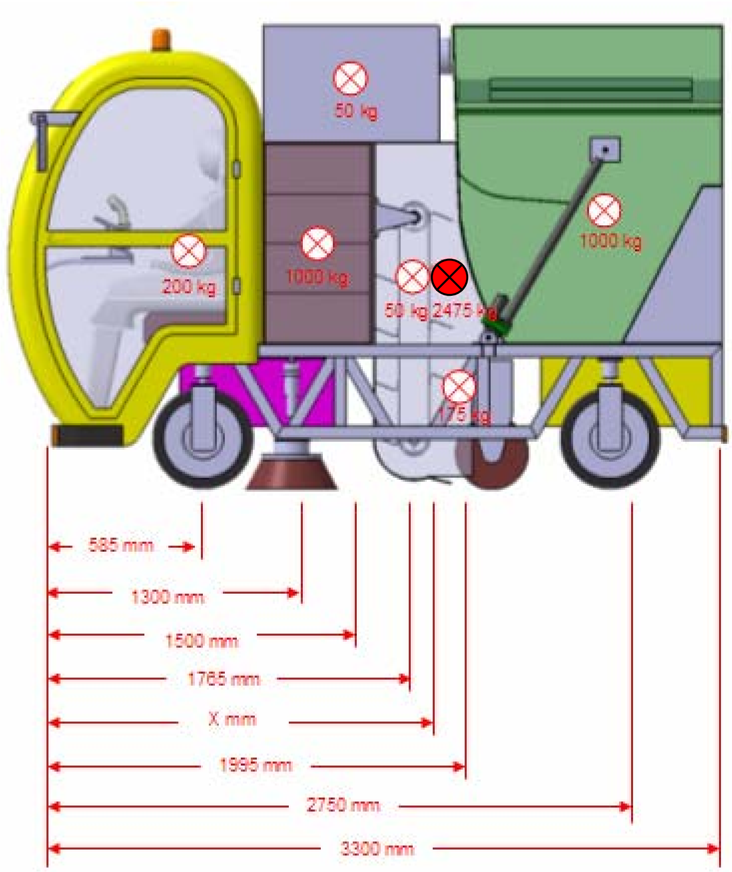

Figure 39 Fully loaded condition

$$(200kg*585mm)+(1000kg*1300mm)+(50kg*1500mm)+(50kg*1765mm)+$$
$$(175kg*1995mm)+(1000kg*2750mm)=(2475*X)$$
$$X=1890mm$$

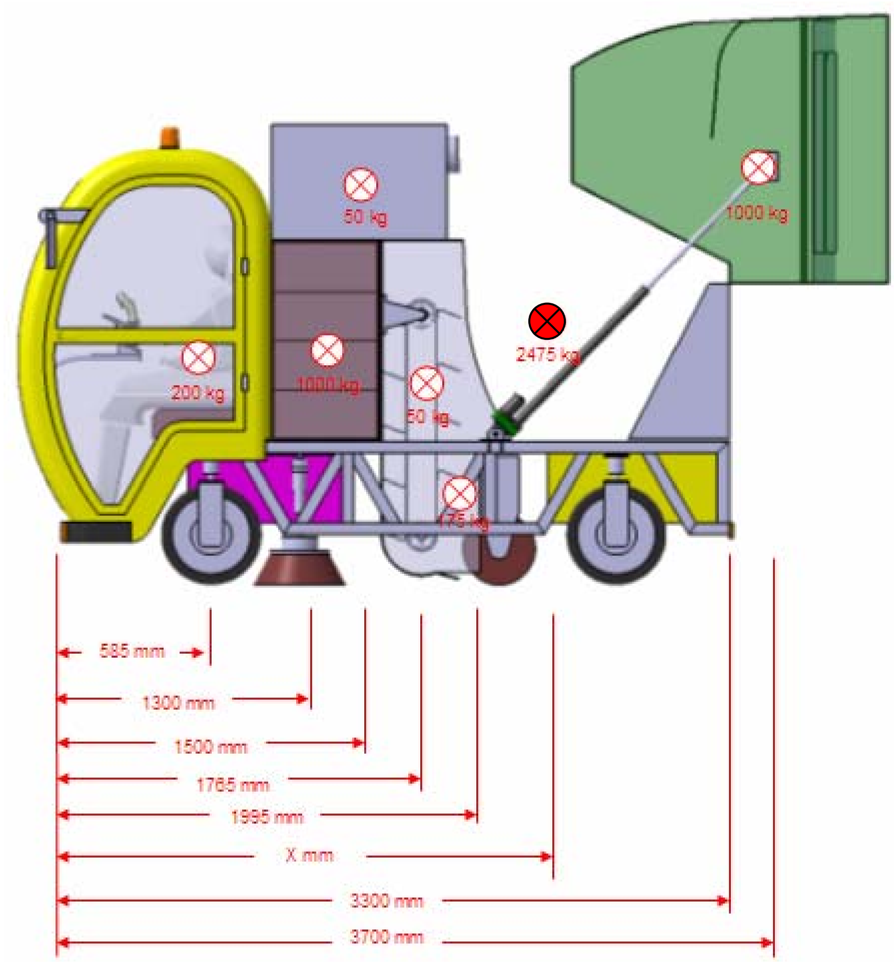

Figure 40 Dumping condition

$$(200kg * 585mm) + (1000kg * 1300mm) + (50kg * 1500mm) + (50kg * 1765mm) +$$
$$(175kg * 1995mm) + (1000kg * 3700mm) = (2475 * X)$$
$$X = 2275mm$$

It is seen that center of gravity locations in X-direction for empty, fully loaded and dumping at fully loaded condition are 1400 mm, 1890 mm and 2275 mm from the bumper tip of the vehicle respectively.

5.2. Cabin

Cabin will be manufactured from composite or light alloy material. Some cabin equipments will be supplied from the market and some will be manufactured. Off-the-shelf equipments like driver seat, warning light, joystick, steering wheel, mirrors, front lights, windshield wiper mechanism, handle mechanism, etc. will be bought and mounted on the cabin. Other parts will be manufactured according to the cabin design.

Driver seat and control panel are on the right side of the cabin. The joystick, steering wheel and their equipments are mounted on the control panel. The left side of the driver is left for any equipment that may be needed in the detailed cabin design phase.

Cabin design and dimensions represented in **Figure 41** and **Figure 42** can be changed in the next phases of the project.

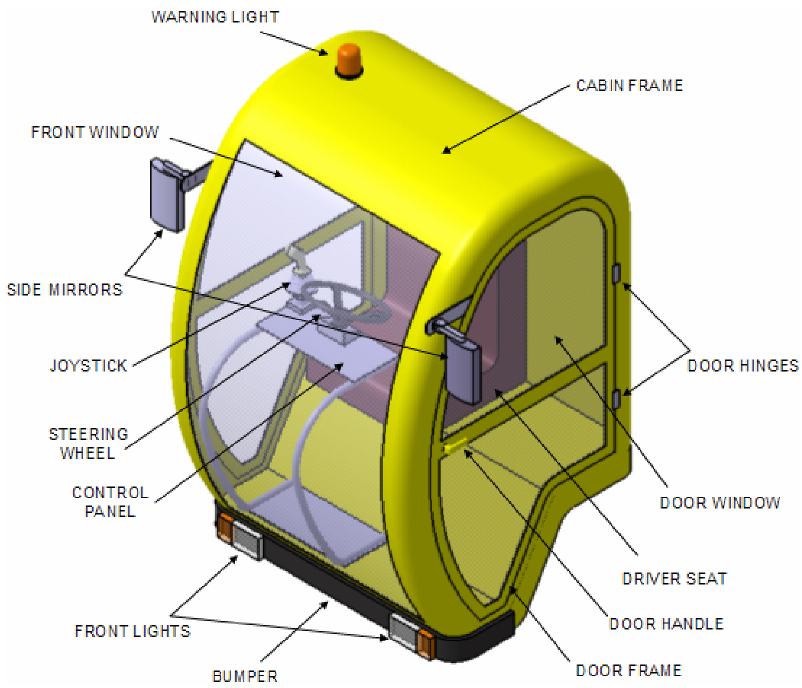

Figure 41 Cabin

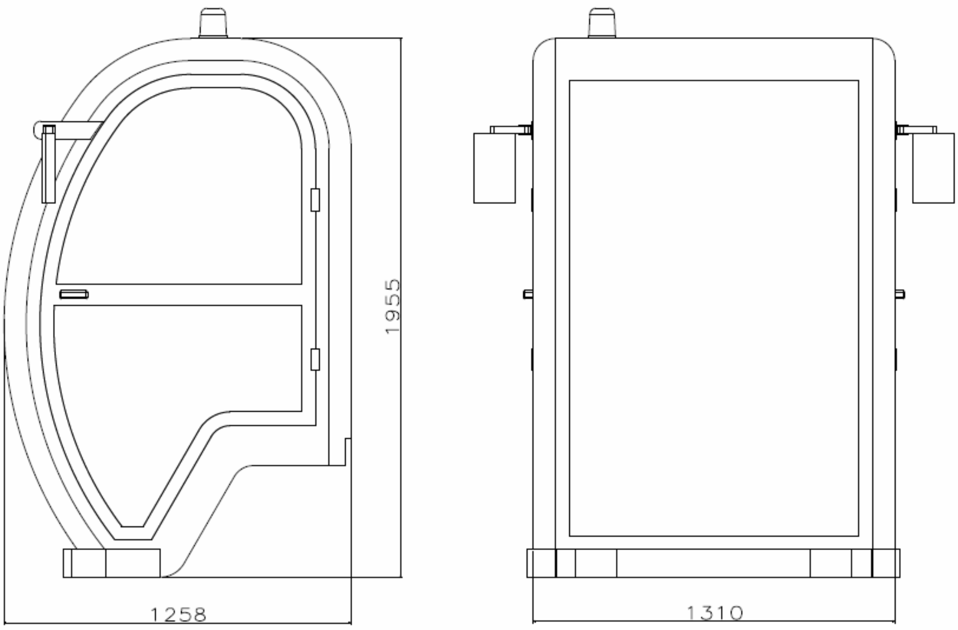

Figure 42 Cabin outer dimensions

5.3. Chassis

The chassis of the sweeper is constructed by using 60x40x3 [mm] steel tubes. All of the equipments are mounted on the chassis therefore it provides integrity of the body.

The initial chassis design is a 2D rectangular frame. It is modified and a 3D chassis frame is constructed to provide rigidity to the structure and also to shorten the overall height of the sweeper.

Three basic 3D chassis frame designs are made. The first design is not taken into consideration so the static analyses are made for the second and third designs.

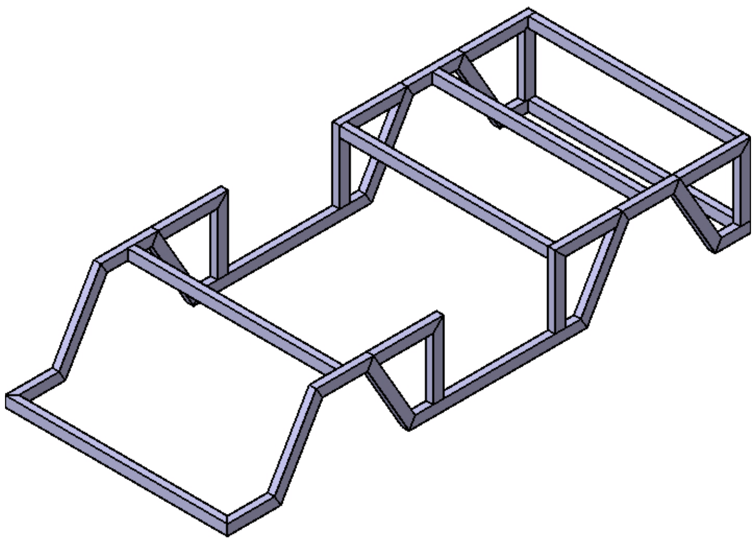

Figure 43 First 3D chassis design

Second chassis is constructed from 60x40x3 [mm] steel tubes and weighs approximately 100 kg. First FEA is made for this chassis construction. As the material of the chassis would either be St52-3 or St44-3, the results obtained from the analysis are interpreted according to the St52-3 and St44-3 steel tube mechanical properties.

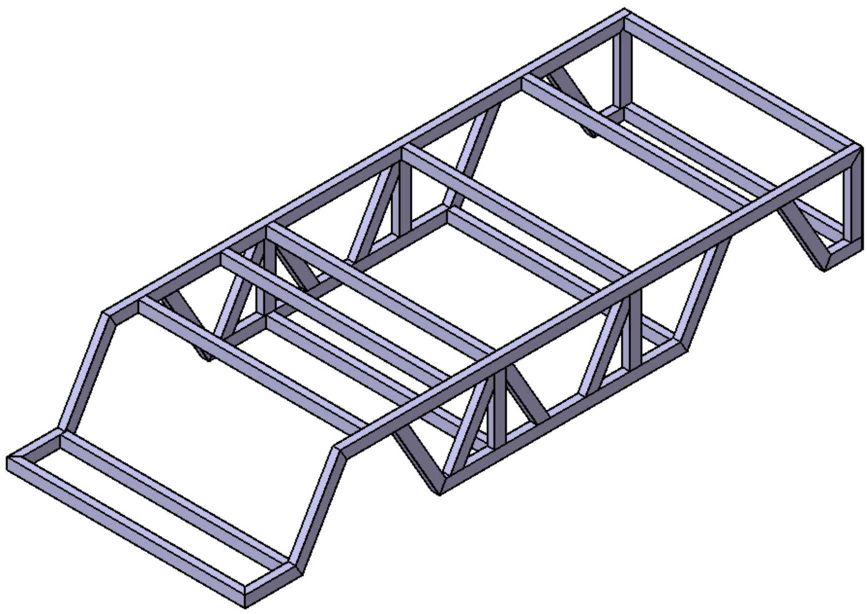

Figure 44 Second 3D chassis design

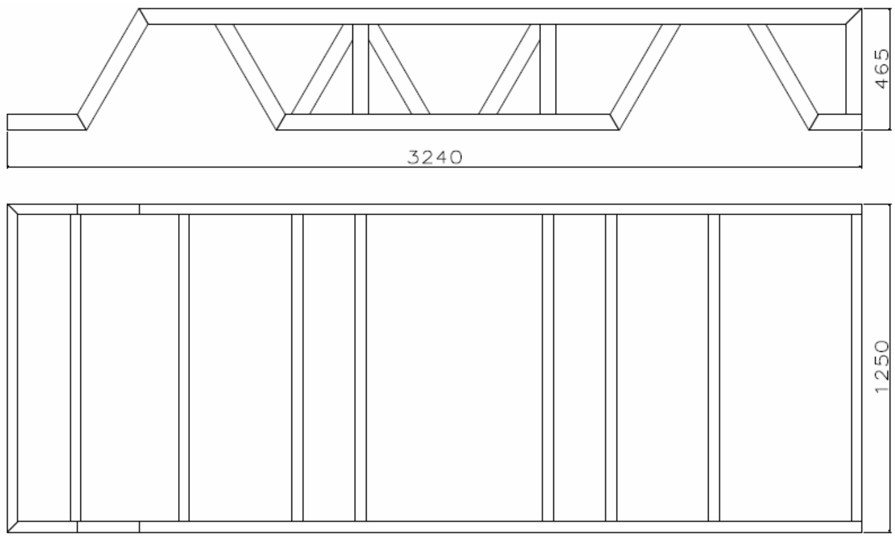

Figure 45 Second 3D chassis outer dimensions

This second chassis design is acceptable and safe from analysis point of view but it is modified due to other reasons which can be summarized as follows:

- St 52-3 or St 44-3 steel tubes cannot be easily found in the market
- Height of the chassis can cause problems during climbing to the pavements
- Mounting details of the wheels require modification on the chassis

In the new design, 60x40x3 [mm] St37-2 grade steel tubes are used for the ease of procurement.

