ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF GRADUATE STUDIES

DEVELOPING MANUALLY DRIVEN STREET CLEANING MACHINE (SCM)

A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirement of the Degree of Masters of Science in Mechanical Engineering

(Mechanical Design Stream)

By

Aklilu Teklemariam

Advisor

Dr.-Ing. Zewdu Abdi

December 2013

Addis Ababa University

Addis Ababa institute of Technology

School of Mechanical and Industrial Engineering

Developing Manually Driven Street Cleaning Machine (SCM)

By Aklilu Teklemariam Gossa

Approved by board of Examiners

Daniel Tilahun (Dr.)	________	02/06/14
Chairman of the school	Signature	Date
Dr.-Ing. Zewdu Abdi	________	03/04/2014
Advisor	Signature	Date
Dr. Daniel Tilahun	________	02/06/14
Internal Examiner	Signature	Date
Dr.-Ing. Tamrat Tesfaye	________	31/5-14
External Examiner	Signature	Date

Abstract

In this research project, a mechanism was developed to remove dirt from surface of street and sidewalks. Before concept generation and selection, characteristics, types and distribution of debris on street surface was analysed to facilitate the next design phase. During conceptual design phase, different concepts were proposed using concept generation methods and the best concepts were selected. From the selected concepts, the design was developed in accordance with technical and economic criteria and general arrangement, component shapes and materials were determined. Moreover, the components and assembly were analysed and tested using SolidWorks motion analysis tools and SolidWorks simulation tool.

The machine is compact and manually driven, and capable of reducing the cost of road surface cleaning work. It also prevents dust from being blown up without spraying water on the road surface during the cleaning process. At optimum working speed, it absorbs dirt efficiently without damaging the road surface. Moreover, it applies an absorbing force to the debris effectively.

In its working process, the coarse debris cleaning mechanism will clean larger litters first, and then the spur gear mechanism drives the roller brush rotating at optimum speed, and thus produces negative pressure to direct the fine debris into the container. By pushing the machine, it moves the coarse and fine debris towards the dirt container. Therefore, it saves power and reduces labor force more than manually cleaning using brooms, and reduces cost when compared to employing street sweepers.

Acknowledgement

I would first and foremost like to thank my advisor, Dr.-Ing. Zewdu Abdi for his intellectual contributions, and personal encouragements. His continuous interest was a constant source of motivation for me throughout the research work. I am grateful to the staff of the School of Mechanical and Industrial Engineering, Addis Ababa Institute of Technology, who have provided the most cooperative assistance to my research work.

Finally, I would like to thank those who have watched and helped me grow. Though not reflected in the technical content of this document, the support, encouragement, and love provided by my wife, family and friends are perhaps the greatest reason for my success.

Contents

List of Figures

List of Tables

Nomenclature

SCM	Street cleaning machine
MSW	Municipal solid waste
USWM	Urban solid waste management
FEA	Finite element analysis
FEM	Finite element methods
CMP	Chemical-mechanical planarization
3-D	Three dimensional
2-D	Two dimensional
CAD	Computer aided design

CHAPTER ONE: INTRODUCTION

Street sweeping is one facet of a solid waste management system; unfortunately, very little information is available in the literature on the various aspects associated with street sweeping. The wastes deposited on the streets create health problems, pollution and a negative visual impact, particularly on visitors, and thus indirectly affects the economy of cities and towns.

Despite the fact that municipalities may spend approximately 10% to 20% of their budgets on street cleaning and sweeping, the process is not normally optimized [1]. There are several types of tools, equipment, and methods (both manual and mechanical) available for street cleaning. Because of the tasks and costs involved in the process, street cleaning is also a system in which there are opportunities for savings by simply improving the efficiency of the process.

1.1 Mechanical Sweeping

The majority of mechanical sweepers are mobile units that use a vacuum system to collect the waste materials. Generally, the suction action is complemented by one or more rotating brushes for dislodging residues that adhere to the surface of the road. There is a wide range of mechanical sweepers. They vary in size from very small units controlled by a pedestrian, to large mechanical sweepers mounted on a vehicular chassis. The large mechanical sweepers generally are equipped with an auxiliary engine to generate the vacuum and, in some cases, are fitted with a hose that can be controlled by an operator to pick up refuse from areas that are difficult to reach (i.e., dry leaves from drainage ditches). The operating speed of the smallest machines is about 2 to 3 km/hr, that of the largest sweepers is 10 km/hr or greater. Mechanical sweepers are efficient for the collection of light litter, fine dust, and sand from roadways.

The conditions typically found in economically developing countries limit the role of mechanical sweepers to that of simply supplementing manual sweeping. Mechanical sweepers normally are found in the large metropolitan areas of developing countries. The degree to which mechanical sweepers are utilized for a specific application should be based on thorough analyses of advantages and disadvantages, as well as the costs associated with using them as opposed to using manual sweepers. In addition, mechanical sweepers have the tendency to be extremely maintenance-intensive units. The internal mechanisms may be damaged in the process of collecting large objects illegally disposed on the streets. Consequently, these machines should be supported by well equipped maintenance facilities stocked with a complete inventory of replacement parts.

In general, street sweepers are a significant capital expenditure ranging from nearly $100,000 for mechanical broom sweepers to over $250,000 for high-efficiency vacuum-assisted machines. When compared to other heavy equipment (dump trucks, loaders, etc.) for maintenance operations by state, regional and local governments, capital cost of street sweepers is typical [2].

1.2 Design of Sweeping Systems

The typical task of a manual sweeper can be divided into two main phases: 1) sweeping and loading the wastes into a storage container, and 2) transporting the full container to a transfer point where it can be emptied. In terms of efficiency, the first activity is productive while the second is not. The second activity is not productive because the time used in transporting the container for unloading is time that is not spent performing the main task of sweeping. Similarly to the waste collection phase of waste management, one of the main objectives in designing a system for manual sweeping is to maintain the total amount of time spent on transport to a minimum. This objective can be accomplished in either of two ways:

1) Minimizing the distance over which the collected wastes have to be transported, or
2) Providing the maximum size of receptacle for the wastes that are collected.

1.3 Scope of the Study

The scope of this research was to develop manually driven mechanism for street surface cleaning purpose by analyzing debris characteristics, types and distributions. The designed mechanism was analysed and validated using SolidWorks simulation software.

1.4 Statement of the Problem

Urban solid waste management (USWM) problems facing cities in the developed and developing world are well documented; however, progress in tackling them is very slow in the later. In order to secure the future of urban environments in the developing world from continuous or perpetual decay, it is important to design a device which is capable of collecting litters from streets in safe manner, with minimum cost and time, and that are affordable to the developing nations those unable to buy mechanical broom sweepers and high-efficiency vacuum-assisted machines.

In our country, Ethiopia the street cleaning process is done manually using brooms, shovels, and handcarts. Hence, it is not efficient to collect large enough litters within optimum time. It also affects the health of the workers, exposing them to dust and poisonous substances. The cleaning quality using broom is lower than that of cleaning quality using machines. As a result less cost but easy to drive and collect solid wastes, with manually driven machine become essential.

1.5 Objective of the Study

General Objective

The main objective of this research is designing and developing human powered brushing mechanism for street cleaning.

Specific Objectives

- Identifying debris characteristics, types and distributions
- Developing design concepts for cleaning mechanism
- Concept identification and working concepts
- Analyzing brush characteristics
- Developing design calculations
- Detail design of each components
- Simulation of components working together

1.6 Research Methods, Materials and Procedures

Methods

The methods employed to carry out the research:

- Literature survey from different sources such as journals, books, websites and previously done research papers.
- Identification of debris characteristics, types and distributions was studied by taking samples of varieties of litters from roads and sidewalks.
- Samples taken 2m x 2m area including both roads and sidewalks and debris distributions per square meter were:
    - ✓ Plastics 1.5g
    - ✓ Papers 3.9g
    - ✓ Sand and dust 7.3g
    - ✓ Leaves 2.85g

- Exploring alternatives design concepts using concept development process which includes:
  - ✓ Clarifying the Problem
  - ✓ Searching internally
  - ✓ Searching externally
  - ✓ Exploring systematically
  - ✓ Reflecting on the Solutions and the Process.

Materials

To accomplish this research project, the materials used are listed below:

- ✓ Meter: to measure sample area
- ✓ Electronic balance: to determine litter masses
- ✓ Broom: to sweep debris
- ✓ Shovel: to lift debris
- ✓ Plastic bag: to handle litters

Procedures

The machine was designed and tested after analyzing the debris characteristics, types and distributions on roads and sidewalks. The procedure is shown in figure 1.1

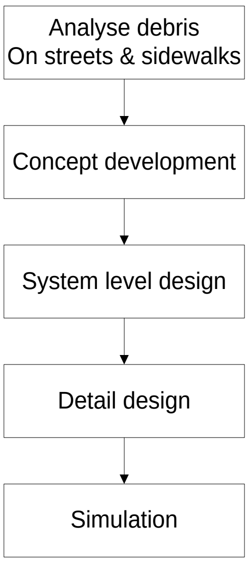


Figure 1.1 Design procedure used to develop street cleaning machine

CHAPTER TWO: LITERATURE REVIEW

2. 1 Analysis of Debris Characteristics, Types and Distributions

Solid wastes could be defined as non-liquid and nongaseous products of human activities, regarded as being useless. It could take the forms of refuse, garbage and sludge [3].The information on the nature of debris on roads, its composition, physical and chemical characteristics and the quantities generated are basic needs for the design of appropriate cleaning device.

2.1.1 Sources, Types and Quantities of Solid Wastes

Knowledge of the sources and types of solid wastes, along with data on the composition and rates of generation, is basic to the design and operation of the functional elements associated with the management of solid wastes. The materials that are collected under the term solid waste include many different substances from a multitude of sources. The sources of solid wastes are dependent on the socioeconomic and technological levels of a society.

- ❖ A small rural community may have known types of solid wastes from known sources (i.e. the wastes are more homogenous). Wastes from industrial and mining areas are also more homogenous.
- ❖ Urban communities (metropolitan cities) have many sources (The wastes are more heterogeneous).

There are different sources and types of solid wastes as shown in table 2-1

Table 2-1: Sources and types of solid wastes

S.No	Source	Typical waste generators	Types of solid wastes
1	Residential	Single and multifamily dwellings	Food wastes, Paper, cardboard, plastics, textiles, leather, yard wastes, wood, glass, metals, ashes, special wastes (e.g. Bulky items, consumer electronics, white goods, batteries, oil tires), and Household hazardous wastes.
2	Industrial	Light and heavy manufacturing, fabrication, Construction sites, power and chemical plants	Housekeeping wastes, packaging, food wastes, construction and demolition materials, hazardous wastes, ashes, and special wastes.
3	Commercial	Stores, hotels, restaurants, markets, office buildings, etc	Housekeeping wastes, packaging, food wastes, construction and demolition materials, hazardous wastes, and ashes
4	Institutional	Schools, hospitals, prisons, government centers	Same as commercial

S.No	Source	Typical waste generators	Types of solid wastes
5	Construction and demolition	New construction sites, road repair, renovation sites, demolition of buildings	Wood, Steel, concrete, dirt, etc.
6	Municipal services	Street cleaning, landscaping, parks, beaches, other recreational areas, water and wastewater treatment	Industrial process wastes, scrap materials, off- specification products, slag tailings
7	Process	Heavy and light manufacturing, refineries, chemical plants, power plants, mineral extraction and processing	Industrial process wastes, scrap materials, off-specification products, slag, tailings
All of the above should be included as" municipal solid waste.			
8	Agriculture	Crops, orchards, vineyards, dairies, feedlots, farms	Spoiled food wastes, agricultural wastes, hazardous wastes (e.g. pesticides)

Source: Adapted in part from [4]

Quantities

There are very significant differences in quantity depending on many factors, such as:

- The size of the population living in the area,
- The type of sources of the area (commercial, residential, touristic, industrial, etc.),
- The quantity of public or private gardens,
- Whether the families living in the area are predominantly poor or rich,
- The season of the year, and
- The cultural aspects of the area affecting the composition, quantity and peak-days of the solid waste produced.

Some typical waste generation rates for low-income, middle-income and high income countries are shown in table 2-2.

Table 2-2 Waste generation rate

	waste generation rates (in kg/ capita/day)		
	Low-income country	Mid-income country	High-income country
Mixed urban waste Large city (>500000)	0.50-0.75	0.55-1.1	0.75-2.2
Mixed urban waste Small to medium city (<500000)	0.65-0.35	0.45-0.75	0.65-1.5
Residential waste only	0.25-0.45	0.35-0.65	0.55-1.0

Source: Adapted in part from [5]

Evidently the best method to calculate the quantity of waste for a given zone is by simply weighing the waste trucks at the entrance of treatment and disposal sites.

When implementing a solid waste management program, solid waste analysis is crucial to determine which techniques, systems and procedures are suitable to the waste stream. There are essentially two different methods of sampling:

- Continuous sampling of a low fraction of waste
- Intensive sampling carried out over one or more relatively short periods. Statistical reliability favours continuous sampling, but practical considerations, including cost, mean that the latter method has to be considered. At a minimum, surveys should collect data covering a period of one week. This will allow for measurement of variation of refuse within cycles of a day or week. To take into account the changes over monthly, seasonal and yearlong periods, it is necessary to either:
- Repeat the survey at different times , or
- Spread the survey period over a long time.

The following approach is recommended for the overall sampling regime:

- Surveys should be carried out over a minimum period of one week. Seasonal variation should be estimated by repeating the survey at different times of the year, which are generally best done over a week in the middle of each of the four seasons.

- o Where baseline data is required, four surveys of one week each should be done in each season over a single year.
- o Where monitoring of long-term trends is needed, a single-week survey should be done every year, in each season, over a four year cycle.
- o If it is possible, it is very useful to carry out a survey differentiating between the different zones of the town, with special emphasis on waste composition. The principal steps to be taken for this analysis are:

1. Weighing the vehicle loads to be analysed upon entering the site.
2. Sampling a statistically significant proportion of incoming loads in each category and sorting and weighing a sample of refuse from those loads into primary categories: paper/ cardboard, glass, plastic, organic matter, wood, etc.
3. Statistical analysis and reporting

An analysis of a specific solid waste source will need a similar approach. The main difference is the sampling method and the weighing location.

2.1.2 Physical, Chemical and Biological Characteristics of Solid Wastes

The major physical characteristics measured in waste are: (1) density, (2) size distribution of components, and (3) moisture content. Other characteristics which may be used in making decision about solid waste management are: (1) colour, (2) voids, (3) shape of components, (4) optical property, (5) magnetic properties, and (6) electric properties [6]. Optical property can be used to segregate opaque materials from transparent substances which would predominately contain glass and plastic. Magnetic separators are designed based on the magnetic characteristics of the waste. Moisture content is essential for leachate calculation and composting. Density is used to assess volume of transportation vehicle and size of the disposal facility. Shape can be used for segregation as flaky substance will behave differently compared to non-flaky substance.

Important chemical properties measured for solid waste are: (1) moisture (water content can change chemical and physical properties), (2) volatile matter, (3) ash, (4) fixed carbon, (5) fusing point of ash, (6) calorific value, (7) percent of carbon, hydrogen, oxygen, sulphur and ash. Solid waste production is a function of land use as well as its composition is inversely proportional to the possible soil damage and bacterial contamination of the environment [7]. Wet waste will host more bacteria compared to dry waste. The nutrition in waste also acts as a key factor which decides population balance of species in the waste and immediate environment. Toxic elements discourage multi-cellular organism in the waste. But microorganisms may still persist at places which may favour some species of micro organism. Saprophytes and fungi will flourish in decomposable matter.

Composition of solid wastes and their determination

Knowing the composition of waste is important for deciding the treatment systems. Numerous factors have an influence on the composition and characteristics of solid waste:

- ✓ The area: residential, commercial, etc.
- ✓ The season and weather (differences in the amount of population during the year, tourist places).
- ✓ The economic level (differences between high and low-income areas). High-income areas usually produce more inorganic materials such as plastics and paper, while low-income areas produce relatively more organic waste.
- ✓ The cultural aspects of the zone.

Urban waste is normally divided into three big groups:

- ➢ Inert waste: metals, glass, soil, slags and ashes
- ➢ Putrescibles: food waste, yard trimmings
- ➢ Combustibles: paper, cardboard, plastics, wood, tyres, leather, textiles.

Composition is the term used to describe the individual components that make up the solid waste stream and their relative distribution, usually by percent by weight. Information on the composition of solid waste is important in evaluating equipment needs, systems and management programs and plans.

Table 2-3: Typical distribution of components in residential municipal solid waste for different countries (in % of total)

Components	Low-income	Middle-income	Upper income
Organic			
• Food waste	40-85	20-65	6-30
• Paper	1-10	8-30	20-45
• Cardboard	-	-	5-15
• Plastics	1-5	2-6	2-8
• Textiles	1-5	2-10	2-6
• Rubber	-	-	0-2
• Leather	-	-	0-2
• Yard Wastes	1-5	1-10	10-20
• Wood	-	-	1-4
Inorganic			
• Glass	5	5	8
• Aluminum	2	2	0
• Dirt, ash etc	20	15	5

Source: Adapted in part from [8]

a. Physical composition of solid wastes

Knowing the physical component of a road solid waste is important for the following purposes:

- ✓ for the selection and operation of equipment and facilities
- ✓ to assess the possibility for resource of energy recovery
- ✓ to design and analyze cleaning mechanism

Ways for physical composition analysis

Individual component study

- Analyze the components of municipal solid waste by type
- Sorting and separation of each and every component is necessary
- Samples each of the heterogeneous refuse of municipal solid waste
- Should be representative (at all seasons of the year)
- Statistical produces (representativeness and randomization)

The types (components) of municipal solid waste may be different from country to country by season, economic condition, developmental level, etc.

Table 2-4: Typical variation observed in the collected composition of residential municipal solid waste.

Waste	Percent by weight		Percent variation	
	Winter season	Summer season	Decrease	Increase
Food waste	11.1	13.5		21.6
Paper	45.2	40.0	11.5	
Plastics	9.1	8.2	9.9	
Other organics	4.0	4.6		15.0
Yard wastes	18.7	24.0		28.3
Glass	3.5	2.5	28.6	
Metals	4.1	3.1	24.4	
Inert and other wastes	4.3	4.1	4.7	
	100.0	100.0		

Source: Adapted in part from [8]

The individual component study involves achieving the present composition of solid waste by volume and by weight. Volume measurements although difficult to measure are essential to disposal methods. E.g. to calculate incinerator sizes and land fill areas and to limit hauling capacity of refuse tracks, etc.

Moisture content

Moisture content of solid waste is the weight loss (expressed in percent) when a sample of solid waste is dried to a constant weight at a temperature of 100 to 105 ºC [9]. The percentage of moisture contained in a solid waste sample can be calculated on a dry or wet basis. Moisture content has a great influence on the heat of combustion as well as in the biological processes of organic matter. It depends on:

a. organic content
b. weather
c. source
d. Heat of combustion (heating value)

The heating value of waste is a measure of the energy released when it is burned. A heating value of about 11.6 x 106 J/kg is needed to sustain combustion. Waste with lower heating value can be burned, but it will not maintain adequate temperature without the addition of auxiliary fuel. The heat of combustion increases when there is more paper, cardboard and plastic in waste because they have a high heating value, and decreases when there is a high content of organic matter, and therefore, of moisture.

- ✓ Carbon to nitrogen (C:N) ratio

Carbon to nitrogen ratio is the ratio of the weight of carbon to the weight of nitrogen present in compost or in materials that are being composted. It is an important parameter in composting processes and should always be between 20 and 35. Lower ratios indicate the loss of nitrogen as ammonium gas and render composting impractical.

The moisture content of solid waste is usually expressed in one of two ways

1. In the wet: weight method of measurement: the moisture in a sample is expressed as a percentage of the wet weight of material.

2. Dry-weight method: it is expressed as a percentage of the dry weight of the material.

Wet-weight and dry-weight moisture content are expressed in eq. 2.1 and eq.2.2 respectively.

$$M_w = \frac{w-d}{w} * 100 \quad \text{……………………………….. eq. 2.1}$$

$$M_d = \frac{w-d}{d} * 100 \quad \text{…………………………………eq. 2.2}$$

Where: M_w = wet- weight moisture content, %

M_d = dry- weight moisture content, %

W = initial mass of sample as delivered, kg

d = mass of sample after drying, kg

Table 2-5: Typical data on moisture content of municipal solid waste

Component	Moisture Content % by weight	
	Range	Typical
Food wastes	50-80	70
Paper	4-10	6
Card board	4-8	5
Plastics	1-4	2
Textiles	6-15	10
Rubber	1-4	2
Leather	8-12	10
Garden trimmings	30-80	60
Wood	15-40	20
Glass	1-4	2
Tin cans	2-4	3
Nonferrous metals	2-4	2
Ferous metals	2-6	3
Dirt, ashes, brick, etc	6-12	8
MSW	15-40	20

Source: Adapted in part from [8]

To obtain the dry weight, the solid waste material is dried in an oven at 77^{o}C for 24 hours [9]. This temperature and time is used to dehydrate the material completely and to limit the vaporization of volatile materials.

• For most industrial solid wastes, the moisture content will vary from 10 – 35 percent.

• The moisture content of municipal solid waste vary depending on

1. Composition of the waste
2. The season of the year
3. Humidity
4. Weather condition especially rain

Density

Under physical composition of solid wastes density, is one of the important parameters. It is defined as the weight of the material per unit volume. The interest in knowing density of solid waste is to assess the total mass and volume of waste that must be managed. It varies depending on the composition of waste. It is normally higher in residential areas where organic matter makes up a large proportion of the waste, and lower in commercial districts where waste contains more paper and cardboard. It also varies with the economic level, being less dense in high income areas where there is a higher percentage of packaging waste. Table 2 shows the density range of municipal solid waste:

Table 2-6: Typical density range of MSW at generation point

Country	Waste density (in kg/m^3)
High-income country	100-175
Mid-income country	175-330
Low-income country	330-600

Source: Adapted in part from [9]

The density of waste may also change during waste transportation. Therefore it is essential to indicate where density has been measured (at the point of generation, in the container, or at the disposal site). Usually the density increases by 20-25% during transport in a non-compaction truck. The density is important for the selection of waste collection equipment. For example, compactor trucks, which press the waste together, are most effective if the waste has a low density, for example, if it has a high proportion of paper, cardboard and plastics.

The densities of solid waste vary markedly with:

1. Geographic location
2. Season of the year
3. Length of time in storage

Great care should be taken in selecting typical weight or density values. The densities of municipal solid wastes as delivered in compaction vehicles have been found to vary from 178 to 415 kg/m^3; a typical value is 297 kg/m^3.

b. Chemical composition

Information on the chemical composition of solid wastes is important in evaluating alternative processing and recovery options. For example, the feasibility of combustion depends on the chemical composition of solid waste. If solid wastes are to be used as fuel, the four most important properties to be known are:

1) **Proximate analysis:** Proximate analysis for combustible components of municipal solid waste includes the following tests

a) Moisture (loss of moisture when heated to 105 ^{0}C for 1hour)

b) Volatile combustible matter (additional loss of weight on ignition at 950 ^{0}C in a covered crucible)

c) Fixed carbon (combustible residue left after volatile matter is removed)

d) Ash (weight of residue after combustion in an open crucible)

2) **Fusing point of ash:** is defined as the temperature at which the ash resulting from the burning of waste will form a solid (clinker) by fusion and agglomeration. Typical fusion temperature for the formation of clinker from solid waste ranges from 1100 to 1200^{o}C.

3) **Ultimate analysis:** the ultimate analysis of a waste component typically involves the determination of the percent of C (carbon), H (hydrogen) O (oxygen), N (nitrogen), S (sulfur) and ash. The results of the ultimate analysis are used to characterize the chemical composition of the organic matter in municipal solid waste.

Table 2-7: Chemical composition of organic matter in municipal solid waste.