The length and width of the chassis remains same but the overall height is shortened 125 mm. With this modification it is aimed to avoid the contact of the bottom part of the chassis with the ground or with the edges of the pavements during climbing.

As St 37-2 steel tubes are used, chassis is supported with additional ribs on both sides to provide structural rigidity. Sheet metal frames with mounting provisions for the wheels are added to the design. Chassis weighs approximately 175 kg.

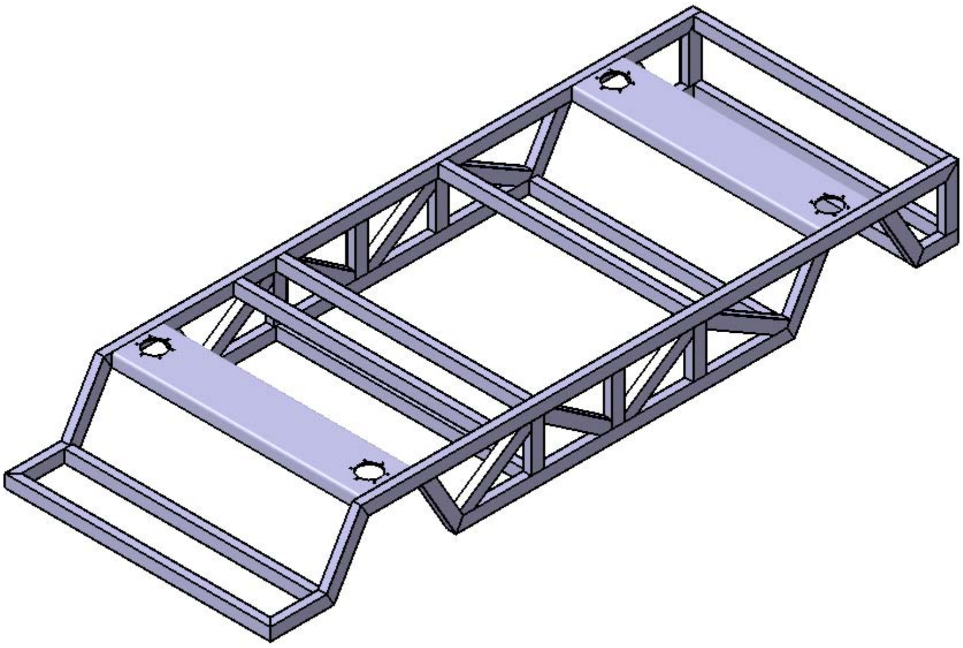

Figure 46 Third 3D chassis design

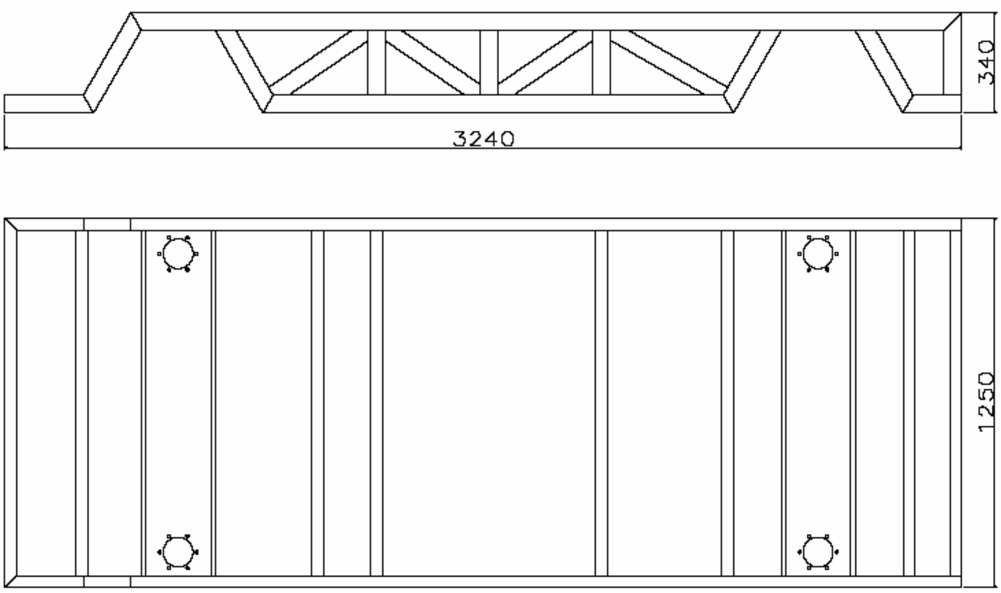

Figure 47 Third 3D chassis outer dimensions

5.3.1. Finite Element Analysis of the Chassis

Finite element analysis is made to determine the deformation and stresses on the chassis construction under loading. Commercial MSC Patran pre and post processor and MSC Nastran solver programs are used for FEA.

The critical case for the FEA is the dumping case. During dumping, the fully loaded hopper which is nearly 1000 kg is rotated around the hinges. This creates moment causing deformation on the chassis. Therefore FEA for the chassis is made for the dumping position.

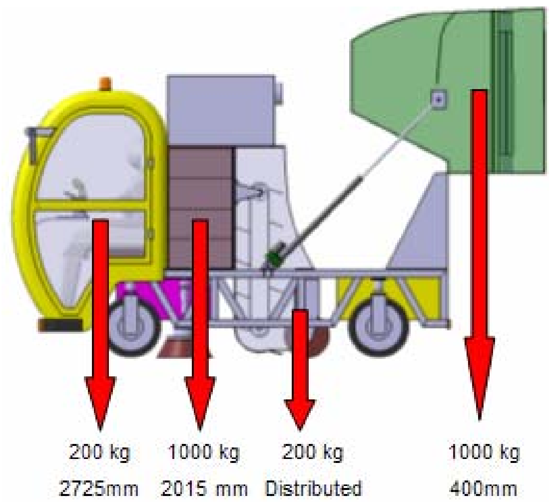

Figure 48 Simplified load distribution on the chassis

Simple moment calculation is done to check if there is any risk of tipping over for this case and it is found that tipping over is not possible. Distances given in **Figure 48** are measured from the rear tip of the chassis.

$$(1962N * 2.725m) + (9810N * 2.015m) + (1962N * 1.450m) > (9810N * 0.400m)$$
$$27958.5Nm > 3924Nm$$

Wireframe of the chassis is modeled by using Catia™ V5 and imported into MSC Patran to create meshes.

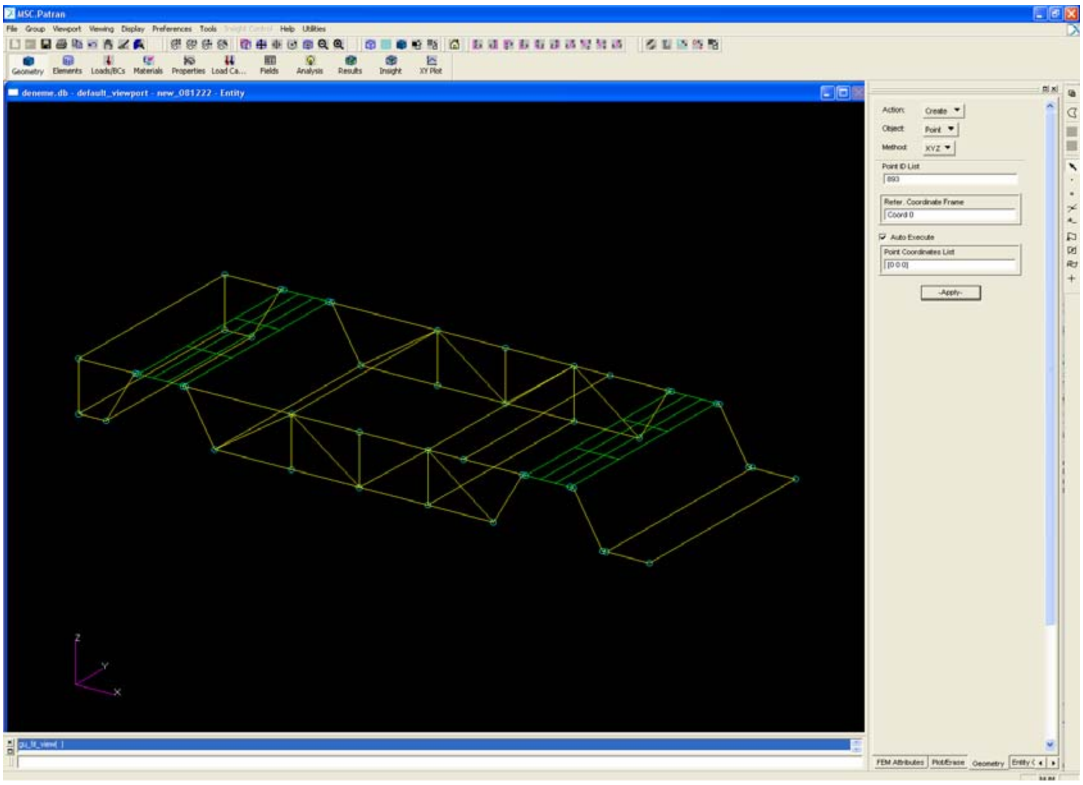

Figure 49 Wireframe models of chassis

Analysis in MSC Patran can be done by either solid mesh, surface mesh or curve mesh. For simplicity curve mesh is chosen. Wireframe is meshed using Quad elements. Two additional nodes are created to simulate the center of gravity of hopper at the dumping position and to simulate the center of gravity of the battery compartment.

These nodes are connected to the chassis by the help of MPCs (Multi Point Constraint). MPC enables to distribute the load on the additional node to the nodes on the chassis. Therefore the loads applied on the additional loads simulating the hopper and battery compartment weights are distributed to the nodes on the chassis defined by MPCs. Distributing the load as it is in the real life instead of giving the load on single nodes gives a realistic solution.