Component	C	H	O	N	S	Ash
Food waste	48.0	6.4	37.6	2.6	0.4	5.0
Paper	43.5	6.0	44.0	0.3	0.4	6.0
Card board	44	5.9	44.6	0.3	0.2	5
Plastic	60	7.2	22.8	-	-	10
Textiles	55	6.6	31.2	4.6	0.15	2.5
Rubber	78.5	10	-	2	-	10
Leather	60	8	11.6	10	0.4	10
Garden trimmings	47.8	6	38	3.4	0.3	4.5
Wood	49.5	6	42.7	0.2	0.1	1.5
Misc. organics	48.5	6.5	37.5	2.2	0.3	5
Dirt, ashes, brick, etc	26.3	3.0	2.0	0.5	0.2	68

Source: Adapted in part from [8]

4) **Energy content:** The energy content of the organic components in municipal solid waste can be determined;

- using a full scale boiler as a calorimeter
- using a laboratory bomb calorimeter
- calculation if the elemental composition is known

Energy values as discarded basis may be converted to a dry basis by using:

$$\frac{\text{kJ}}{\text{kg}}(\text{dry bases}) = \frac{\text{kJ}}{\text{kg}}(\text{as discarded})\left(\frac{100}{100 - \%\text{moisture}}\right)$$

The corresponding equation for a dry ash-free basis is:

$$\frac{\text{kJ}}{\text{kg}}(\text{dry bases}) = \frac{\text{kJ}}{\text{kg}}(\text{as discarded})\left(\frac{100}{100 - \%\ \text{moisture} - \%\ \text{ash}}\right)$$

Table 2-8: Typical data on inert residue and energy content of municipal solid wastes

Component	Inert residue (after complete combustion.) %		Energy, KJ/kg (as discarded basis)	
	Range	Typical	Range	Typical
Food wastes	2-8	5	3,5000-7,000	4,650
Paper	4-8	6	11,600-18,600	16,750
Cardboard	3-6	5	13,950-17,450	16,300
Plastics	6-20	10	27,900 –37,200	32,600
Textiles	2-4	2.5	15,100 –18,600	17,450
Rubber	8-20	10	20,900 – 27,900	23, 250
Leather	8-20	10	15,100 –19,800	17,450
Garden trimmings	2-6	4.5	2,300 – 18,600	6,500
Wood	0.6-2	1.5	17,450-19,800	18,600
Glass	96-99	98	100 - 250	150
Tin cans	96-99		250 – 1,200	700
Non–ferrous metals	90-99	96	-	-
Ferrous metals	94-99	98	250 – 1,200	700
Dirt, ashes, bricks, etc	60-80	70	2,300 – 11, 650	7,000
MSW	-	-	9,300 – 12, 800	10,500

Source: Adapted in part from [8]

c. Biological properties of solid wastes

The most important biological characteristic of the organic fraction of municipal solid waste is that almost all of the organic components can be converted biologically to gases and relatively inert organic and inorganic solids.

Most protozoa feed on bacteria. The free living protozoa can be found in any aerobic environment in which bacteria are present to support their growth. Some of the protozoa are parasitic to humans/animals. Protozoa are primarily aquatic animals but they are also found in solid waste and soil. The ability to form cysts allow them to survive during desiccation and unfavorable conditions. Numerous human diseases are caused by protozoa including amoebic dysentery. Solid waste also hosts substantial amount of fungi. Of about 100,000 species of fungi about 100 are pathogenic to animals and humans [10]. Fungi cause infection to hair, nail, skin, and lung. Infection occurs by person sores in air which may be present in solid waste. Toxins generated by Asperigillus flavus can cause liver cancer and fatty degeneration of liver in people who eat contaminated food [6]. Some of the bacteria can form spores to allow them to survive when nutrients are not available during dry period. These spores can easily carry away by wind. Contamination of wounds and food by spores of Clostridium can lead to fatal consequences. Species such as C.botulinum produce toxins which lead to food poisoning. Species such as C. Persringens, grow speedily in wounds leading to gangrene [10].

2.1.3 Future Changes in Waste Components

In planning for future waste management systems, it will be important to consider the changes that may occur in the composition of solid waste with time. Four waste components that have an important influence on the composition of the wastes collected are food waste, paper, cardboard, yard wastes and plastics.

Food wastes: The quantity of residential food wastes collected has changed significantly over the years as a result of technical advances and changes in public attitude. Two technological advances that have had a significant effect are the development of the food processing and packaging industry and the use of kitchen food waste grinders. The percentage of food waste, by weight, has decreased from about 14 percent in the early 1960s to about 9 percent in 1992. Recently, because the public has become more environmentally aware and concerned, a trend has developed toward the use of more raw, rather than processed, vegetables. While it would increase the quantity of food wastes collected no firm data are available on this subject.

Paper and cardboard: The percentage of paper and cardboard found in solid wastes has increased greatly over the past half century. It is expected that use of paper and cardboard will remain stable for the next few year.

Yard wastes: Yard wastes are vegetative waste resulting from the care and maintenance of landscaped areas, lawns, and gardens. Yard waste includes leaves, grass clippings, brush, garden wastes, tree trunks, holiday trees and prunings from trees or shrubs. Environmental conditions such as droughts have also affected the quantities of yard waste collected in certain location.

2.1.4 Solid Waste Generation

Waste generation encompasses activities in which materials are identified as no longer being of value and are either thrown away or gathered together for disposal. For example, the warping of a candy bar is usually considered to be of little further value to the owner once the candy is consumed and more often that not it is just thrown away, especially outdoors. It is important in waste generation to note that there is an identification step and that this step varies with each individual waste. Knowledge of the quantities of solid wastes generated, separated for recycling, and collected for further processing or disposal is of fundamental importance to all aspects of solid waste management.

Factors that affect waste generation rates

The effect of source reduction and recycling activities, Public attitudes and legislation, and geographic and physical factors on the generation of solid waste are considered in the following discussion.

1. Effect of source reduction and recycling activities on waste generation:

The effects of source reduction and the extent of recycling activities on waste generation are considered in the following discussion:

Source reduction: Waste reduction may occur through the design, manufacture, and packaging of products with minimum toxic content, minimum volume of material, and /or a longer useful life. Waste reduction may also occur at the household, commercial or industrial facility through selective buying patterns and the reuse of products and materials. Because source reduction is not a major element waste reduction at the present time, it is difficult to estimate the actual impact that source reduction programs have had (or will have) on the total quantity of waste generated. Nevertheless, source reduction will likely become an important factor in reducing the quantity of waste generated in the future. For example, if the postage rate for bulk mail were increased significantly, the quantity of bulk mail would be reduced sharply. Some of the other ways in which source reduction can be achieved follows:

- Decrease unnecessary or excessive packaging
- Develop and use products with greater durability and repairability (e.g., more durable appliances and tyres)
- Substitute reusable products for disposable, single-use products (e.g., reusable plates and cutlery, refillable beverage containers, cloth diap and towels)
- Use fewer resources (e.g., two-sided copying)
- Increase the recycled materials content of products
- Develop rate structures that encourage generators to produce less waste.

Extent of recycling: The existence of recycling programs within a community definitely affects the quantities of wastes collected for further processing or disposal.

2. Effect of public attitudes and legislation on waste generation

Along with source reduction and recycling programs, public attitudes and legislation also significantly affect the quantities generated. Public attitudes ultimately, significant reduction in the quantities of solid wastes generated occur when and if people are willing to change-of their own volition- their habits and lifestyles to conserve natural resources and to reduce the economic burdens associated with the management of solid wastes. A program of continuing education is essential in bringing about a change in public attitudes. Legislation Perhaps the most important factor affecting the generation of certain type of wastes is the existence of local, state, and federal regulations concerning the use of specific materials. Legislation dealing with packaging and beverage container materials is an example. Encouraging the purchase and use of recycled materials by allowing a price differential (typically 5 to 10 percent) for recycled materials is another method.

3. Effect of geographic and physical factors on waste generation

Geographic and physical factors that affect the quantities of waste generated and collected include location, season of the year, the use of kitchen waste food grinders, waste collection frequency, and the characteristics of the service area . Because broad generalizations are of little or no value, the impact of these factors must be evaluated separately in each situation.

Geographic location: Different climates influence both the amount of certain type of solid wastes generated and the time period over which the wastes are generated. For example, substantial variations in the amount of yard and garden wastes generated in various parts of the country are related to climates. That is, in the warmer southern areas, where the growing season is considerably longer than in the northern areas, yard wasters are collected not only in considerably greater amounts but also over a longer time. Because of the variations in the quantities of certain types of solid wastes generated under different climates, special studies should be conducted when such information will have a significant impact on the system. Often, the necessary information can be obtained from a load-count analysis.

Season of the year: The quantities of certain types of solid wastes are also affected by the season of the year. For example, the quantities of food waste related to the growing season for vegetables and fruits, seasonal sampling also will be required to assess changes in the percentage distribution of the waste materials comprising municipal solid waste, especially in areas of the country with extensive vegetation.

Expression of unit generation

In addition to knowing the source and composition of solid waste, it is equally important to have uniform units of expression. For example, universally accepted units for:

- Household waste (kg/capita/day)
- Commercial waste (kg/x/day where x can be m^2 of floor area of commercial establishment, unit volume or birr in sales, the number of employees, etc.)
- Institutional waste (kg/x/day where x can be the number of students, m^2 of the area of park or public place, number of visitors, etc.)
- Market waste (kg/x/day where x can be the number of market lots, m^2 of floor area, birr in sales, etc.)
- Industrial waste (kg/x/day where x can be unit volume or birr of production output, m^2 of floor area, the number of employees, etc.)
- street sweeping waste (kg/km/day)
- drain cleaning waste (kg/km/day)
- total waste (kg/capita/day)

2.2 Development of Street Sweeping Technology

Street sweeping either manual or mechanical has been a normal operation for most municipalities for hundreds of years. The earliest sweepers were manual efforts using a broom, shovel with either push or horse-drawn carts. Street sweeping materials consisted of trash, dirt and vegetation. Thus, aesthetics and sanitation were the two driving forces for municipalities to keep streets clean and protect the citizens. The first motorized sweeper was developed in the early 20th century. The mechanical broom sweeper remains today by far the most common piece of equipment in the majority of cities to keep streets clean of gross pollutants. Today, street sweeping materials have changed, with gross pollutants including more plastics and paper products than would have been present even 50 years ago along with discarded items associated with cars and trucks using the roadway. During the 1970's, regenerative-air street sweeping technology came upon the scene.

Street sweeping involves the use of specialized equipment to remove litter, loose gravel, soil, pet waste, vehicle debris and pollutants, dust and industrial debris from road surfaces. Street sweeping equipment can consist of a truck or truck-like vehicle equipped with multiple brushes, pick-up deflector, holding bin, water sprayer, vacuum nozzle and filter, or a combination of some or all of these features.

Various types of machines have been developed since many years ago for road cleaning purpose. In 1876, Jacob Endson [11] have invented certain new and useful improvements in street sweeping machines which consists improved construction of the frame and stays by which the rotary brush is supported, improved lifting and holding device for the brush, improvement in the manner of attaching and detaching the driving wheels to and from the drafting shaft and employment of an adjustable independent dust guard, which is independent of the rotary brush. In 1916, M.L Osborne [12] have invented new improvements; movably and adjustably supported casing of simple and improved construction wherein the rotary brush is mounted, improved adjusting means for the brush carrying casing and simplify and improve the construction of rotary brush. In 1962, H.I Hanson [13] have invented improvements in a vehicle propelled over the ground; and having a power driven blower or pump thereon that pumps air out of a box like body of the vehicle, producing partial vacuum therein; and the vacuum is communicated to a pick up hose or the like; and causes a stream of air to enter the end of the hose and pick up the material and carry it into the body; and the material is separated from the air in the body; and the air, pumped from the body is discharged by the pump into the atmosphere. In 1992, Davis have invented a street sweeping machine is incorporated in an industrial vacuum machine. Extending transversely of the vehicle is a center casing in which a brush is rotated by a hydraulic motor. A vacuum intake hose is connected to the casing and leads to the vacuum machine. The casing may be raised and lowered between transport and working positions. On one or both sides of the vehicle are sides or "curb sweeping" casings, likewise containing a hydraulically driven brush and connected to a vacuum intake hose. The curb sweeping casing is swivel mounted and spring biased outward to follow the curb on the street being swept. In the main centered casing are hydraulically raised and lowered flaps which improves the vacuum which can be drawn in the casing. Also provided is a stick breaker which breaks up large pieces of debris so that they may be drawn into the vacuum duct.

Latter a street sweeper having a vertical chain driven conveyor apparatus has been developed. The vertical chain driven conveyor apparatus which is provided with a jointed shaft to compensate for chain wear over the life of the chains is provided with an automatically adjusting chain tension adjustment system. It is also provided with locking adjustment mechanism to prevent the chains from losing tension when the sweeper is turned off. An initialization program is operable to restore chain tension when the street sweeper is started and prevent sweeping operations until a desired chain tension has been indicated.

The term high-efficiency sweeper was first coined by the author in 1997 to describe a brand-new vacuum sweeping technology that employed a sophisticated filtration system for dust containment in combination with the use of both main and gutter brooms [14]. This high-efficiency vacuum sweeper (which is no longer in production) was developed by Enviro Whirl Technologies of Centralia in 1995 and later acquired by Schwarze Industries of Huntsville in 1999. The Enviro series machines that Schwarze built and marketed based on the original Enviro Whirl design employed a unique self-cleaning filtration system that can filter “dust” and exhaust only particulate matter less than 2.5 microns. Fugitive dust control was not available at that time by any other sweeper in the nation. And because the Enviro series fan operated only in filtered air with no debris or dust coming in contact with the blades, the manufacturer could provide a lifetime guarantee for the fan, which was unheard of at the time. Tests showed that the pickup ability of the Enviro series’s sweeping technology surpassed even that of the regenerative air sweepers that were available at the time [14]. Because the Enviro series used no water for dust suppression, and because it cleaned to a very-small-micron level, these machines were ideal for any application where dangerous or toxic materials were present. This included usage in industrial and manufacturing settings where material needed to be recycled, reused, or securely contained and disposed of after pickup. Unfortunately, the Enviro machines were much more expensive to purchase, and the relatively unknown cost of maintenance remained a concern. But, more importantly, because they were mounted onto a tractor chassis rather than a truck chassis, their top non-sweeping speed of about 25 miles per hour was seen as a disadvantage in the municipal sweeping marketplace, especially for large cities. Schwarze no longer produces the Enviro machines, and their only established market was as an industrial sweeper for exclusive use on industrial sites where toxic and/or hazardous materials needed to be cleaned up and/or recycled. Historically, that's where the vast majority of the limited Enviro series sales actually occurred.

Elgin Sweeper Company of Elgin developed a patented dust suppression system with a powerful vacuum fan to create an airstream; main and side broom skirting for dust capture; and a long-life, low-maintenance filter between the hopper and the vacuum fan. These components together create a highly effective method for controlling fugitive dust generation that usually occurs during sweeping. This dust suppression system is also available for Elgin's mechanical sweeper called the Eagle. In addition, Elgin recently released another fugitive dust control system that was available on its regenerative air model called the Crosswind NX. Real-world pickup performance testing of the waterless Eagle and the Crosswind NX conducted by Pacific Water Resources Inc. in July 2008 verified that these sweepers provided excellent overall pickup, including small-micron particles, and did not create any observable fugitive dust losses [14]. These are the underlying requirements for classification as a high-efficiency sweeper.

CHAPTER THREE: DESIGN CONCEPTS AND PRODUCT ARCHITECTURE

The conceptual design phase included primarily the determination of the general layout and design of the road cleaning mechanism. The first step in this phase was the identification of design goals. By considering customer needs, the following fundamental machine requirements were considered:

- Easy to use: not too much instruction is needed.
- Cleaning capability: collecting wet, dry, fine and coarse litters. Clean without damaging road surface.
- Light weight: easy to push, turn, handle and move from place to place.
- Space requirement: minimum space to place or transport the machine after cleaning activities.
- Low cost: affordable to sell for medium and high income communities, small enterprises, private and governmental institutions, and organizations.
- Save time and reduce labor effort: cleaning large surface within short period of time comparing with cleaning manually using brooms.

Product Specification:

Based on the above machine requirements specification of the product was specified as follows:

Sweeping width: 700mm

Maximum sweeping capacity: 2100 square meter per hour

Container capacity: 50 liter

Mass of the machine: not more than 10kg

Debris density: 297kg/m^3

3.1 Function Structure

To simplify the design process and to get plenty of alternative concepts, it important to establish function structures. The function structures are classified into overall function structure and sub functions structure.

Overall function structure:

The overall function shows the problem in general with inputs and output relationships. Here the inputs are material (debris on roads) and energy (human power) whereas the outputs are material (debris on dirt container) and energy (kinetic energy). Figure 3.1 shows the overall function structure.

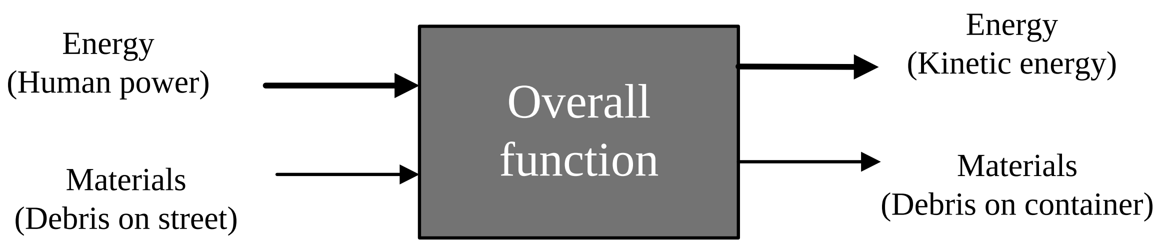


Figure 3.1 Overall function structure

Sub functions structure:

Decomposing complex problem into simpler sub-problems is essential because many design challenges are too complex to solve as a single problem. Consequently, the overall function structure was decomposed into sub functions structure (shown in figure 3.2) in order to search alternative solutions for each sub functions.

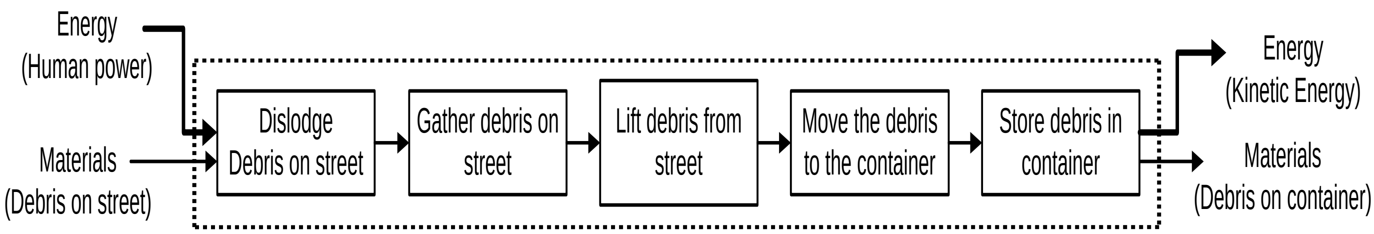
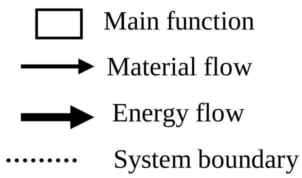


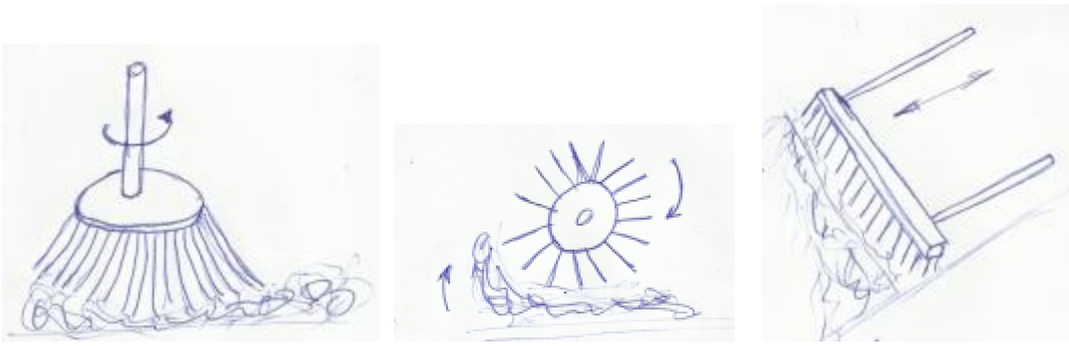
Figure 3.2 Sub functions Structure



Dislodge debris on street:

Some debris might be adhered to the surface of street; others might not be placed in suitable position for sweeping process. Therefore, to facilitate the cleaning action the debris from street surface must be dislodged. For this sub function four design concepts were generated:

- Concept1: generating pressure difference (blowing) near the surface of the street hence the debris has been misplaced or leaves their original position. The mechanism for creation of pressure difference is achieved by using compressor.
- Concept 2: attaching disc brush on rotating shaft – while the brush rotates it moves the debris on the surface of street hence it facilitates the task for the next sub function. Figure 3.3 a) shows the sketch of this concept.
- Concept 3: using rolling brush – the rolling of the brush causes disturbances on the litters and makes them to gather. The sketch of this concept is shown in figure 3.3 b).
- Concept 4: attaching brushes on oscillating mechanism – the movement of the mechanism forward and back ward pushes debris from initial positions, as shown in figure 3.3 c).



a) b) c)

Figure 3.3 Sketches for a) concept 2, b) concept 3 and c) concept 4

All the above design concepts have their own advantages and disadvantages. Therefore, to select the best concept decision matrix was made and concept 2 was selected as shown in table 3-1 below.

Table 3-1 Decision matrix for dislodge debris on street sub function

Criteria	Weight	Concept 1	Concept 2	Concept 3	Concept 4
Cost	2	5	9	6	5
Simplicity	1	4	7	7	5
Weight	1.5	4	8	7	6
Longevity	1	6	7	7	6
Safety	1	8	9	7	5
Manufacturability	1	4	8	7	7
Dust blowing up	0.5	4	7	8	6
Space utilization	1	5	8	6	4
Power consumption	0.5	4	9	8	6
Reduce design complexity	0.5	5	7	7	6
Sum		47.5	80.5	68	55

Gather debris on road surface:

Before gathering the debris, it has been disturbed so that it will be easy to draw together. In order to make the litters come to specific position in individual or in group by considering their mass and size can be achieved by using a disc brush engaged, in a rotating shaft for collecting large size debris and rolling brush to gather fine debris.

Lift debris from road surface:

The debris which is gathered round has to be lifted up from the street surface. For this purpose two design concepts were considered.

- Concept 1: for coarse debris the lifting process is achieved by using attached disc brush on rotating shaft and near to the end of the brush a guide (inclined surface) is employed to facilitate upward motion of debris. The rotational speed of brushes generates pressure difference between the street surface and above inclined surface (guider). To lift up fine debris, rolling brush is used; while it rolls, the debris is forced to carry on roller brush bristles and guided by using curved surface. Moreover, there is less pressure above the roller brush during rotation this enhances the debris lifting process.
- Concept 2: using compressor or fan is another alternative to lift up the debris from street surface into the dirt container. The fan or compressor creates negative pressure inside the dirt container which enables to lift debris from street surface. To select one of the two design concepts decision matrix was made and concept one was selected (Table 3-2).

Table 3-2 Decision matrix for lift debris from road surface sub function

Criteria	Weight	Concept 1	Concept 2
Cost	2	9	5
Simplicity	1	8	5
Weight	1.5	7	4
Longevity	1	8	5
Safety	1	8	5
Manufacturability	1	9	4
Dust blowing up	0.5	8	5
Space utilization	1	9	6
Power consumption	0.5	8	5
Reduce design complexity	0.5	7	5
Sum		82	48.5

Move the debris to the container:

After lifting up the debris from street surface, the next task will be move the debris to the container. To accomplish the task three design concepts were considered.