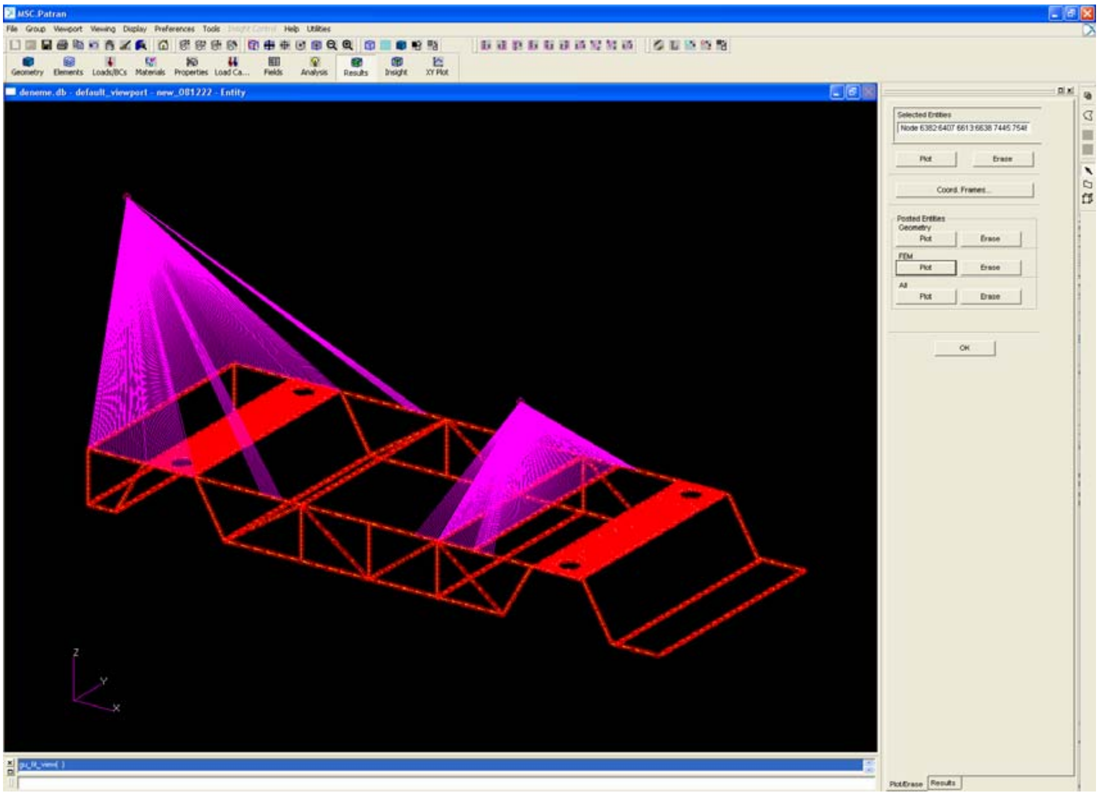

Figure 50 Meshed wireframe

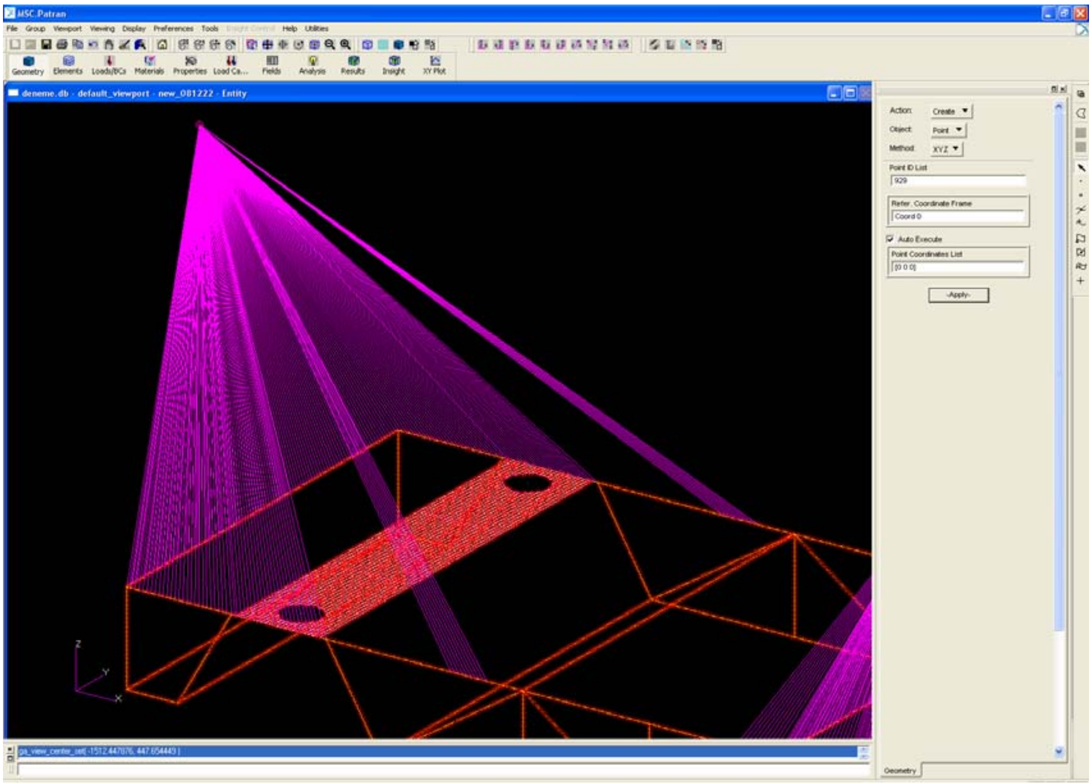

Figure 51 MPC simulating the hopper at dumping position

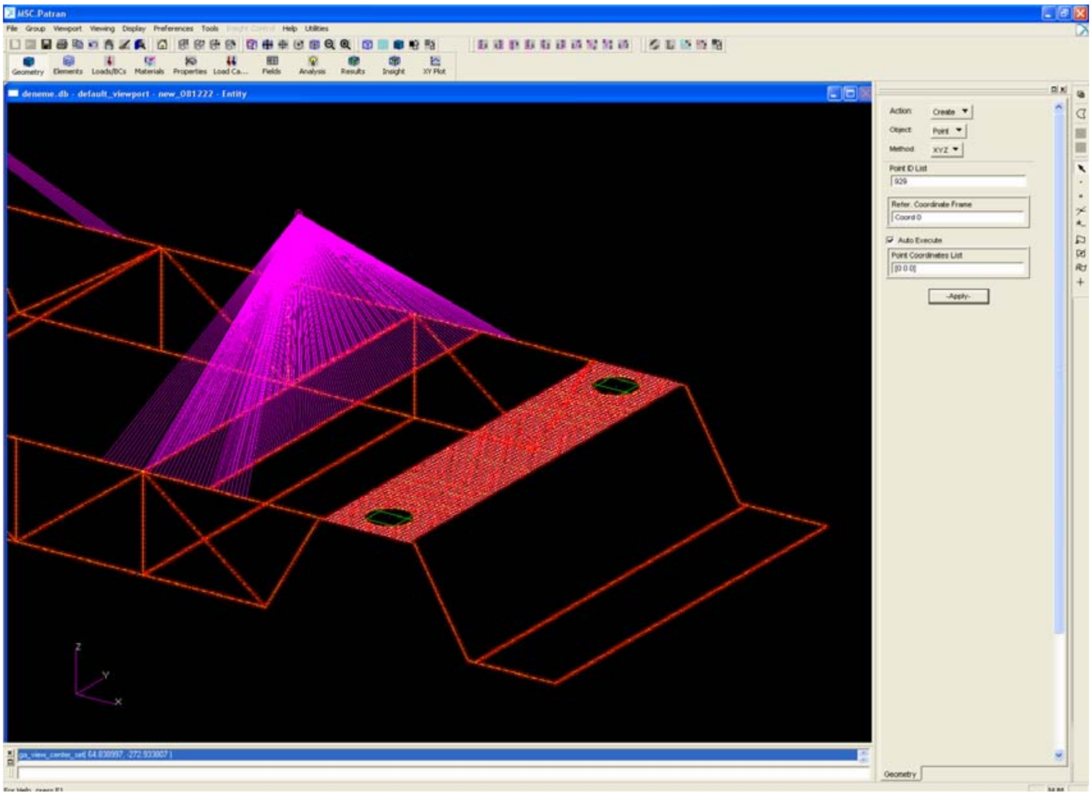

Figure 52 MPC simulating the battery compartment

Chassis is held at the wheel mounting locations. All edge nodes around the holes on the sheet metal parts where the wheels will be mounted are selected as support nodes.

There will be singularities at these nodes and the stress results will come out to be extremely high around these holding points. The reason for singularity is that these nodes are held as rigid nodes. In other words they are not allowed to move in any direction under loading whereas this is not true in real life. This creates nonrealistic stress results and as a common application stress values around such nodes are not taken into consideration. For these areas hand calculations are preferred.

Loads are defined. Inertial load of 1716.75N (175 kg) due to weight of the chassis is given by defining gravity. Hopper and battery compartment loads due to their weights are rounded to 10000N and applied on the additional nodes to be distributed by MPCs. Cabin load due to its weight is applied on single nodes as given in **Figure 53**.

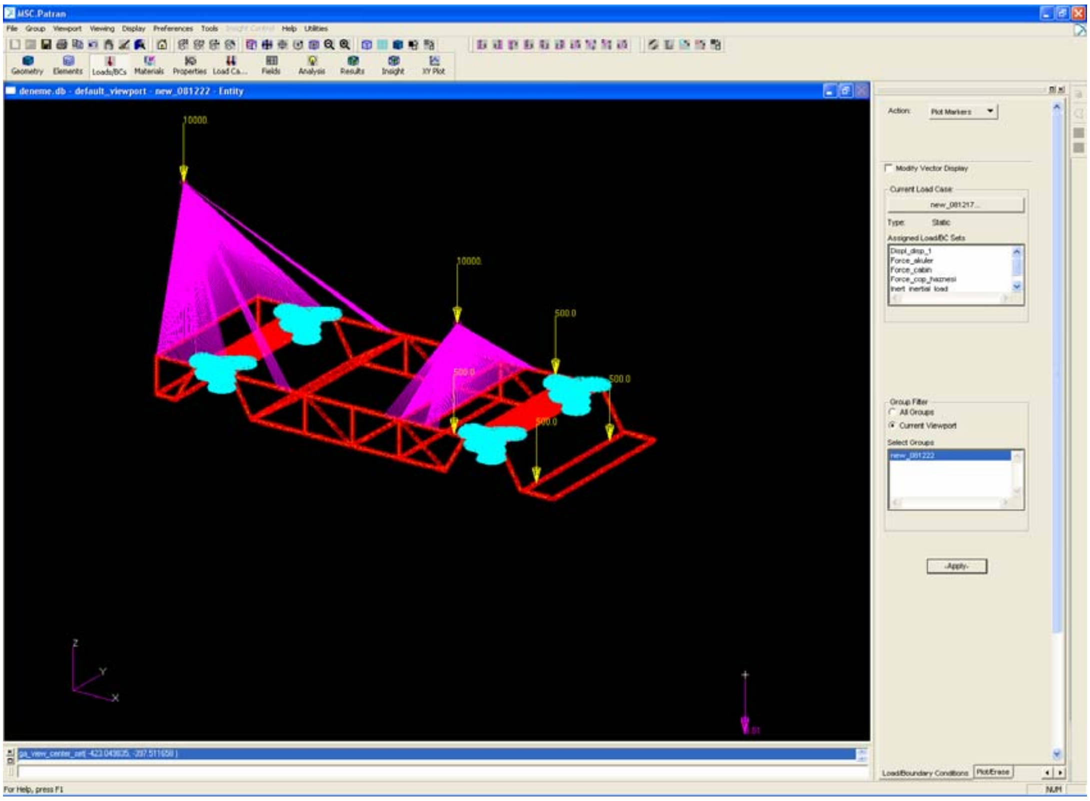

Figure 53 Support points of the chassis and defined loads

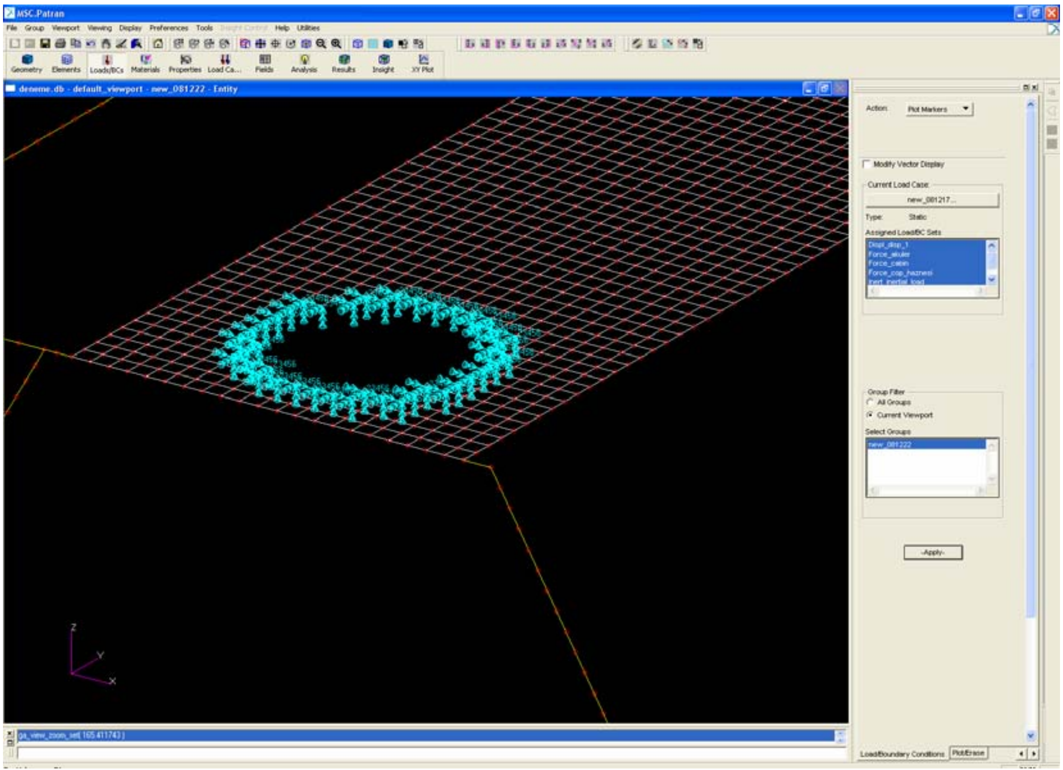

Figure 54 Support nodes

Steel material is created in MSC Patran and its mechanical properties are defined as follows [21].

- Elastic modulus : 20000
- Poisson ratio : 0.3
- Density : 7860 kg/m3

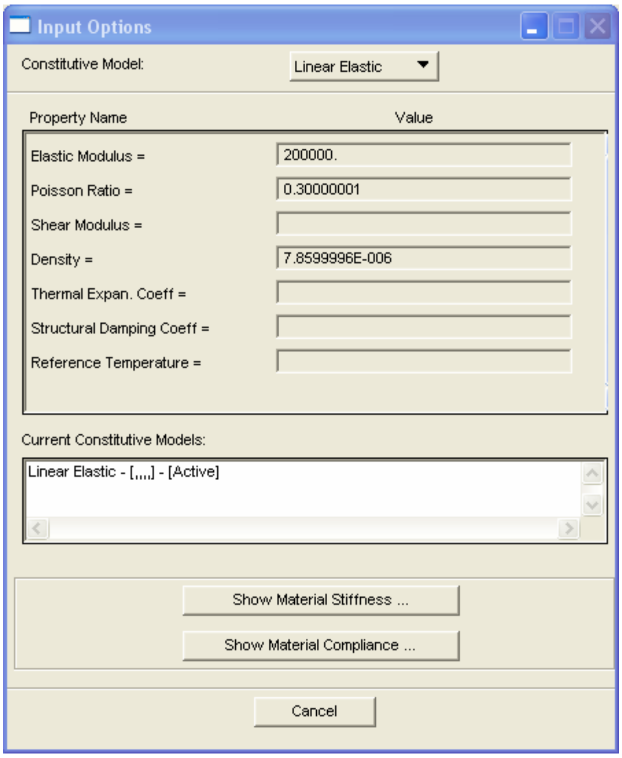

Figure 55 Steel properties definition

Bar cross-sections are defined. There are two bar profiles (Bar 1 and Bar 2) for horizontal and vertical orientations. Steel material is applied on both bar cross-sections. Then these bar cross-sections are applied on the wireframe of the chassis which is meshed for analysis.

Sheet metal parts that are used for the mounting of the wheels are modeled as surfaces. Then 8 mm thickness is defined for these surfaces and steel material is applied on these parts.