- Concept 1: using conveyor from ends of guider to the dirt container.
- Concept 2: using two disc brushes on oppositely rotating shafts will make easy, the litters to move forward to the container. The sketch of this concept is shown in figure 3.4 below.
- Concept 3: creating vacuum inside container by using a compressor or fan.

Figure 3.4 Sketch of concept 2

To choose the best design concept, decision matrix was made and concept 2 was selected as shown in table 3-3.

Table 3-3 Decision matrix for move the debris to the container sub function

Criteria	Weight	Concept 1	Concept 2	Concept 3
Cost	2	5	9	4
Simplicity	1	6	8	5
Weight	1.5	6	7	3
Longevity	1	6	8	7
Safety	1	5	7	7
Manufacturability	1	7	8	4
Dust blowing up	0.5	5	7	6
Space utilization	1	5	8	4
Power consumption	0.5	5	8	5
Reduce design complexity	0.5	6	7	6
Sum		56	78.5	48

Store debris in dirt container:

For this sub function two design concepts were taken into account.

- Concept 1: using large container to sweep large area without unloading of the container for long period of time.
- Concept 2: using medium size container that a single person can unload the container easily.

  To select one of the two design concepts, decision matrix was made and concept 2 was selected as shown in table 3-4.

Table 3-4 Decision matrix for store debris in dirt container sub function

Criteria	Weight	Concept 1	Concept 2
Cost	2	7	9
Weight	1.5	6	8
Longevity	1	6	8
Manufacturability	1	7	8
Space utilization	1.5	5	9
Reduce design complexity	1.5	6	8
Aesthetics	1.5	6	9
Sum		61.5	85

3.2 System Synthesis

To fulfill the overall function, it is then necessary to generate overall solutions by combining the working principles into a working structure. The basis of such a combination is the established function structure, which reflects logically and physically possible or useful associations of the sub functions [15]. The disturbing, gathering, lifting and moving sub functions are fulfilled by same function carrier as shown in the selected design concepts. To satisfy the overall function, the working principles of the various sub functions have been combined and this combination results in the working structure of a solution. It is through this combination of working principles that the solution principle for fulfilling the overall task can be recognized. The working structure derived from the function structure thus represents how the solution will work at the fundamental principle level. The designs which are necessary to build the system are shown in figure 3.5 as working structure.

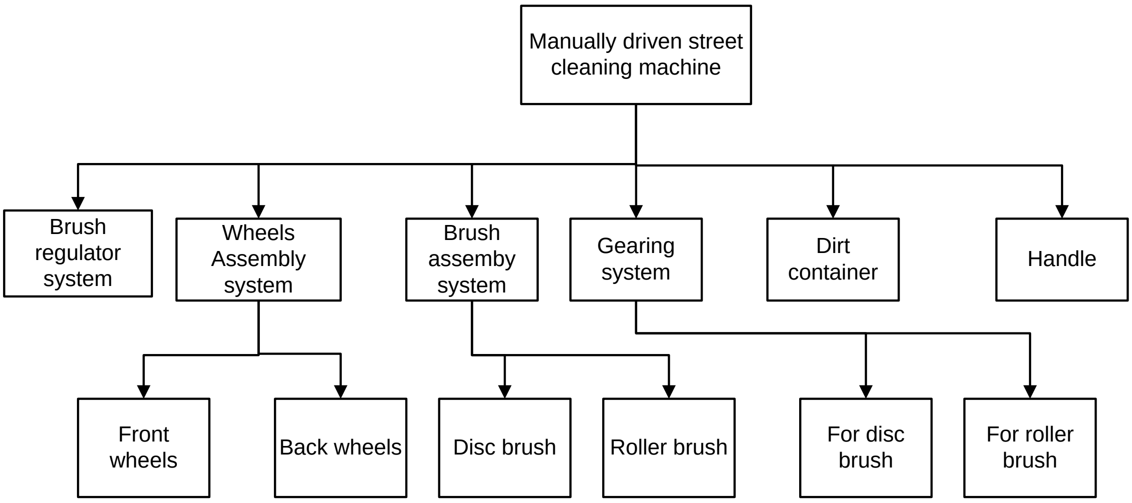


Figure 3.5 Schematic diagram of working structures

3.3 Power Transmission

Power transmission is the movement of energy from its place of generation to a location where it is applied to performing useful work. The source of power for this machine is direct human power applied on the handle. When the average human force is applied on the handle, it directly pushes the wheels of the machine hence it moves forward. The power can be transmitted to the required point using mechanical components such as belts, ropes, chains and gears. Among these, worm gear pairs were selected to transmit the front wheels rotational motion to the vertical axis rotation of the disc brushes whereas spur gears were selected to transfer back wheels rotational motion for horizontal axis rotation of roller brush. Figure 3.6 shows the power transmission in the system.

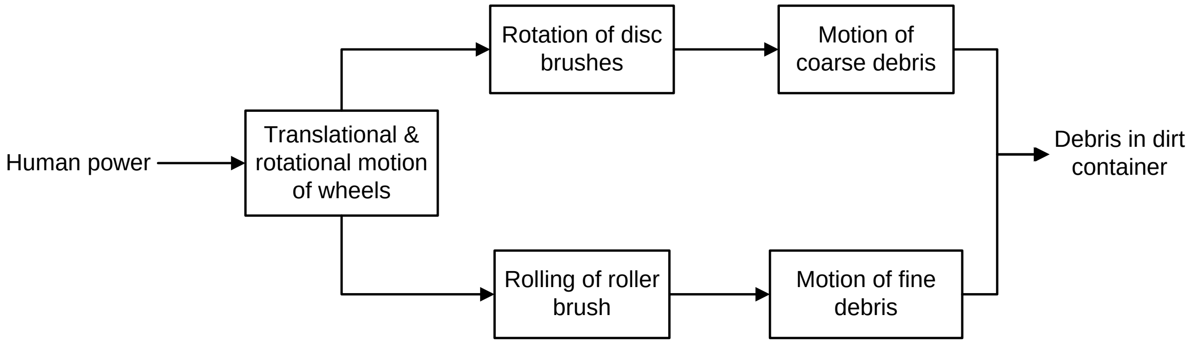


Figure 3.6 Schematic diagram of power transmission

3.4 Product Architecture and Embodiment Design

Having elaborated the principle solution during the conceptual phase, the underlying ideas could be firmed up. During the embodiment phase, the overall layout design (general arrangement and spatial compatibility), the preliminary form designs (component shapes and materials) and the production processes has been determined. During all of this, technological and economic considerations are of paramount importance. The design is developed with the help of scale drawings, critically reviewed, and subjected to a technical and economic evaluation.

Unlike conceptual design, embodiment design involves a large number of corrective steps in which analysis and synthesis constantly alternate and complements each other. This explains why the familiar methods underlying the search for solutions and evaluation must be complemented with methods facilitating the identification of errors (design faults) and optimization. The collection of information on materials, production processes, repeat parts and standards involves considerable effort.

Establishing product architecture:

Product architecture is used to define the basic physical building blocks of the product in terms of what they do and what their interfaces are to the rest of the device. To establish product architecture, we made a schematic of the product, and cluster the elements of the schematic to achieve the best type of desired product. Figure 3.7 shows the constituent elements of the product; figure 3.8 shows the clustered form of the constituent elements of the product and figure 3.9 shows the geometric layout of the machine.

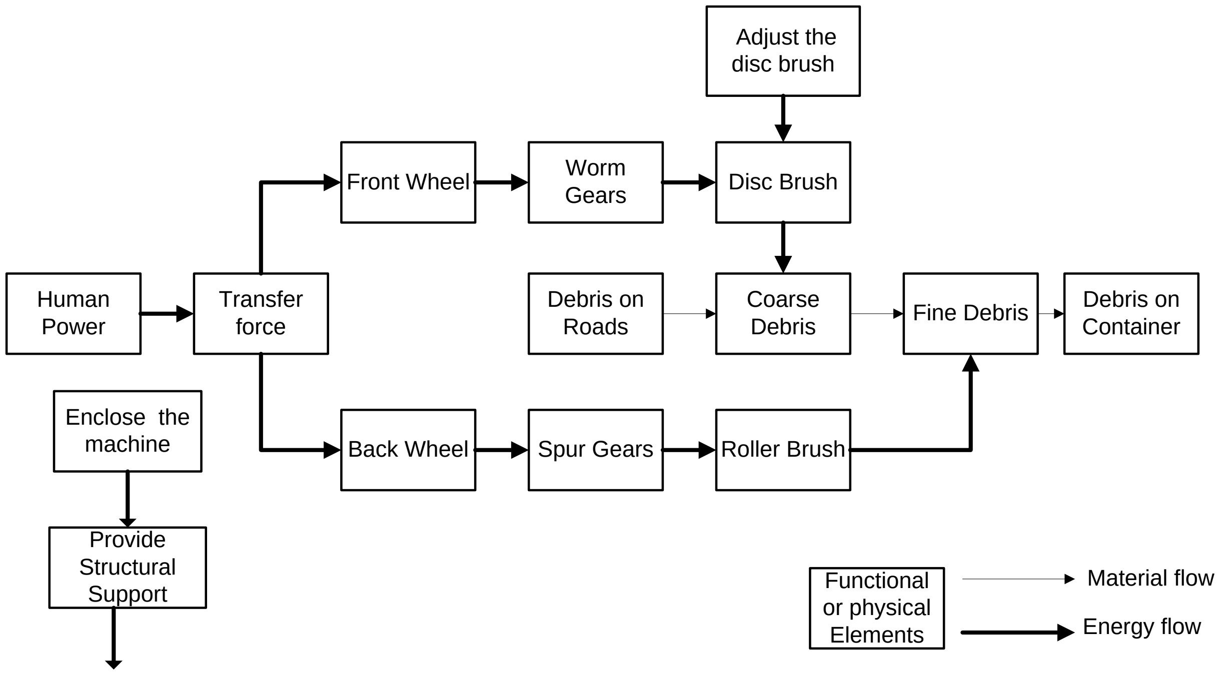


Figure 3.7 Schematic diagram of human powered street cleaning machine

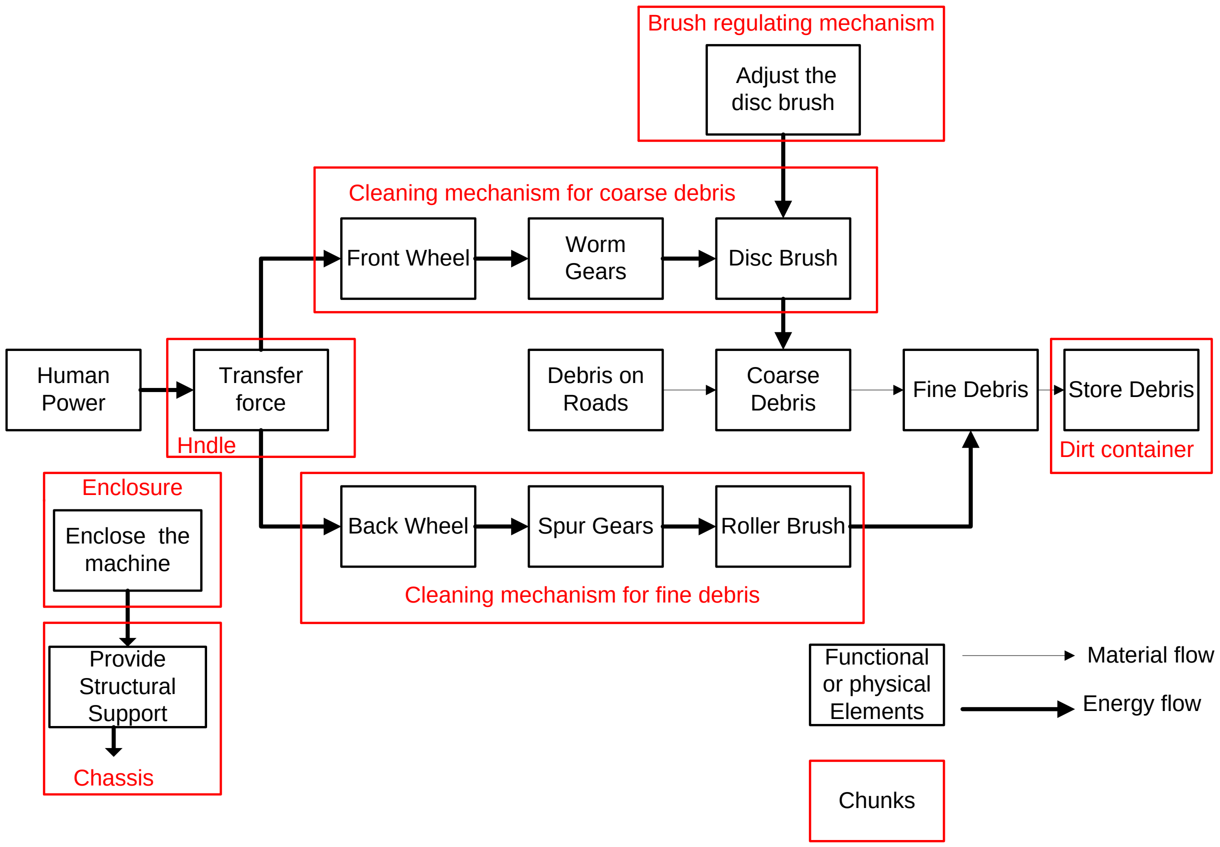


Figure 3.8 Cluster Elements into Chunks

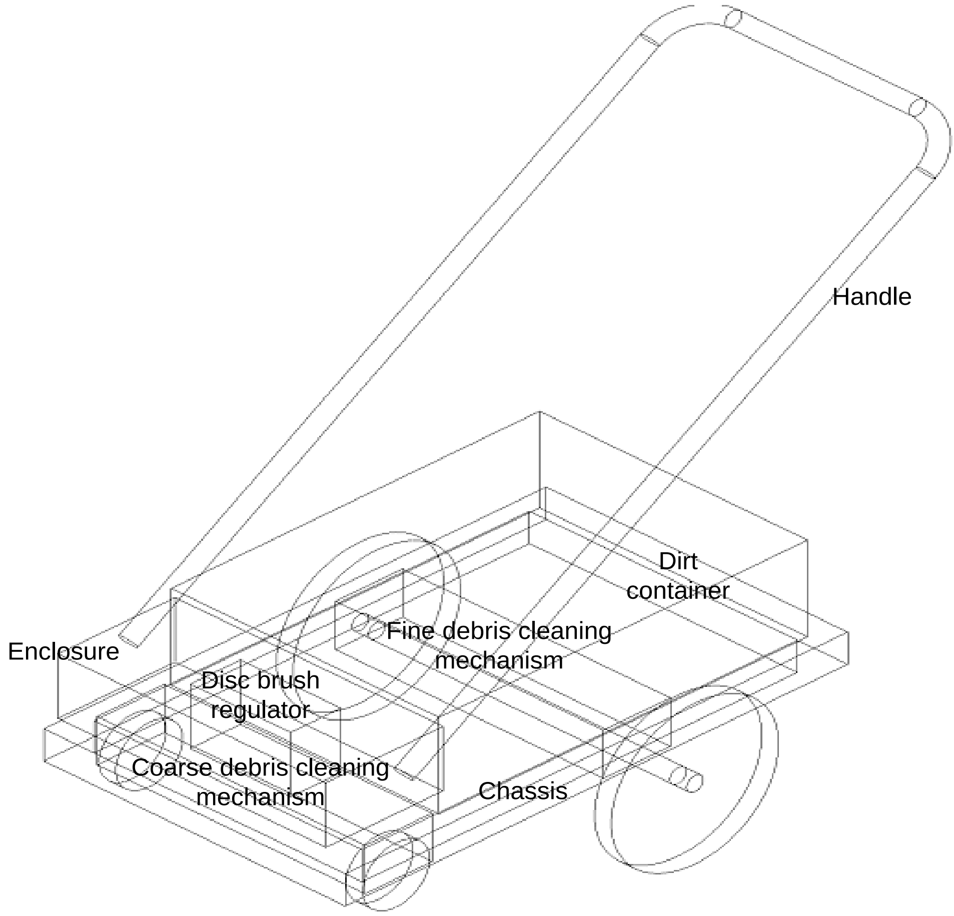


Figure 3.9 Geometric layout of human powered street cleaning machine

After determining the general arrangements and spatial compatibility of the product, the next step was the preliminary form designs (component shapes). Parts, assembly and optimization of the machine were done using SolidWorks 2012 CAD soft ware. The working drawings of SCM are attached at the back of this research paper.

3.5 Material Selection

3.5.1 The Need for Material Selection

During the last decades many new materials and material types have been developed. At present of the order of 100 000 engineering materials exist. In addition many materials have successively obtained improved properties. This has been possible due to the development of the materials but also due to the appearance of new production methods. As a consequence of this rapid development many material types can be used for a given component.

The most important motive why material selection is performed is to ensure that the component functions well i. e. failures do not occur too frequently. Further reasons are to make full use of the materials and to obtain cost effective components. In fact minimization of cost is usually the main objective in engineering design at the same time as a number of requirements should be satisfied. Due consideration has also to be taken to the value of weight savings in transport applications. In special cases other objectives like the maximization of performance may be of importance.

Design of an engineering component involves three interrelated problems:

i) Selecting a material,

ii) Specifying a shape, and

iii) Choosing a manufacturing process.

Getting this selection right the first time by selecting the optimal combination your design has enormous benefits. It leads to lower product costs, faster time-to-market, and a reduction in the number of in-service failures and, sometimes, significant advantages relative to your competition. When we talk about choosing materials for a component, we take into account many different factors. These factors can be broken down into the following areas.

- Material Properties

  The expected level of performance from the material

- Material cost and availability

  Material must be priced appropriately (not cheap but right)

  Material must be available (better to have multiple sources)

- Processing

  Must consider how to make the part, for example:

  Casting

  Machining

  Welding

  Molding

- Environment

  The effect that the service environment has on the part

  The effect the part has on the environment

  The effect that processing has on the environment

Now clearly these issues are inter-linked in some fashion. For example, cost is a direct result of how difficult a material is to obtain and to machine. And the effect of the environment on the material is clearly related to the material properties.

As mechanical engineers we deal mostly with metals. Metal properties tend to be well understood and metals are somewhat forgiving materials. We can make small mistakes (sometimes big ones) and get away with a poor design as a result of metal's forgiving nature. We see ceramics and composites all around us, but they tend to be used in special applications because of fabrication costs. This however, is changing. Plastics are among the most common modern material choices. In large volume production, plastics are inexpensive. In small volume productions, plastics can be an extremely expensive choice due to high tooling costs.

3.5.2 Selected Materials for Different Parts

The selected materials for these product components are listed in table 3.5. During the selection process we considered different factors such as corrosion, weight, strength, cost, availability and manufacturability of the components.

Table 3.5 The selected materials for the street cleaning machine.

S.No.	Part name	Selected materials	Reason for selection
1	Front wheel	Plastics (nylon, acetal (delrin), polyurethane, phenolic, polymide)	- Good strength -Ease of fabrication - Good corrosion, wear and abrasion resistance -They have the ability to reduce weight and noise
2	Back wheel	Plastics(nylon, acetal (delrin), polyurethane, phenolic, polymide)	“
3	Worm and Worm gear	Plastics (nylon, acetal (delrin), polyurethane, phenolic, polymide)	“
4	Front wheel & worm gear connector	Stainless steel or mild steel	Strength
5	Spur gear	Plastics (nylon, acetal (delrin), polyurethane, phenolic, polymide)	- Good strength -Ease of fabrication - Good corrosion, wear and abrasion resistance -They have the ability to reduce weight and noise - They have good strength - They have self-lubricating property
6	Back wheel axle	Aluminum or mild steel	Strength
7	Disc and roller brush bristles	Plastics (nylon, polyethylene, polypropylene)	Good strength, impact and toughness properties, good resistance to abrasion and chemicals
8	Disc and roller brush bristle holder	Plastics (nylon, ABS, polyethylene, phenolic, polypropylene)	Good strength, impact and toughness properties, good resistance to abrasion and chemicals
9	Front enclosure and frame	Plastics (ABS, polyethylene, phenolic, polypropylene, polystyrene, polycarbonate)	Good strength, impact and toughness properties, good resistance to abrasion and chemicals
11	Dirt container	Plastics (ABS, polyethylene, phenolic, polypropylene, polystyrene, polycarbonate)	Good strength, impact and toughness properties, good resistance to abrasion and chemicals
12	Handle	mild steel tube	Strength
13	Disc brush holder	Plastics (nylon, ABS, polyethylene, phenolic)	Good strength, impact and toughness properties, good resistance to abrasion and chemicals

CHAPTER FOUR: COMPONENT LEVEL DESIGN AND ANALYSIS

4.1 Kinematic Modeling and Analysis of SCM

Kinematic design of SCM refers to the determination of the dimensional parameters and sizes of components. Those parts which transmit motion have been determined to have optimum size. Indeed, kinematic design is a fundamental step in a design procedure of any mechanical system and its accuracy will affect strongly the basic properties of a mechanical systems. A kinematic design procedure is aimed to obtain closed-form formulation and/or numerical algorithms, which can be used not only for design purposes but even to investigate effects of design parameters on design characteristics and operation performance of machines.

4.1.1The Design Problem

The product architecture of SCM is composed of wheels for translation and rotation movements, worm and worm gears for rotation movement, a disc brush for coarse debris cleaning, roller brush for fine debris sweeping, and spur gears for rotation of roller brush.

A kinematic study of the product deals with the determination of configuration and motion of motion transfer components by looking at the geometry during the motion, but without considering the actions that generate or limit the SCM motion. Therefore, a kinematic study makes possible to determine and design the motion characteristics of the product but independently from the mechanical design details.

Design calculation of kinematic chain of mechanisms is usually attached through three problems, namely type synthesis, number synthesis, and dimensional synthesis. Number synthesis concerns with the determination of the number of links and joints in the chain, which are useful or necessary to obtain a desired mobility of a mechanism. Similarly, type synthesis concerns with the determination of the structure of the kinematic chain, i.e. the type of joints and kinematic architecture that are useful or necessary to obtain a desired mobility of the mechanism. Finally, dimensional synthesis (i.e. kinematic design) concerns with the calculation of the link sizes and range mobility of joints that are useful to obtain a desired motion of the mechanism.

4.1.2 Kinematics of SCM

The SCM comprises two worm gear mechanisms and two spur gear mechanisms. The worm is connected to the front wheel and worm gear by connector and the disc brush is interconnected to the spline on the worm gear hub. Hence the rotation of the front wheel gives angular motion of the disc brush through worm which enables it to collect debris from street to dirt container. The forward motion of the disc brush with respect to the ground is gained from the translational motion of the wheels. The spur gear mechanisms enable the roller brush to gather fine debris towards dirt container. The spur gears are mounted on shaft that connects the two back wheels while the pinion gears are mounted under frame that supports the dirt container. The roller brush is engaged in the pinion gears. The sizes of wheels and gears have great influence on the cleaning efficiency of both the roller and disc brushes. Therefore, the kinematic relations have been established. The machine has symmetry as shown in figure 4.1, therefore, the relation derived for one side of the machine works for the other side.

Worm 7 is rigidly mounted on wheel 4 and coupled with worm gear 5 using the connector 6. The disc brush 3 is attached on the disc holder 2. The disc brush holder rotates freely on the disc brush holder frame 8 which is rigidly mounted on the front enclosure and frame 9 and it is adjusted by pulling or pushing the adjuster bar 1. On the other hand the spur gear 13 is mounted on back wheel 14 and engaged with pinion gear 12. The roller brush 11 is connected to both left and right sides pinion gears so it can get rotation and torque. Shaft 15 balances the rotation of both back wheels. When the machine moves forward the two disc brushes rotate inward about perpendicular axis to the guider plate 10 and the roller brush rotate towards dirt container in horizontal axis.

Obviously, this motion transmission from wheels to brushes is not a direct drive, therefore, the relations between the linear velocity of the machine and the angular velocities of wheels as well as the angular velocity of the gears and brushes have to be established.