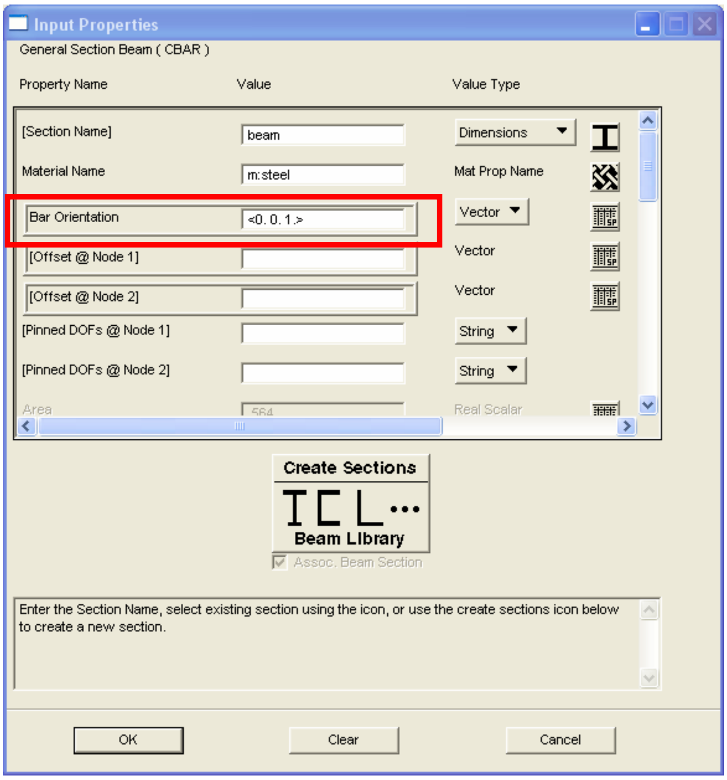

Figure 56 Bar 1 definition

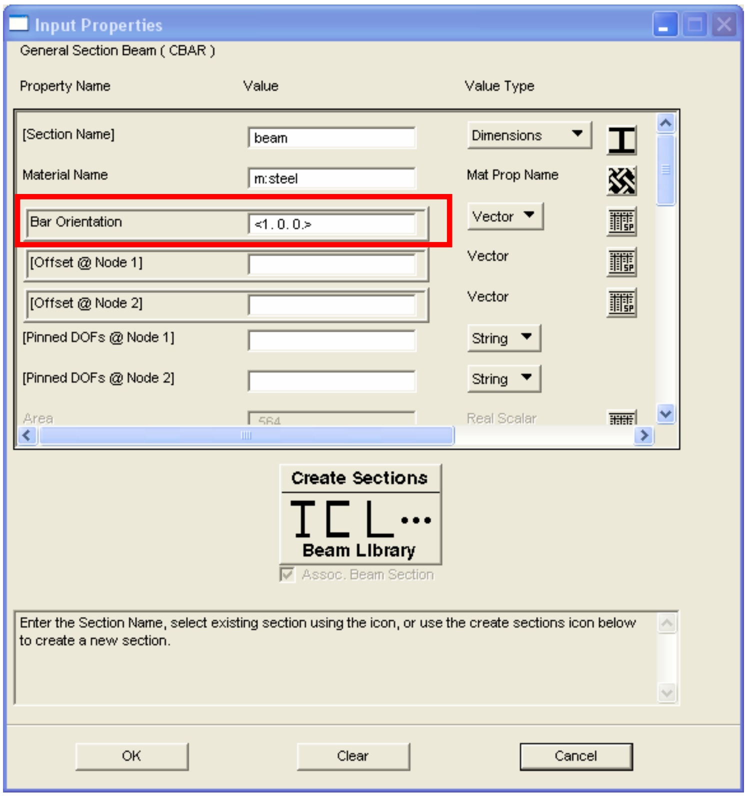

Figure 57 Bar 2 definition

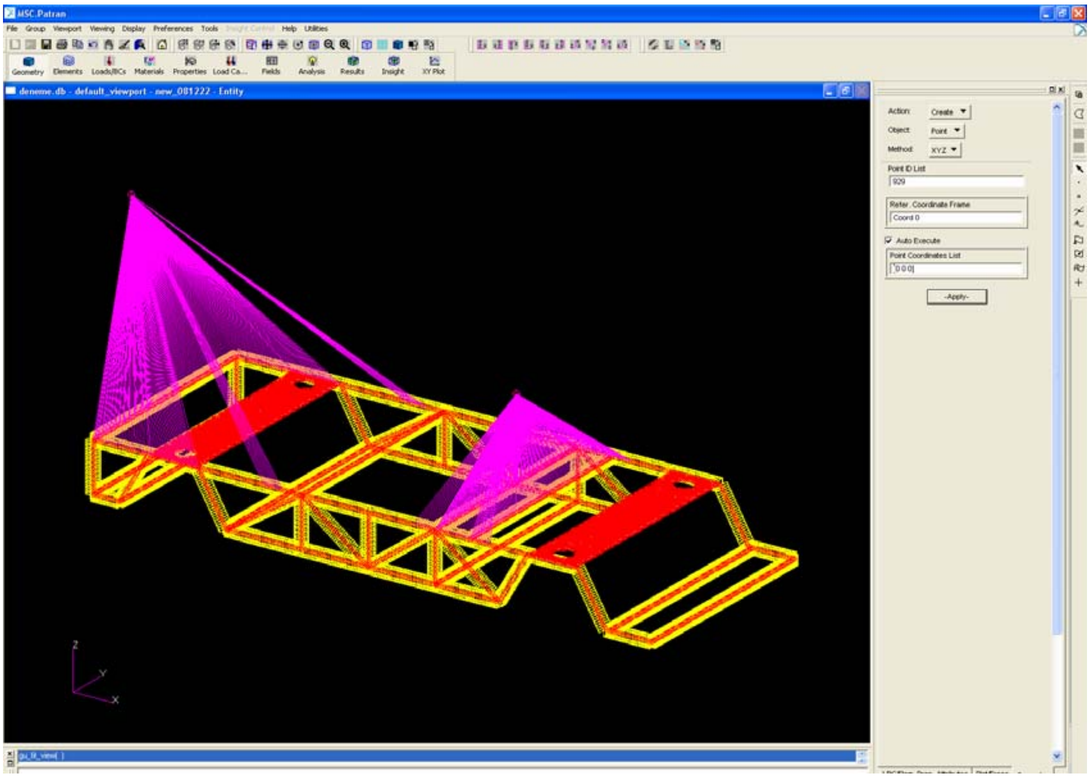

Figure 58 Meshed chassis wireframe with bar cross-sections

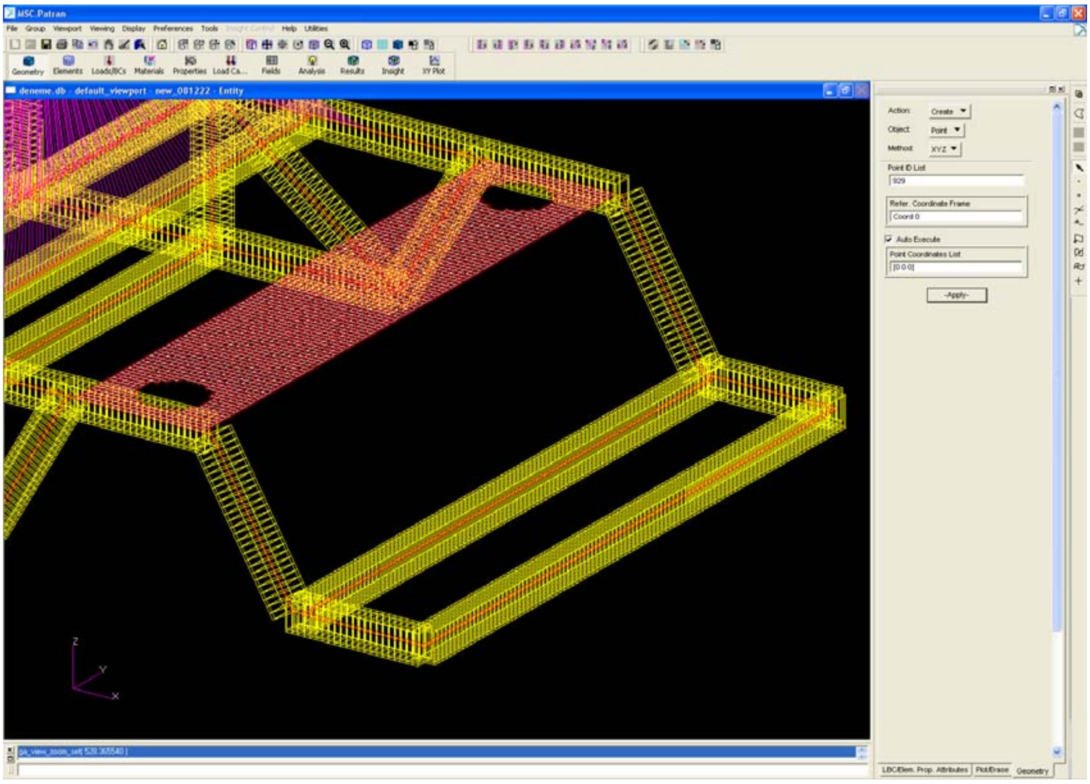

Figure 59 Meshed chassis wireframe with bar cross-sections

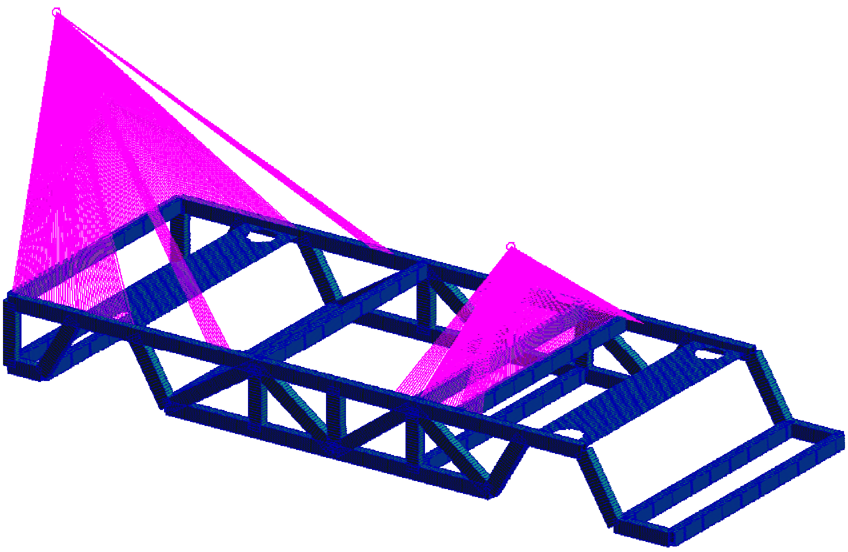

Figure 60 Rendered view of chassis

Analysis is solved in MSC Nastran and output files are imported to MSC Patran. The deformations and stresses are plotted. Maximum deformation is found at the rear side of the chassis and it is 6.45 mm. The deformations are shown below in true scale.

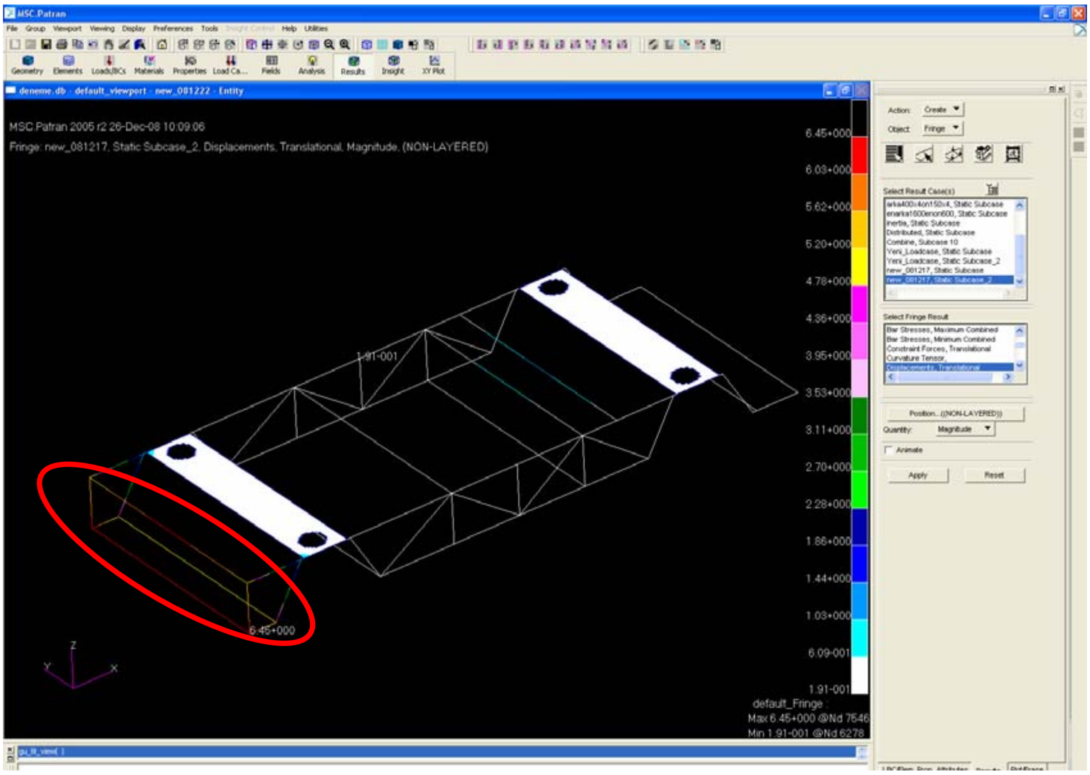

Figure 61 Maximum deformation on the chassis

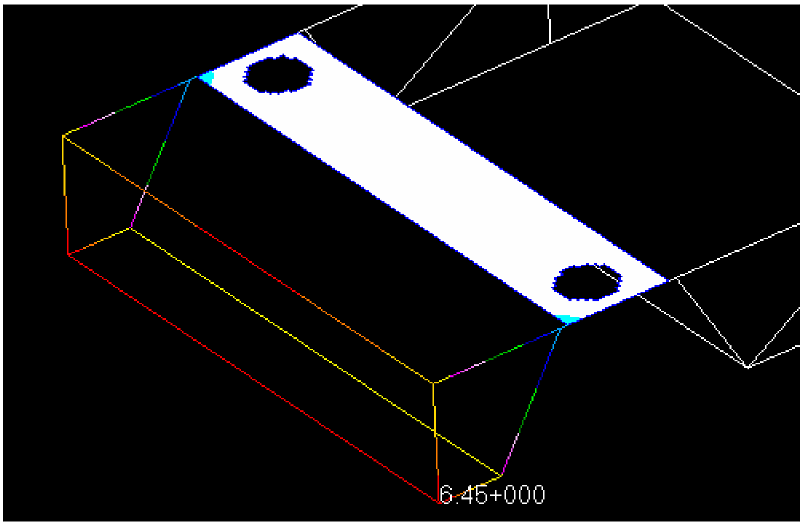

Figure 62 Maximum deformation on the chassis

Maximum bending stress is found as 283 MPa at the rear side of the chassis where sheet metal is welded to the chassis on its edges. Maximum bending stress location is shown in **Figure 63** and **Figure 64**. Maximum combined stress is found as 284 MPa at the rear side of the chassis. Its location is shown in **Figure 65** and **Figure 66**.