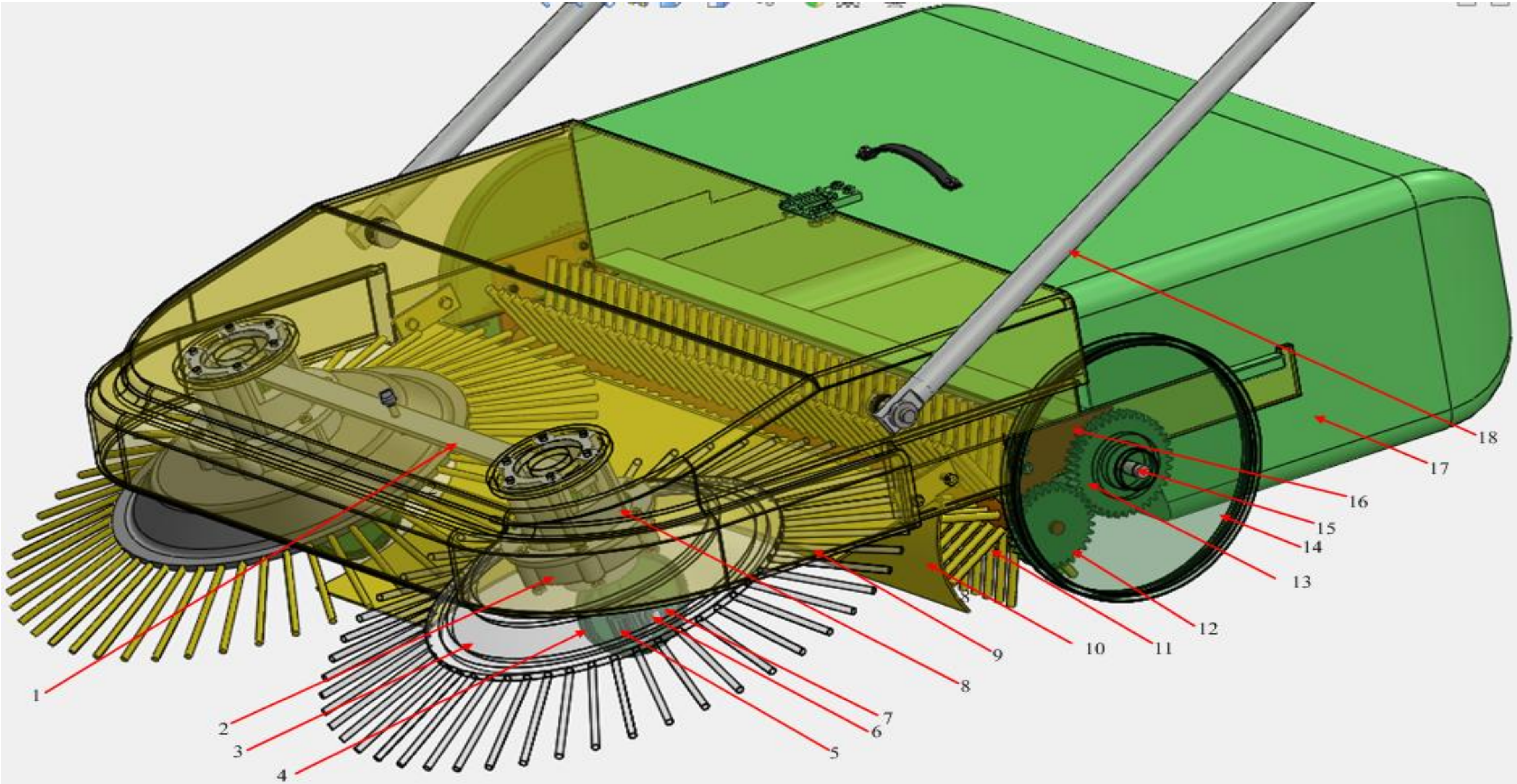


Figure 4.1 3-D view of SCM

The notations used in deriving the kinematic relations are described below:

z_p: number of teeth of pinion gear

z_g: number of teeth of spur gear

z_w: number of teeth of worm gear

T_w: number of threads or starts of worm

V: linear speed of the machine

ω_p: angular speed of pinion gear

ω_g: angular speed of spur gear

ω_w: angular speed of worm

ω_{wg}: angular speed of worm gear

ω_{fw}: angular speed of front wheels

ω_{bw}: angular speed of back wheels

d_p: pitch diameter of pinion gear

d_g: pitch diameter of spur gear

R: radius of back wheels

r: radius of front wheels

The angular velocity of the front and back wheels are related to the linear speed of the machine as:

$$\omega_{fw} = \frac{V}{r} \quad \text{and} \quad \omega_{bw} = \frac{V}{R} \quad \text{………….. eq. 4.1}$$

The angular velocity of the worm is equal to the angular velocity of the front wheel because it is rigidly attached; the same is true for the spur gear and back wheel.

Hence, $\omega_w = \omega_{fw}$ and $\omega_g = \omega_{bw}$

The angular speed of worm gear and spur gear will be

$$\omega_{wg} = \frac{z_w}{T_w} * \omega_w = \frac{z_w}{T_w} * \frac{V}{r} = \frac{z_w V}{T_w r} \quad \text{…………eq. 4.2}$$

$$\omega_g = \frac{z_g}{z_p} * \omega_p = \frac{z_g}{z_p} * \frac{V}{R} = \frac{z_g V}{z_p R} \quad \text{………………………eq. 4.3}$$

The angular speed of disc brushes is equal to the angular speed of worm gear in fact they are connected using spline shaft. Similarly the angular speed of the roller brush is equal to the angular speed of pinion gear.

4.2 Design of Wheels

The wheels have two purposes: 1) to support and move the machine 2) The front wheels serve as a source of rotational motion for the worm and worm gears while the back wheels for the spur gears. Therefore, the wheels should have flat surface in the side that the gears to be joined. The gears are joined to the wheels by using bolts and nuts, rivets, adhesives or can be manufactured as integral part of the wheels. The sizes of the wheels are determined based on the average angular speed of disc brush for front wheels whereas roller brush speeds for back wheels. Hence the linear speeds of the wheels are given as human average working speed which is 0.833m/s [16].

From eq. 4.1 we have

$$\omega_{fw} = \frac{V}{r} \quad \text{and} \quad \omega_{bw} = \frac{V}{R}$$

ω_{fw} and ω_{bw} was determined based on the recommended angular speed of brushes for effective cleaning and from gear design section we get $\omega_{fw} = \omega_w = 5.235$rad/s and $\omega_{bw} = \omega_g = 8.33$rad/s. The radius of front wheel and back wheel will be

$$r = \frac{0.833}{\omega_{fw}} = \frac{0.833}{20.94} = 0.04\text{m} = 40\text{mm}$$

$$R = \frac{0.833}{\omega_{bw}} = \frac{0.833}{8.33} = 0.1\text{m} = 100\text{mm}$$

There are standard wheels available in market with different sizes and loading capacities. Thus, the selected wheels should have the following features:

- Ergonomic: extraordinarily easy to push
- Wheel dampens shock and vibration thus reducing noise.
- High impact strength: resists fracture from repeated shock loads.
- Higher resilience: wheel returns to original shape without deforming when deflected by loads or rapidly applied stresses.
- Longer life: shows minimal wear in extended use-resists abrasion, water and many hazardous chemicals.
- Chemical resistance

Force analysis of wheels:

The loads that the four wheels support are the weight of the machine, the weight of debris inside the container and the applied force. The forces on the system are shown in figure 4.2. Human working power is given as 75 watt [17].

$$P = \frac{Q}{t} = \frac{F_x d}{t} = F_x \frac{d}{t} = F_x V \text{ ………………eq. 4.4}$$

Where P: Human working power

V: Human working speed

Q: Work done

F_x: Applied human force

… d: Distance moved by the applied force

.. t: Time required to cover the distance

Hence, $F_x = \frac{P}{V} = \frac{75}{0.833} = 90N$

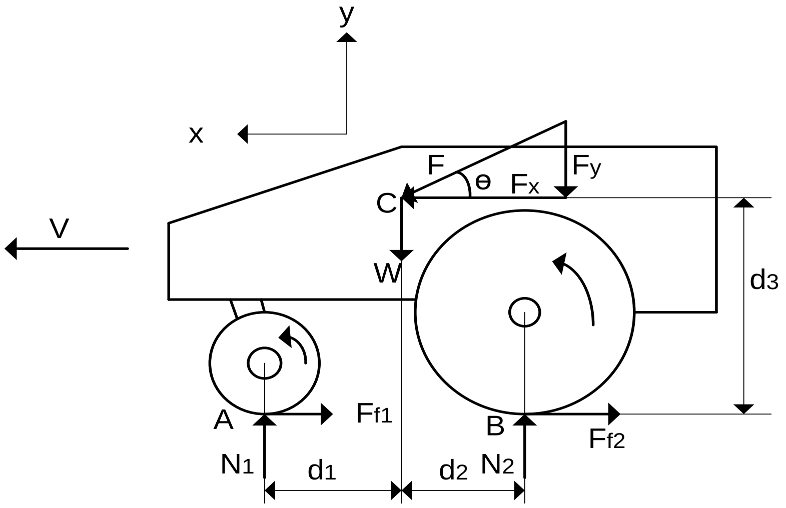


Figure 4.2 Force systems on SCM

The resultant force (F) along the handle axis is computed as follows:

$F = \frac{F_x}{\cos\theta} = \frac{90}{\cos 30} = 103.93N$ θ is taken to be 30^0 to drive the machine easily

$F_y = F_x \tan\theta = 90\tan 30 = 51.96N$

The normal forces on the wheels can be computed as follows:

$$\sum F_y = 0$$

$$N_1 + N_2 - \frac{(W + F_y)}{2} = 0$$

$$N_1 + N_2 = \frac{W+F_y}{2} \quad \text{...........eq. 4.5}$$

$$\sum M_A = 0$$

$$N_2\,(d_1 + d_2) + \frac{F_x d_3}{2} - \frac{(F_y+W)}{2} d_1 = 0 \quad \text{......... eq. 4.6}$$

Solving eq. 4.5 and eq. 4.6

$$N_1 = \frac{1}{2}\left[\frac{(F_y+W)d_2+F_x d_3}{d_1+d_2}\right] \quad \text{and} \quad N_2 = \frac{1}{2}\left[\frac{(F_y+W)d_1-F_x d_3}{d_1+d_2}\right] \quad \text{........ eq. 4.7}$$

W is weight of the machine plus debris in the container which is equal to 250N.

d_1, d_2 and d_3 are set values equals 0.133m, 0.133m and 0.167m respectively.

N_1 and N_2 are normal forces as shown in figure 4.2 above

F_{1f} and F_{2f} are friction forces between wheels and street surface

Substituting the values in eq. 4.7

N_1 = 103.734N and N_2 = 47.23N

Force along the worm gear axis = N_1*cos15 = 103.734*cos15 = 100.199N

Force perpendicular to the worm gear axis = N_1*sin15 = 26.848N

The static friction forces can be obtained using Newton's law of motion:

$\sum F_x = ma = o$; the velocity assumed to be constant

$F_x - (F_{f1} + F_{f2}) = 0$

$F_x - (\mu_1 N_1 + \mu_2 N_2) = 0$ using the same material for all wheels $\mu_1 = \mu_2 = \mu$

$F_x - \mu(N_1 + N_2) = 0$

$$F_x = \mu\left(\frac{1}{2}\left[\frac{(F_y + W)d_2 + F_x d_3}{d_1 + d_2}\right] + \frac{1}{2}\left[\frac{(F_y + W)d_1 - F_x d_3}{d_1 + d_2}\right]\right) = 0$$

$$F_x = \mu\frac{1}{2}(F_y + W)$$

To move the machine $\mu \frac{1}{2}(F_y + W) < F_x$ ……… eq. 4.8

The static coefficient of friction of nylon on asphalt is 0.4 and substituting the values in eq. 4.8 we get:

$$0.4 * \frac{1}{2}(51.96 + 250) < F_x$$

$$60.392N < 90N = F_x$$

Torque produced by the rotation of wheels is computed as follows:

From front wheel

$$T_{fw} = F_{fw} * r \;; \quad F_{fw} = \frac{1}{4}F_x = \frac{1}{4} * 90 = 22.5N$$

$$T_{fw} = 22.5 * 0.04 = 0.9Nm$$

From back wheel

$$T_{bw} = F_{bw} * R = 22.5 * 0.1 = 2.25Nm$$

4.3 Design of Gears

Gear is toothed wheel that engages another toothed mechanism in order to change the speed or direction of transmitted motion. It is a component within a transmission device that transmits rotational force to another gear or device. A gear is different from a pulley in that it is a round wheel which has linkages ("teeth" or "cogs") that mesh with other gear teeth, allowing force to be fully transferred without slippage. Depending on their construction and arrangement, geared devices can transmit forces at different speeds, torques, or in a different direction, from the power source. The most common situation is for a gear to mesh with another gear.