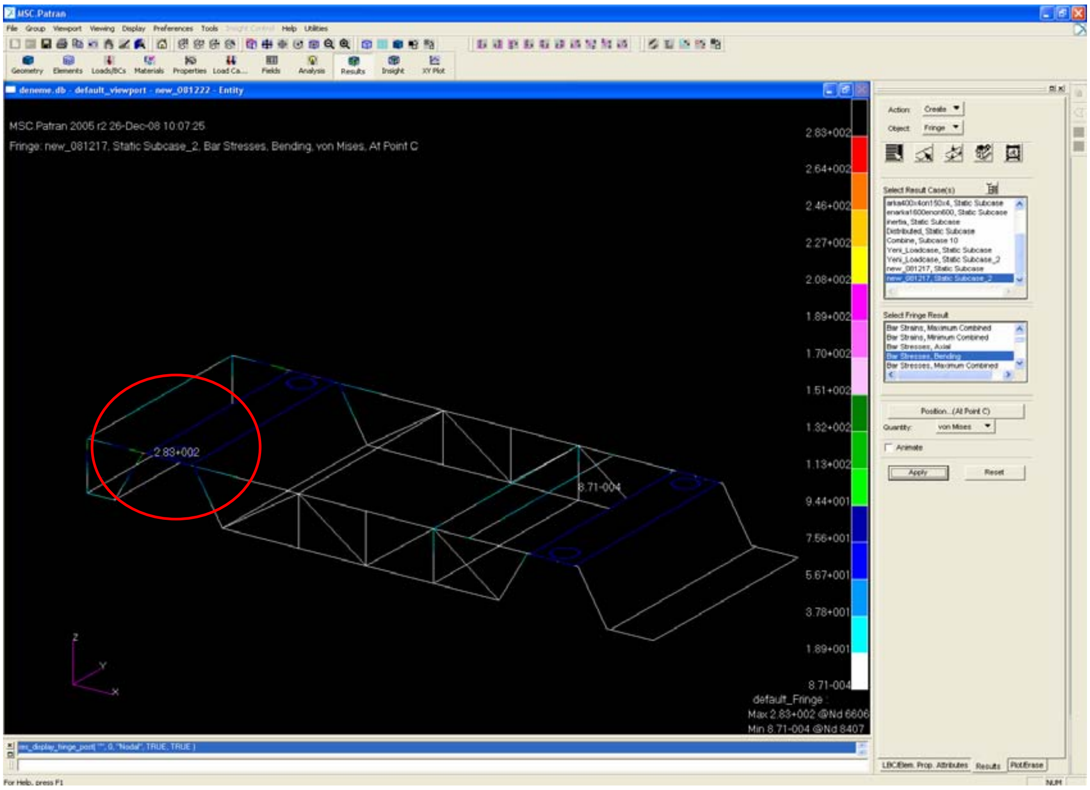

Figure 63 Maximum bending stress

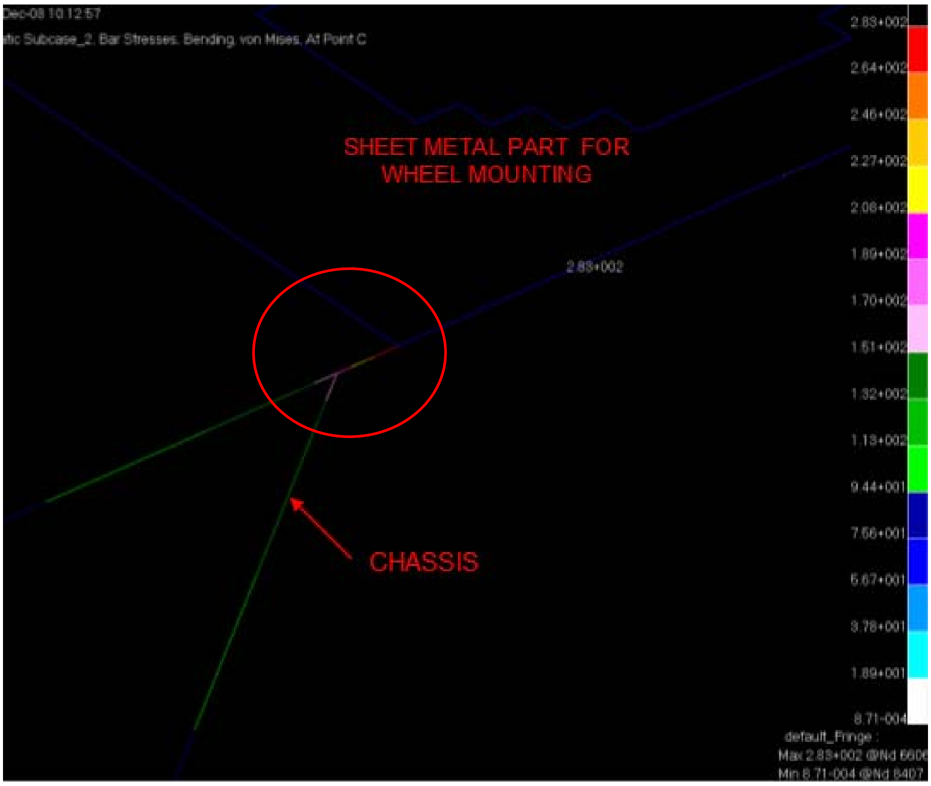

Figure 64 Maximum bending stress location

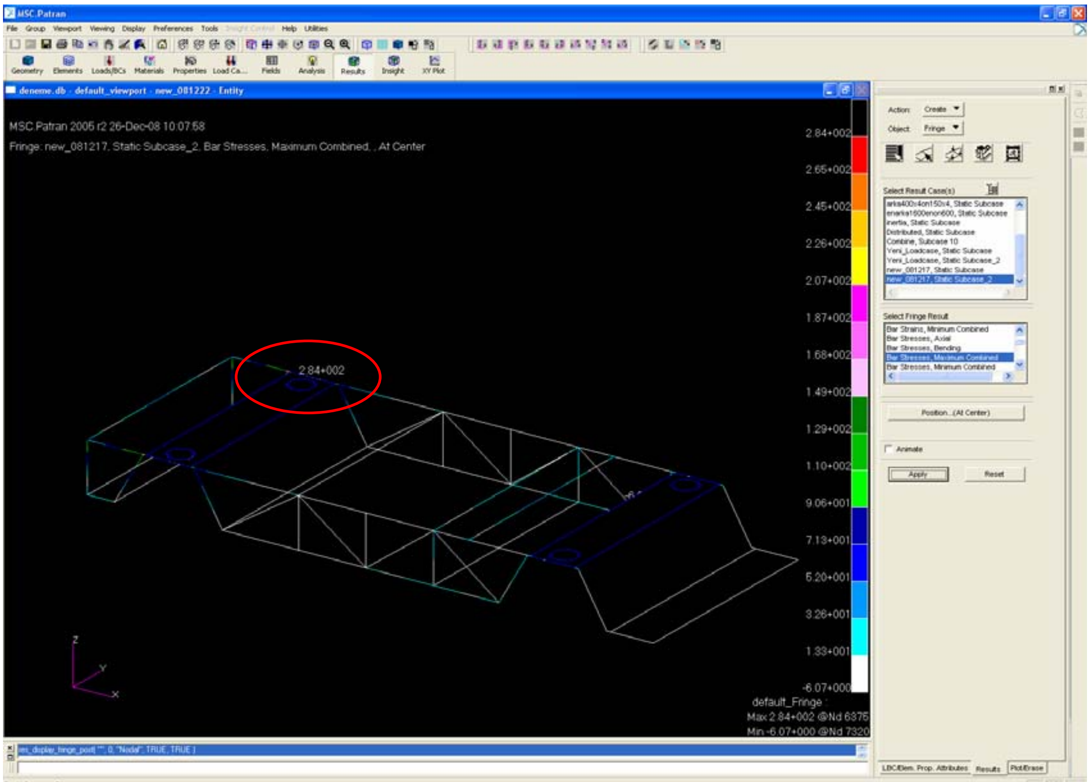

Figure 65 Maximum combined stress

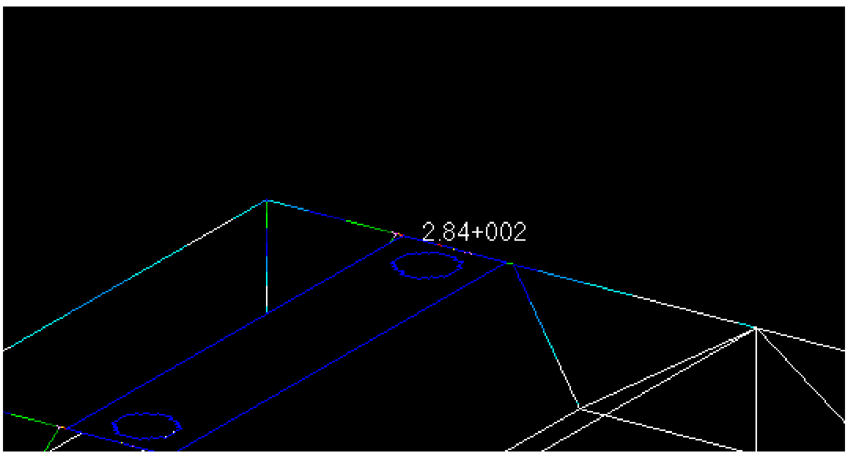

Figure 66 Maximum combined stress

According to the analysis, it is concluded that the deformation is within the acceptable limit which is 0-10 mm for deformation.

Maximum bending stress and maximum combined stress are 283 MPa and 284 MPa. These stress values are read at the junction area of chassis and sheet metal part for wheel mounting rear side of the chassis. Maximum bending and maximum combined stress values exceed the upper yield point of the St37-2 steel (for ≤16 mm thickness) 235 MPa [22].

In the analysis, the length where bending stress is read between 227 MPa and 283 MPa is approximately 10 mm. In real model, due to thicknesses of the parts, there is no such gap between the junction and sheet metal part but it is concluded that these junction areas must be strengthened by welding additional steel tubes. During the manufacturing process cross ribs are added at the critical locations as shown in **Figure 67**. Except these areas, the chassis has a factor of safety within the range of 2.0-3.0 and is capable of carrying the assumed loads without failure.

Figure 67 Critical locations from stress point of view

5.4. Cleaning System

The European manufacturers of road sweepers have agreed a Europe wide system to allow buyers to identify the clean road sweepers [26]. The certificate is based on a common test procedure to measure the performance of the sweepers in reducing fine dust particulates, abbreviated as PM10 (aerodynamic diameters are smaller than 10 μm). The industry's common label and certificate identifies sweepers that successfully passed the test procedure and all machines fulfilling the common requirements and limits will be marked with a label issued by EUnited Municipal Equipment, the European industry association of this sector.

To be competitive in the domestic and international market, new VSM 060 must have a cleaning capability to offer reducing fine dust particles at least PM10 level and even better PM2.5 level. For efficient cleaning a powerful vacuum and filtration system is required.

Figure 68 PM10 certification logo [23]

In the current Müsan VSM 060 sweeper, the cleaning system which is a combination of mechanical broom and vacuum systems is insufficient for its debris collection efficiency. Some big particles like cans, bottles, leaflets, etc. may cause clogging and cannot be collected properly. In the new design, expectations about the cleaning system performance can be summarized as follows:

- Redesign of mechanical cleaning system such that clogging due to big debris will be avoided
- Redesign of fan and filtration system to provide enough particle carrying air velocity at the hopper inlet
- Minimization of pressure loss through the system components
- Minimum dust emission to the environment
- Low energy consumption

Literature survey is made to investigate the cleaning systems of the mechanical sweepers, vacuum sweepers and regenerative air sweepers in the market. The working principles of these systems are analyzed and design alternatives for new VSM 060 sweeper are studied. It is decided that the new design will also incorporate mechanical and vacuum cleaning systems. Mechanical system will be made up of brooms and an elevator system which will enable to collect coarse particles. Vacuum system will only be used for collecting fine dust particles. These two subsystems will separately be explained in the following chapters.

Vacuum system for the new sweeper will be improved by the help of fan tests and Computational Fluid Dynamics (CFD) analysis. CFD analyses are made by Punto Mühendislik Ltd. Şti. by using a commercial program, CFdesign. At end of these studies the performance requirements of components like fan, filter, etc. will be defined. Some components will be manufactured and some will be supplied from the market.

In the case of finding a fan corresponding to the needs of the new sweeper design's requirements, it will be used for the new sweeper otherwise a new fan will be designed and a prototype will be constructed. Whether it is supplied from the market or designed and constructed according to the needs, both the new fan and the fan that is already being used in the current sweeper will be subjected to performance tests in the test set-up built in the Müsan A.Ş. Facilities.

5.4.1. CFD Analysis of the Current VSM 060 Sweeper

In the current sweeper design, debris on the path is collected and directed towards the main broom by the help of gutter brooms. The main broom impels debris into the hopper and coarse particles are trapped at the lower section of the hopper. The suction fan sucks fine particles through the filter. Fine particles up to 6 μm cannot pass the filter and are collected at the upper part of the hopper. The suction fan is designed and manufactured by the Müsan A.Ş. Company. The fan data supplied by Müsan A.Ş. is given in Table 14.

Table 6 Fan properties

Fan Diameter (mm)	250
Blade Width (mm)	95
Hub Pitch (mm)	30
Pitch (mm)	95
Number of Blades	8
Sense of Rotation	CCW
Rotational Speed	5747
Suction Diameter (mm)	90
Blow Diameter (mm)	96
Suction Velocity (m/s)	29,5
Blow Velocity (m/s)	37
Suction Area (mm^2)	6361.7
Blow Area (mm^2)	4512
Flow Rate (m^2/h)	675,6

CFD analyses are made by Punto Mühendislik Ltd. Şti. by using CFdesign program to obtain the fan characteristic curve of the currently used fan and to understand the air flow rates, vacuum level and pressure losses in the whole cleaning system of current sweeper.

First analysis is made according to the assumption that inlet and outlet pressures are same (0 Pa). The latter analyses are made when the outlet pressures are 15 mbar and 25 mbar. The characteristic curve of the fan found by CFD analyses is shown in **Figure 69**. According to the tests carried out by Müsan A.Ş. for ΔP=0 condition, the real fan air flow rate data comes out to be 675 m^3/h. There is a 10% deviation between the analyses results and the test data which is counted as acceptable. This deviation may arise from the reading errors during the test and numerical modeling errors.

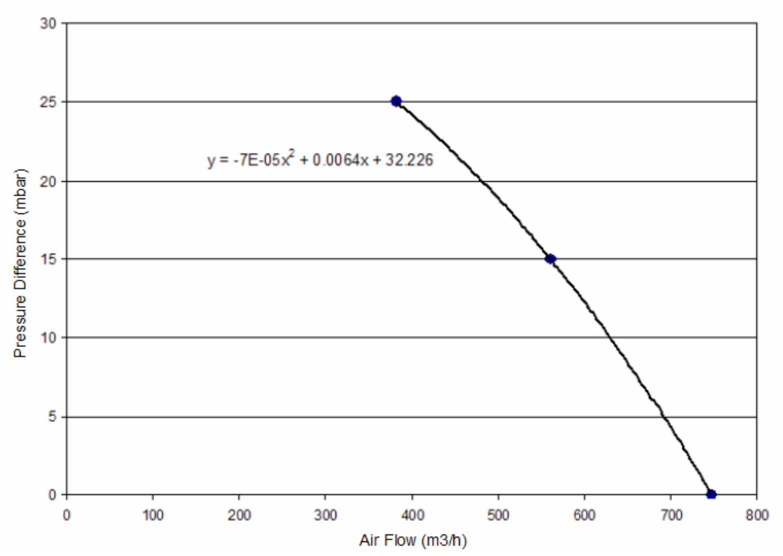

Figure 69 Characteristic curve of the fan

The whole vacuum cleaning system of the current sweeper is modeled in CFdesign program and analyses are made to understand the system behavior. Velocity distribution in the system is shown in **Figure 70**.

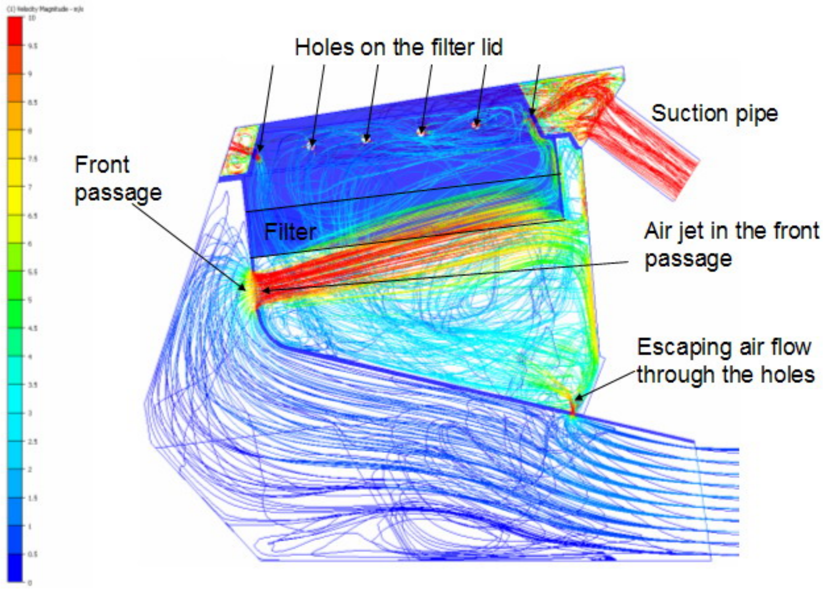

Figure 70 Stream traces in the system

Pressure loss occurs on the frame above the filter, this pressure loss reduces the suction performance. The mostly used part of the filter is the middle part. Therefore this part will be blocked by the dust after a while.

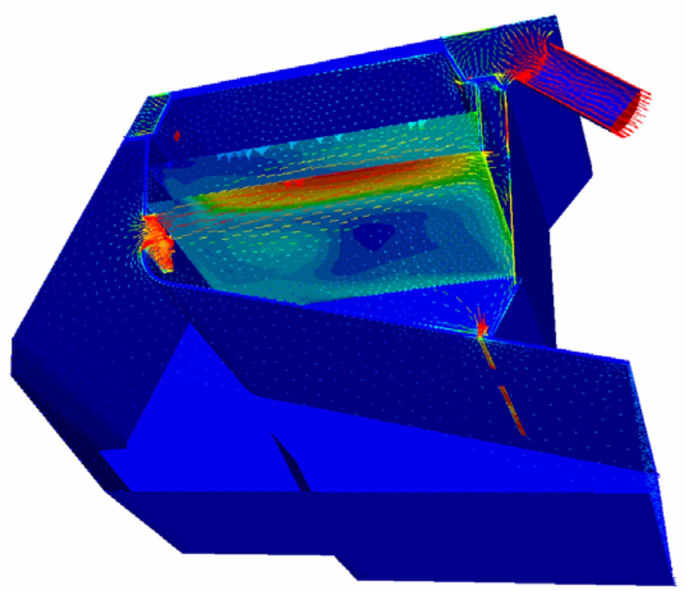

Figure 71 Velocity distribution on the filter

This analysis shows that when the fan encounters a pressure loss, its suction performance is reduced.

To increase cleaning performance;

- Air flow rate to carry the debris must be increased as much as possible.
- Pressure loss must be minimized throughout the system.
- Component design must be made such that it causes minimum pressure loss.
- Air flow through the filter must be equalized at every point in order to avoid blockage on some areas.

5.4.2. CFD Analyses and Design Studies for the New VSM 060 Sweeper

CFD analyses are made to develop a fan and filtration system for the new sweeper design by Punto Mühendislik Ltd. Şti. The results of the last analysis are represented below.

To decide the particle carrying air velocity, data given in Table 7 and 8, typical solid particle sizes [24] and the pneumatic solid transportation velocities for some solid particles [25] are investigated. It is decided to obtain an air velocity of 10-15 m/s at the hopper inlet. The fan capacity to obtain this velocity is calculated and fan sizing is made by the help of CFD analysis.

Table 7 Typical solid particle sizes [24]

Product	Typical Particle Size (micron = 0.001 mm)
Outdoor dust	0.5
Sand blasting	1.4
Foundry dust	1.0 - 200
Granite cutting	1.4
Coal mining	1.0
Raindrops	500 - 5000
Mist	40 - 500
Fog	1 - 40
Fly ash	3 - 70
Pulverized coal	10 - 400

Table 8 Pneumatic solid transportation velocities [25]

Product	**Carrying Velocities *(m/s)***
Ashes, powdered clinker	30 - 43
Cement	30 - 46
Coal, powered	20 - 28
Coffee beans	15 - 20
Cork	17 - 28
Corn, wheat, rye	25 - 36
Cotton	22 - 30
Flour	17 - 30
Grain dust	10 - 15
Grinding and foundry dust	17 - 23
Jute	22 - 30
Lead dust	20 - 30
Leather dust	8 - 12
Lime	25 - 36
Limestone dust	10 - 15
Metal dust	15 - 18
Oats	22 - 30
Plastic molding powder	15 - 17
Plastic dust	10 - 12
Pulp chips	22 - 36
Rags	22 - 33
Rubber dust	10 - 15
Sand	30 - 46
Sandblast	17 - 23
Sawdust and shavings, light	10 - 15
Sawdust and shavings, heavy	17 - 23
Textile dust	10 - 15
Wood chips	20 - 25
Wool	22 - 30

The fan sizing analysis is made for the following sweeper configuration.

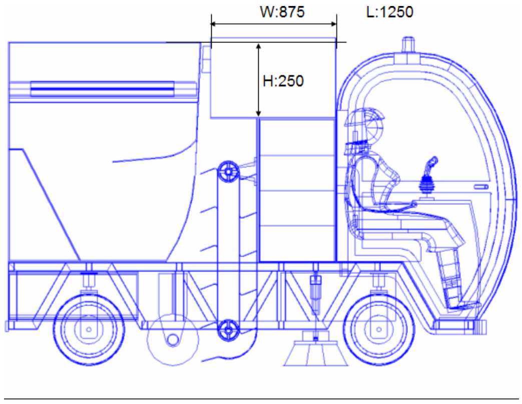

Figure 72 Sweeper configuration for the fan sizing analysis

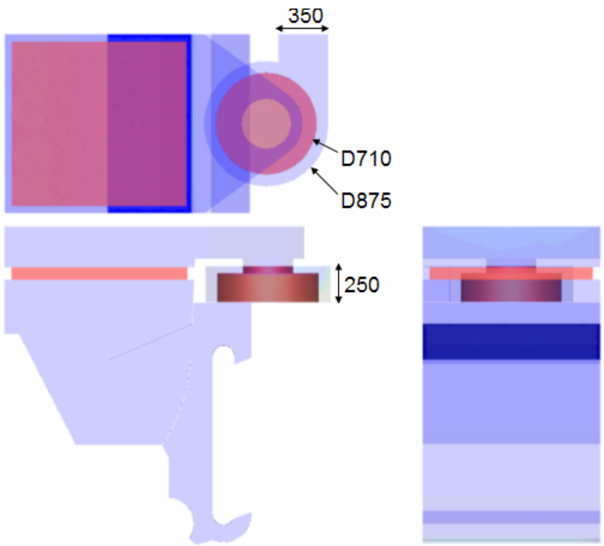

Figure 73 Suction system modeled for analysis and fan dimensions

A : Hopper inlet area

Q : Air flow rate

$$A = 0.207m \times 1.25m$$
$$A = 0.258m^2$$

For V=10 m/s air inlet velocity

$$Q = V \times A$$
$$Q = 10m/s \times 0.258m/s \qquad (5.1)$$
$$Q = 2.58m^3/s$$

Fan rotational speed is assumed to be 1450 rpm and fan flow rate (Q_{fan}) is taken 2.6 m^3/s.

$$Q_{fan} = 2.6m^3/s = 9360m^3\ /\text{h}$$

$$A_{filter} = 1.23 \times 1.15$$
$$A_{filter} = 1.415m^2$$

When the air flow rate is 2.6 m^3/s, the air velocity before the filter is 1.84 m/s. According to the test results of the current system, filter loss coefficient is calculated as 1.8.

Analysis is made for turbulent flow (k-epsilon model) in CFdesign. The velocity distribution is given in **Figure 74** and **Figure 75**.

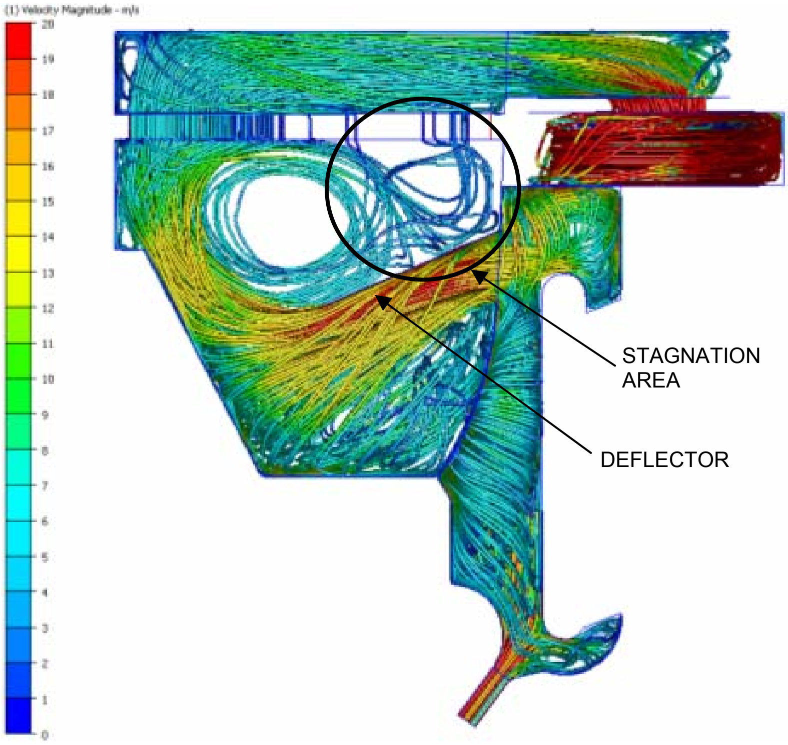

Figure 74 Stream traces throughout the system

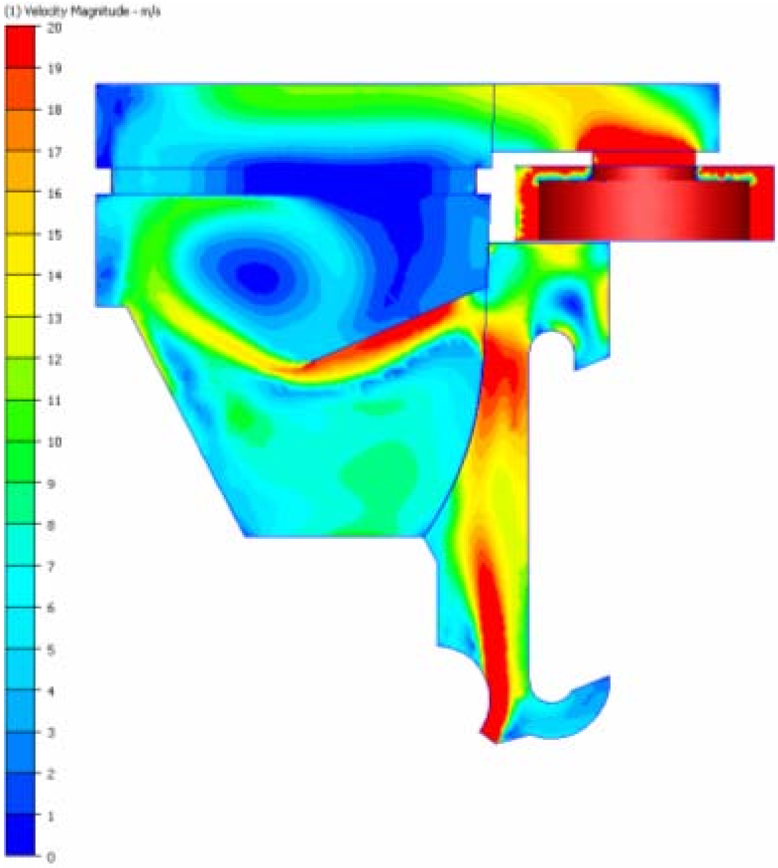

Figure 75 Velocity distribution throughout the system

It is observed that there is a stagnation area above the deflector and right side of the filter is not used. This would cause clogging on the left side of the filter after a while. The design of the deflector must be changed to avoid uneven flow distribution across the filter.

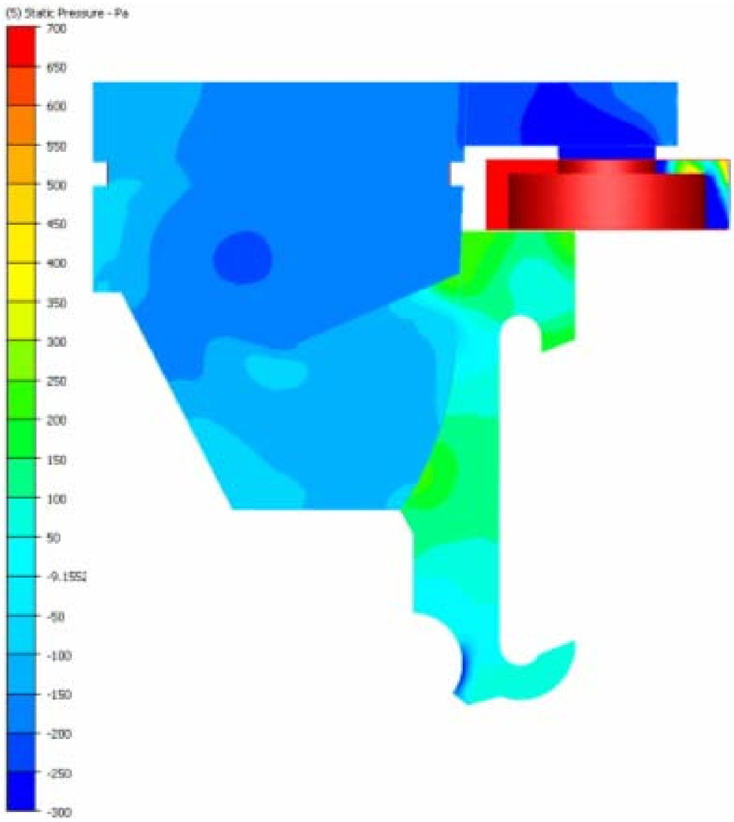

Figure 76 Pressure distribution throughout the system

The pressure at the inlet of the fan is approximately -800 Pa. The power calculation is done for this value.

P : Power

Q : Air flow rate

Δp : Pressure

$$P = Q \times \rho \times g \times h$$
$$P = Q \times \Delta p$$
$$P = 2.6 m^3 / s \times 800 Pa$$
$$P = 2080 W \qquad (5.2)$$

This power requirement is much higher than what is expected for suction system although the pressure loss across the pendants of the elevator system is not taken into consideration. If this pressure loss is also accounted then the power requirement would be higher than 2.1 kW. This value must be optimized according to the power budget of the whole vehicle.

Proposals are requested from 3 fan manufacturers (Fanmak Sogutma ve Vantilatör San. ve Tic. Ltd. Şti., Emak Mühendislik, Gürsan Fan Sanayii A.Ş.) for a fan with 800 Pa pressure and 10000 m^3/h air flow rate. Proposed fans of the firms can not be fitted on the vehicle due to lack of space.

The analysis is done according to air velocity of 10-15 m/s at the hopper inlet but from these results it is concluded that this value must be reconsidered. And also the fan volume can be reduced by choosing a fan with higher speed. But as the fan input power varies with the cube of the fan speed ratio, an increase in the speed will result in increase in the power requirement. Therefore an optimum solution will be found according to the hopper inlet air velocity requirement. It will be decided whether to use one or more than one fan in the system. Subsequent to this decision, market search will be done for procurement. In the case of not finding a fan to comply the requirements then a new fan prototype will be designed and constructed.

5.4.3. Mechanical Cleaning System

Mechanical cleaning system is composed of main broom, gutter brooms and elevator system. Design of these components is the scope of the concurrent thesis.

Brooms will be activated by DC motors and linear actuators will be used for the vertical movement. Brush diameter of the gutter brooms and main broom will be approximately 500 mm and 400 mm respectively.

Elevator system is composed of pulley system, belt and pendants. Pendants will be made of hard rubber material to enable debris collection and at the same time avoid breakage when debris hit to them. These pendants will be fixed on the belt which is rotated around pulleys.

Gutter brooms direct the debris on the path towards the main broom and the main broom impels the debris towards the elevator system. At the lower section, elevator casing is curved, forming a space for the debris collection. The pendants sweep the debris which is collected at this area and carry to the upper section. At the upper section the debris are discharged to the hopper.

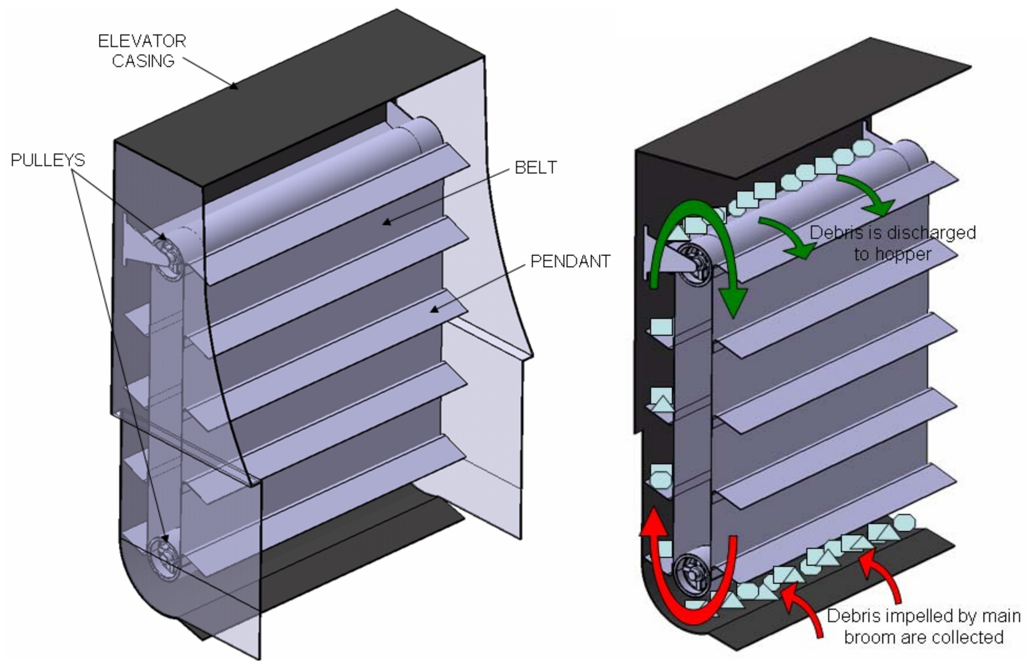

Figure 77 Elevator system and operation

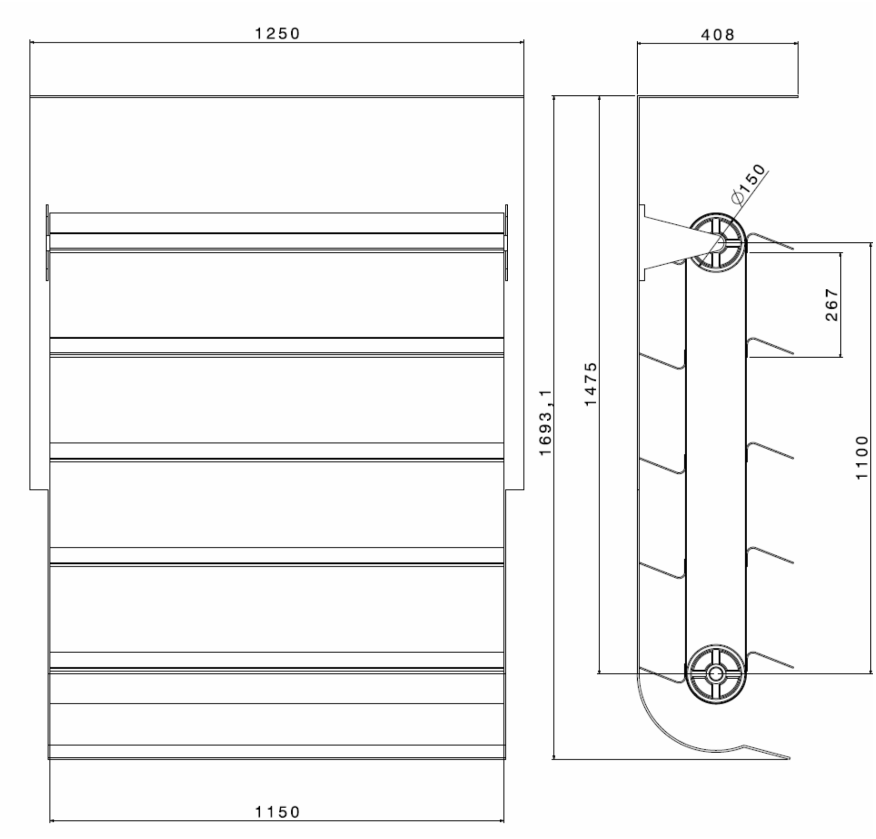

Figure 78 Elevator system outer dimensions

5.5. Electrical Systems

There are specific motor products for electrically driven vehicles. These products are brushless DC motors with gearbox, hub motors with or without wheels, linear actuators or complete traction system with DC motor, axle, differential, gearbox and wheels, etc. For the VSM 060 sweeper's traction system and subsystems' operations different types of motors will be utilized. The decision is made for each situation according to the type of application.

Figure 79 Traction systems with gearbox and axle [26]

Figure 80 Hub motor [26, 27]

Motor control will be done by using microcontrollers, drivers and sensors. The speed may be varied from 0 to the rated speed of the motor simply by adjusting the applied voltage. This control capability may be used to maintain a given motion even for extensive load variations [28].

The basic principle of the motor control is shown in the schema below in **Figure 81**.

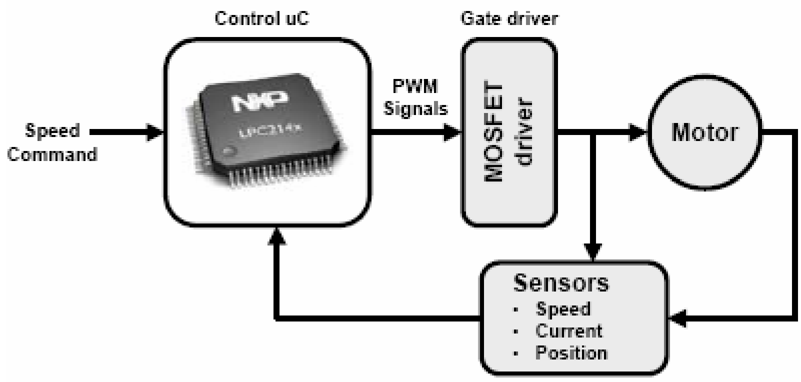

Figure 81 Motor control schema [29]

Pulse-width modulation (PWM) or duty-cycle variation methods are commonly used in speed control of DC motors. The duty cycle is defined as the percentage of digital 'high' to digital 'low' plus digital 'high' pulse-width during a PWM period [30].

Electrical system component designs, firmware developments and system integration to the vehicle will be done by Emsa Otomasyon ve Bilişim Teknolojileri A.Ş.

DC motors and linear actuators for subsystems can be listed as follows:

- Wheel traction hub motors
- Wheel rotation motors
- Elevator system pulley rotation motors
- Vacuum fan motors
- Main and gutter brooms' rotation motors
- Main and gutter brooms' lifting and lowering linear actuators
- Hopper dumping linear actuators
- Hopper lid opening and closing motors
- Linear actuators for assembling upper and lower part of the hopper
- Eccentric motor for filter cleaning

5.1.1. Traction System

The power requirement of the wheel motors is defined according to the power calculation for traction. It is decided that 4 DC motors with 2.5 kW power are suitable for the application. Market search is done for procurement of these motors and a final decision is made according to the total price and lead time.

4 pieces of 48 V DC electric car hub motors having rim diameter of 14 inches with 2.5 kW power and the drivers of these car hub motors are ordered from Chinese Company.

These electric car hub motors, their tires and the drivers are delivered. Equipments are tested by Emsa Otomasyon ve Bilişim Teknolojileri A.Ş. Firm after the delivery.

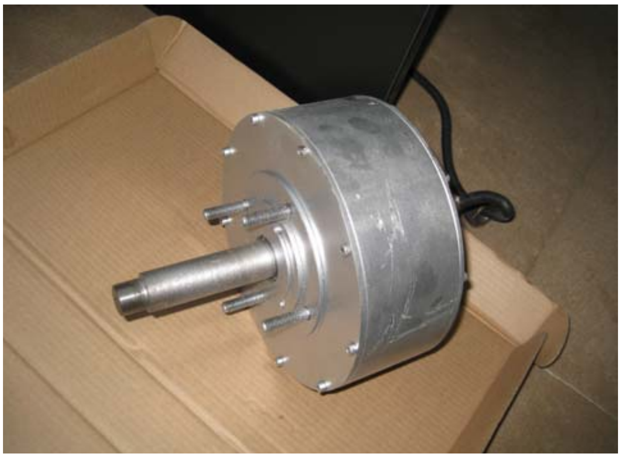

Figure 82 Electric car hub motor

Figure 83 Tire and rim of the car hub motor

The outer diameter of the tire is approximately 500 mm. The design of the rim is such that the car hub motor is not centered when it is mounted. Therefore alternative rim design studies are made by Müsan A.Ş. Also a brake system design is made and integrated to the rim design.

The wheels are mounted to fork structures to enable rotation around vertical axis. Torque needed to rotate the wheel around its vertical axis is found as 120 Nm from the tests. At the top of the fork structure, there is a DC motor and a gearbox for rotation of the wheel which are shown in **Figure 85** and **Figure 86**.

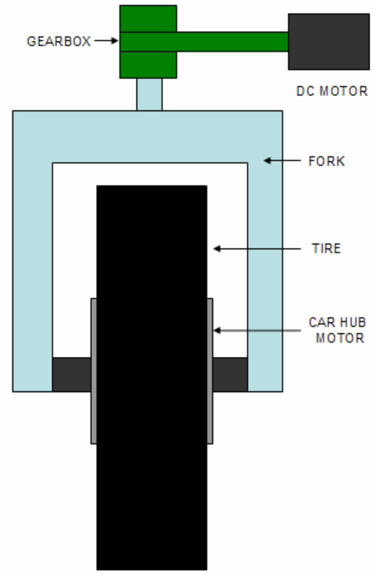

Figure 84 Fork structure

The whole fork structure is designed and wheels are mounted on the chassis as follows:

Figure 85 Fork structure, wheel and DC motor

Figure 86 DC motor and gearbox at the top of the fork structure

The rotation around vertical axis enables 90 degree sideward movement of the vehicle therefore this system will be applied to all wheels. There will be no need for difficult maneuvers to come closer to the curbs and pavements.

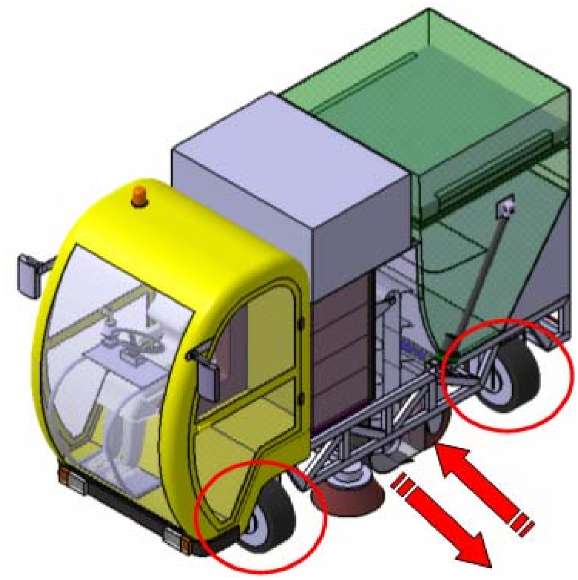

Figure 87 Sideward movement

5.1.2. Dumping System

Dumping of the hopper is achieved by the help of linear actuators which are located on both sides of the vehicle. Linear actuators will be mounted to the chassis on one side and to the hopper on the other side.

Initially some possible connection points are determined on both chassis and hopper then it is checked if these points can be used for mounting. The distances between the two possible points are measured for neutral and dumping positions. The distance between two points is the main criteria for selecting a proper linear actuator as this distance defines the stroke of the actuator.

Appropriate mounting points are determined after trial and error process and linear actuator is selected according to these points. The selected linear actuator is a heavy type Superjack linear actuator with 36 inches stroke [31].

Figure 88 Superjack linear actuators

Table 9 Technical specification of the linear actuator

Stroke Length	36"
Static Load	3000lbs (13.35 kN)
Dynamic Load	1200lbs (5.4 kN)
Speed(Rated Load)	5.2mm/sec
Input Voltage	36VDC

The speed of the linear actuator is very slow for the dumping application therefore the gears of the DC motor or the motor itself will be modified to increase the speed at rated load.

The neutral and dumping positions of the vehicle are shown in **Figure 89** and **Figure 90**.

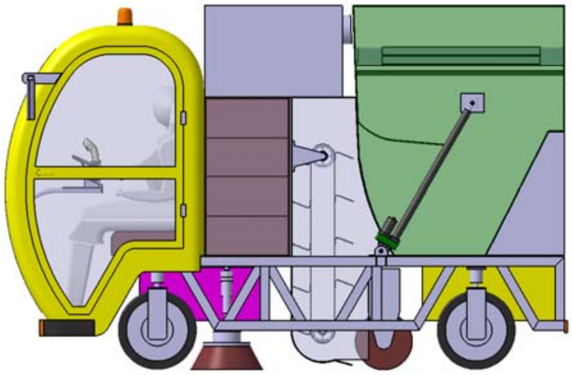

Figure 89 Neutral position of the linear actuators

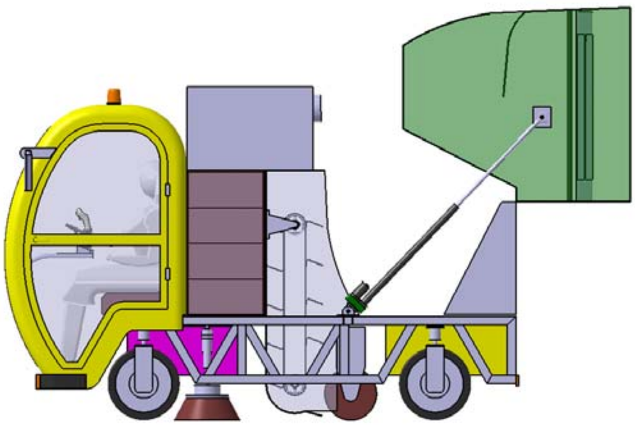

Figure 90 Dumping position of the linear actuators

Linear actuators are mounted on the chassis by the help of adapter parts in which the motors of the actuators are located. This adapter part will rotate around the bolt located through a clevis supported on the chassis. For the mounting on the outer skin of the hopper another clevis part is designed. The bolt on this part passes through the ring at the end of the rod. Mountings are shown in the **Figure 91**.

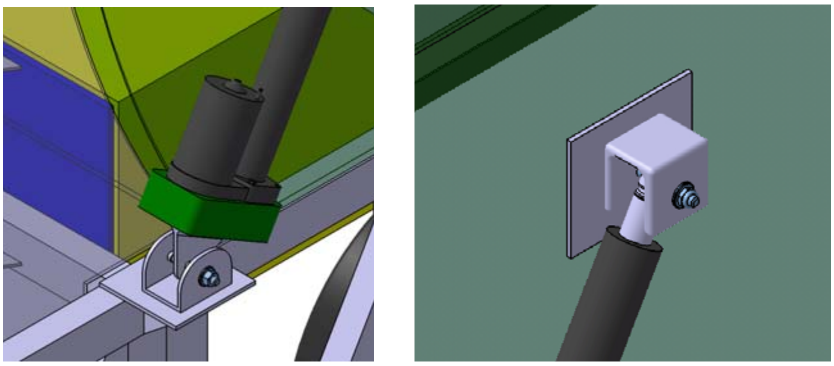

Figure 91 Clevis on the chassis and hopper

For this configuration moment calculation is done and stroke is measured. Stroke is found out to be approximately 800 mm.

Moment calculation can be done for the initial position as the cg (center of gravity) of the hopper assembly will shift towards the hinges during dumping. This will have a positive effect on the linear actuator load.

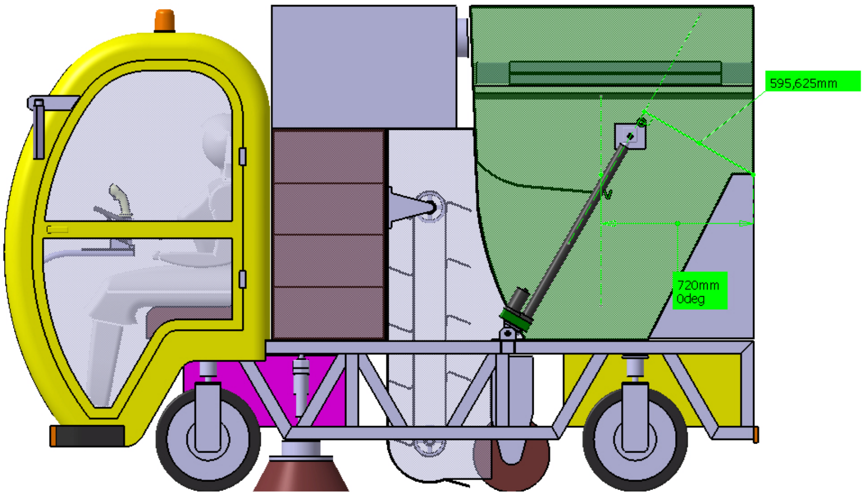

Figure 92 Moment arm lengths

The loaded hopper weight is assumed to be 1000 kg and the horizontal distance of the cg of the hopper from the hinges is assumed to be 720 mm. The load for one linear actuator comes out to be 5925.5 N.

$$2 * F * 596 = 9810 * 720$$
$$F = 5925.5N$$

This value is less than the static load of the actuator which is 3000 lbs (13344.7 N) and slightly more than the dynamic load 1200 lbs (5337.9 N) but as electric motors can be overloaded for a short time and being slightly more than the dynamic load will not affect the operation. Also it must be taken into consideration that this load value will decrease as the hopper is rotated around its hinges causing the center of gravity of the hopper assembly to be shifted towards the hinges and shortening the moment arm.

5.1.3. Batteries

Traction batteries are used to provide motive power for electric or hybrid vehicles [32]. The major emphasis on traction battery design is the necessity of a high capacity to weight and volume ratio, since the vehicle must also carry its power source. Traction batteries are generally deep cycled and require a fast charging rate for usually within 24 hours. Typical applications are motive power for forklifts, electric carts, etc.

The battery selection for VSM 060 is done according to the power requirement and for ease of procurement a local supplier is preferred. Battery power requirement for four hours of operation is estimated to be 1000 Ah. According to this data, battery selection is made. The batteries are ordered from Yiğit Battery Firm. The technical specifications of batteries are given in Table 17 [33]. 16 batteries are needed to acquire 1000 Ah power.

Table 10 Battery specifications [33]

Group Number	725-101
Width	276 mm
Length	518 mm
Height	245 mm
Capacity	225 Ah
Weight	42.7 kg (dry), 64.3 kg (wet)

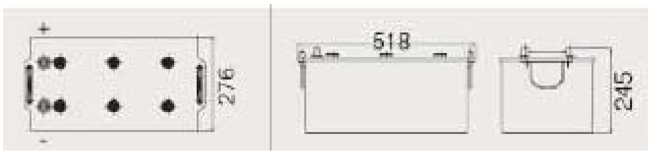

Figure 93 Battery dimensions

CHAPTER 6

DISCUSSION AND CONCLUSION

This thesis aims to accomplish the design, development and manufacturing studies of new Müsan VSM 060 sweeper under SAN-TEZ project number 00028.STZ.2007-1 which is supported by Ministry of Industry and Trade-Turkey and Müsan A.Ş. (Makina Üretim Sanayi ve Ticaret A.Ş.). The new vehicle design is achieved by using commercial 3D modeling program Catia™ V5 R14, commercial FEA programs MSC Patran and MSC Nastran and commercial CFD program CFdesign.

The former Müsan VSM 060 sweeper design is carefully investigated and its deficiencies are identified. Extinction of these deficiencies is the basis for new vehicle's design requirements.

As the sweepers that are driven with internal combustion engines are not suitable for indoor usage due to exhaust emission and noise, it is decided to design Müsan VSM 060 sweeper as a fully electrically driven vehicle. Each subsystem will be actuated by individual electric motors that are controlled by microcontrollers. Rechargeable batteries will supply power to the electric motors. The main advantages of this kind of a vehicle are no exhaust and noise emissions to the environment and therefore less operator lung diseases and increase in the maneuverability of the vehicle. Also there will be no fuel cost. The disadvantages will be limited operation time due to battery usage and total battery weight.

For the configuration design of new sweeper, Catia™ V5 is used. The main parts are chassis, wheel assemblies, battery compartment, cabin assembly, hopper assembly, elevator system, brooms, fan and motor controller compartment.

Chassis is constructed as a 3D welded frame by using 60x40x3 [mm] St37-2 grade steel tubes. The dimensions of the chassis are 3240x340x1250 [mm]. Using St 44-3 or St 52-3 steel tubes for the chassis construction would be better from strength point of view but these steel tubes are not easily found in the market, so St37-2 steel is preferred for the ease of procurement. Moment calculation is done to check tipping over case. Finite element analyses are made for the chassis. FEA is accomplished by using commercial analysis tools MSC Patran pre and post processor and MSC Nastran solver.

According to the analyses results, maximum deformation occurs at the rear side of the chassis and it is 6.45 mm. Maximum bending stress is found to be 283 MPa at the rear side where sheet metal part is welded to the chassis on its edges. Maximum combined stress is found as 284 MPa again at the same location.

Deformation comes out to be within the acceptable range which is defined as 0-10 mm. The bending stress and combined stress values exceeds the upper yield point of St37-2 steel (for ≤16 mm thickness) 235 MPa [31]. In the analysis, the length of the wireframe chassis where stress values are read between 227 MPa and 283 MPa is approximately 10 mm whereas in real life, due to thicknesses of the parts, there is no such gap between the junction and sheet metal part. From the analysis it is interpreted that these junction areas are the most critical parts from stress point of view and must be strengthened by welding additional steel tubes. Except these singular areas, the chassis has a factor of safety within the range of 2.0-3.0 and is capable of carrying the assumed loads without failure. Cross ribs are added at the aforementioned critical locations to decrease the deformation and stress results.

Electrical system design, firmware development and system integration to the vehicle is done by Emsa Otomasyon ve Bilişim Teknolojileri A.Ş. Different electric motors and linear actuators are used to activate the subsystems such as traction system, elevator system, vacuum system, broom activation, hopper rotation system, etc.

Power requirement for the traction electric motors is calculated. This value varies according to the total force applied by the vehicle which is the summation of rolling resistance force, gradient resistance force, air resistance force and inertial force. Average power requirement for the traction motors is accepted as 10 kW and 4 pieces of 48 V DC electric car hub motors having rim diameter of 14 inches with 2.5 kW power and their drivers are purchased from Chinese Manufacturer Company. These equipments are delivered and tested by Emsa Otomasyon ve Bilişim Teknolojileri A.Ş. after the delivery. Original rims of the wheels are not used so alternative rim design with a brake system and fork fitting designs are made by Müsan A.Ş.

The wheels are mounted to fork structures that enable rotation around vertical axis by the help of gearbox mechanism at the top of the fitting and it is possible to make 90 degrees sideward movement without difficult maneuvers to come closer to the curbs and pavements.

For the dumping mechanism of the hopper, linear actuators which are mounted on both sides of the vehicle by the help of adapter clevis parts are used.

Battery power requirement for four hours of operation is estimated to be 1000 Ah and 16 pieces of 725-101 code numbered batteries are ordered from Yiğit Battery Firm.

The current Müsan VSM 060 sweeper's cleaning system is insufficient for its debris collection efficiency as big particles like bottles, cans, etc. cause clogging at the hopper inlet and cannot be collected properly. Current sweeper's cleaning system is a combination of mechanical broom and vacuum cleaning systems. Literature survey is done and it is decided to use both of these systems also in the new vehicle design.

Mechanical cleaning system in the new vehicle will be made up of brooms and an elevator system to collect coarse particles and vacuum system will only be used for collecting fine dust particles.

The new vacuum cleaning system will be constructed by the help of development tests to be done in the test setup built in Müsan A.Ş. facilities and CFD analyses which are made by Punto Mühendislik Ltd. Şti. by using a commercial program, CFdesign.

Initially, tests and CFD analyses are done for the current sweeper's cleaning system components to identify the deficiencies in the system. Then some cleaning system alternatives are prepared for the new design and their CFD analyses are made.

It is decided to obtain an air velocity of 10 m/s at the hopper inlet. Fan flow rate comes out to be 2.6 m^3/s and fan velocity is taken 1450 rpm. When the analysis is done by using these values, the suction pressure at the inlet of the fan is found approximately -800 Pa and power requirement for the fan is found as 2.1 kW without taking the pressure loss through the pendants of the elevator system into consideration. Any fan from the market to comply these requirements can not be fitted on the vehicle design as they are much larger in dimensions.

From these results it is understood that air velocity at the hopper inlet must be reconsidered. Also fan volume can be reduced by choosing a fan with higher speed but as the fan input power varies with the cube of the fan speed ratio, an optimization must be made for the fan sizing and power requirement.

The studies that are investigated throughout this thesis are successfully accomplished. Configuration design of the vehicle and detailed design of structural parts are completed. The structural parts whose finite element analyses are done within this thesis are manufactured and ready to be used.

CHAPTER 7

FUTURE WORK

Preliminary design phase of the new Müsan VSM 060 sweeper is completed but the whole design process is not finished yet. The subsystems except the chassis and wheels are subject to developments during the detailed design phase.

The chassis structure is constructed and wheel assemblies are mounted on the chassis. Detailed cabin design will be completed and manufactured. Off-the-shelf equipments of the cabin will be procured. Batteries will be supplied and battery compartment will be manufactured.

Fan design studies will go on and an optimization will be made by taking the air velocity, size of the fan and power requirement of the fan into consideration.

After the optimization studies, market search will be done for procurement. In the case of not finding a fan to comply the requirements then a new fan prototype will be designed and constructed according to the requirements of the system.

Fan and elevator system design studies will be carried on with the concurrent thesis study.

Hopper design will be finalized. The deflector inside the hopper negatively affects the path of the air stream and causes a stagnation area so optimization studies for the deflector design are still going on.

The speed of the linear actuators for the hopper dumping mechanism must be increased. Either the DC motors or the gears inside the actuators will be modified.

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APPENDIX

TECHNICAL DRAWINGS OF THE MANUFACTURED PARTS

Technical drawings of the chassis are given in the Appendix.

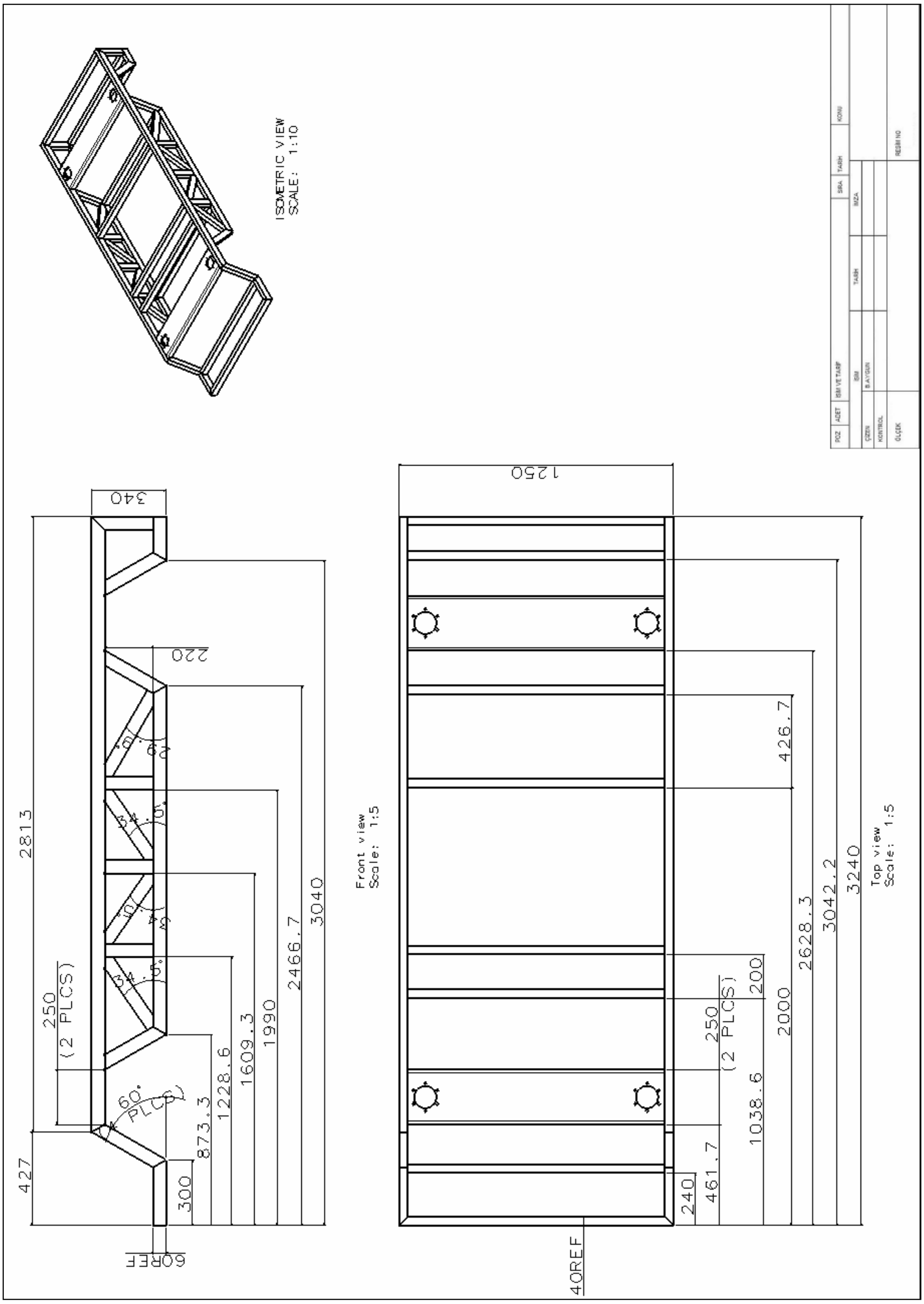

Figure 94 Chassis Assembly

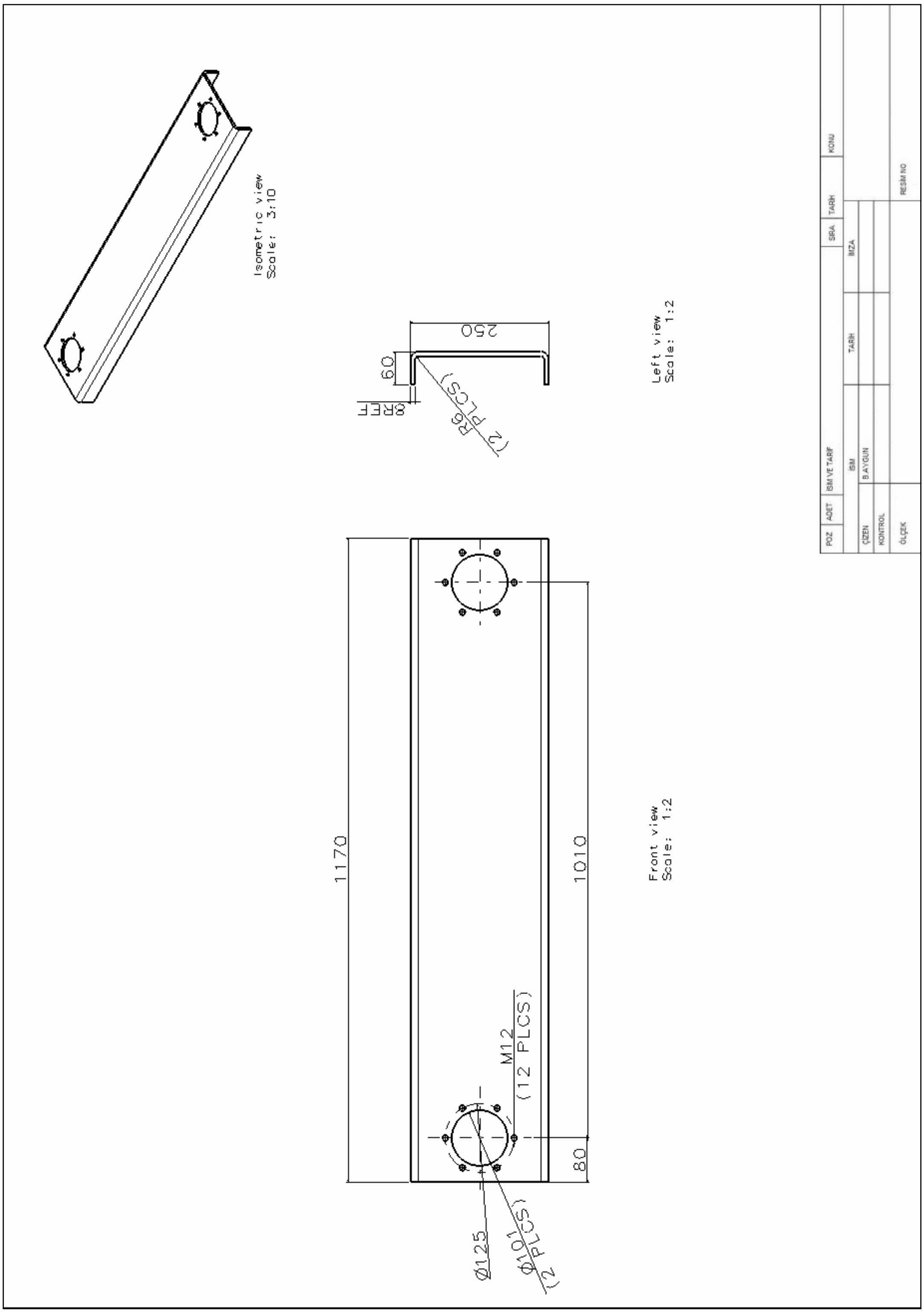

Figure 95 Wheel mounting plate