Gear's most important feature is that gears of unequal sizes (diameters) can be combined to produce a mechanical advantage, so that the rotational speed and torque of the second gear are different from that of the first.

To overcome the problem of slippage as in belt drives, gears are used which produce positive drive with uniform angular velocity.

4.3.1 Design of Spur Gear

Spur gear teeth is parallel to axis of rotation can transmit power from one shaft to another parallel shaft. Spur gears are the simplest and most common type of gear. Their general form is a cylinder or disk. The teeth project radially, and with these "straight-cut gears".

Spur gears are gears in the same plane that move opposite of each other because they are meshed together. In figure 4.3 gear 'A' is called the 'driver' because this is turned by a motor or other mechanism. As gear 'A' turns it meshes with gear 'B' and it begins to turn as well.

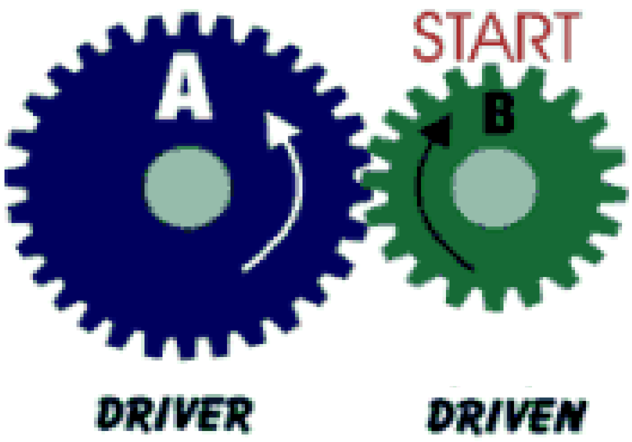


Figure 4.3 Spur gears

The objective of design of the spur gear set is to transmit motion from back wheels to the roller brush with high velocity ratio. Therefore, it is kept the number of teeth of the gears as low as possible to minimize weight and cost while still fulfilling the design objectives. The input parameters which are necessary to determine the size of gear are discussed in this section.

To get effective cleaning process, the recommended brush rotation speed is 100rpm [18]. Hence the spur pinion gear which is attached to the roller brush has the recommended speed. The module selected for the gears is 2 which have available module cutter in many workshops for manufacture. The number of teeth in the pinion gear is 30. By considering space, material and center distances between gears, the velocity ratio is decided to be 1.257. The other parameters of the gears are computed below:

Pitch diameter of the pinion gear (d_p) = m z_p = 2*20 = 40

$$\text{Velocity ratio} = \frac{\omega_p}{\omega_g} = 1.257$$

$$\omega_g = \frac{\omega_p}{1.257} = \frac{100}{1.257} = 79.554\text{rpm}$$

The number of teeth on the spur gear will be

$$\frac{z_g}{z_p} = \frac{\omega_p}{\omega_g} = 1.257$$

$$z_g = 1.257 * z_p = 1.257*30 = 37.7 \approx 38$$

Pitch diameter of the gear (d_g) = m z_g =2*38 = 76mm

Pitch diameter of the pinion gear (d_p) = m z_p = 2*30 = 60mm

Power transmitting capacity of plastic spur gears:

The characteristics of gears made of plastic materials are so different from those of metal gears that they should be considered in a class by themselves. Because of the low modulus of elasticity, most of the effects of small errors in tooth form and spacing are absorbed at the tooth surfaces by the elastic deformation, and have but little effect on the strength of the gears. The strength and force calculation is based on gear technical reference [19].

The spur gear's transmission force (F_n) which is normal to the tooth surface, as in Figure 4.4, can be resolved into a tangential component (F_t) and a radial component (F_r) and the force calculations are shown in table 4.1.

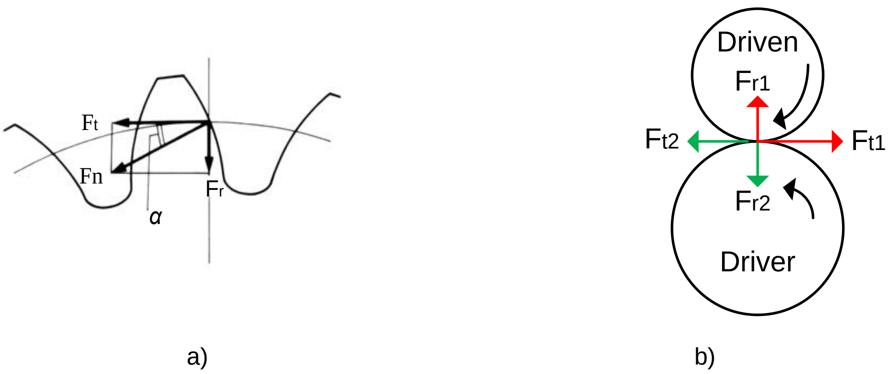


Figure 4.4 Forces acting on a spur gear mesh a) radial and tangential components in a single gear b) directions of forces acting on a spur gear mesh

Table 4.1 Forces on meshing spur gears

No	Specifications	Symbol	Unit	Formula	Spur Gear	
					Gear	Pinion
1	Module	m	mm	Set value	2	
2	Normal pressure angle	α	Degree		20	
3	Number of teeth	z	-		38	30
4	Input torque	T_1	Nm		2.25	-
5	Pitch diameter	d	mm	mz	76	60
6	Tangential force	F_t	N	$\frac{2000T}{d}$	59.21	
7	Radial force	F_r		$F_t \tan\alpha$	21.55	
8	Output torque	T_2	Nm	$\frac{F_t d_2}{2000}$	-	1.776

The allowable tangential force (F_{ta}) kilogram force (kgf) at the pitch circle of nylon spur gear can be obtained from the lewis formula.

$$F_{ta} = myb\sigma_b f \quad \text{…………..eq. 4.9}$$

Where m: module (mm)

y: tooth profile factor at pitch point

b: face width (mm)

σ_b: Allowable bending stress (kgf/mm^2)

F: speed factor

m = 2mm, b = 12mm

From tables

y = 0.606 for z = 30, 20^0 full depth tooth

$\sigma_b = 1.25$kg/mm^2 for unlubricated and at temperature 40C^0

f = 1 for unlubricated

F_{ta} = 2*0.606*12*1.25*1 = 18.18kgf = 18.18*9.81 = 178.346N

Factor of safety (FOS) = $\frac{\text{Allowable Tangential force}}{\text{Applied Tangential force}} = \frac{F_{ta}}{F_t} = \frac{178}{59.21} = 3.012$

Hence, FOS>1 it is safe.

4.3.2 Design of Worm and Worm Gear

Many worm gears have an interesting property that no other gear set has: the worm can easily turn the gear, but the gear cannot turn the worm. This is because the angle on the worm is so shallow that when the gear tries to spin it, the friction between the gear and the worm holds the worm in place.

Figure 4.5 Worm and worm gear

This feature is useful for machines such as conveyor systems, in which the locking feature can act as a brake for the conveyor when the motor is not turning. One other very interesting usage of worm gears is in the torque-sensing (torsen) differential, which is used on some high-performance cars and trucks. They are used in right-angle or skew shaft drives. The presence of sliding action in the system even though results in quieter operation, it gives rise to considerable frictional heat, and hence they need good lubrication for heat dissipation and for improving the efficiency. High reductions are possible which results in compact drive.

The objective of design of the worm and worm gear set is to transmit motion from front wheels to the disc brushes with low velocity ratio. By considering space, material and center distance between gears, the following gear parameters were selected.

- module (m) = 1.5mm
- number of teeth in the worm gear (z_w) = 12
- Velocity ratio = 2

The other parameters of the gears are computed using the above values as an input.

The number of threads or starts on the worm will be

$$\frac{z_w}{T_w} = \frac{\omega_w}{\omega_{wg}} = 2$$

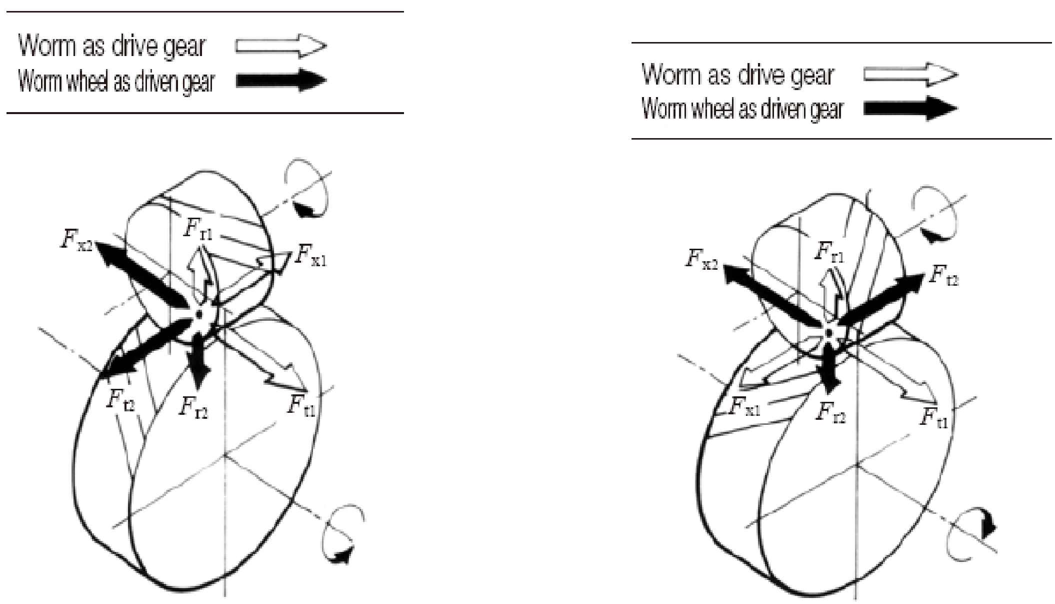
$$T_w = \frac{z_w}{2} = \frac{12}{2} = 6$$

Worm speed (ω_w) = $2 * \omega_{wg}$ = 2*100 = 200rpm

Pitch diameter of the worm gear (d_{wg}) = m z_w =1.5*12 = 18mm

Force analysis of worm gears:

The tangential, axial, and radial force components acting on a worm and worm gear are illustrated in the Figure 4.6 and the forces and torques value are computed in table 4.2.



a) Right hand worm gear mesh

b) Left hand worm gear mesh

Figure 4.6 Direction of forces acting on worm gear mesh

Table 4.2 Forces on worm gear mesh

No	Specification	Symbol	Unit	Formula		Worm gear pair	
						Worm	Worm gear
1	Shaft angle	Σ	Degree	Set value		90	
2	Axial /Transverse module	m_x/ m_t	mm			1.5	
3	Normal pressure angle	α	Degree			20	
4	Number of teeth	z	-			6	12
5	Pitch diameter (worm)	d_1	mm			17	-
6	Coefficient of friction	μ	-			0.04	
7	Input torque	T_1	Nm			0.9	
8	Pitch diameter (worm gear)	d_2		-	$m_t z_2$	-	18
9	Reference cylinder lead angle	γ	Degree	$tan^{-1}\left(\frac{m_x z_1}{d_1}\right)$		27.897	
10	Tangential force	F_{t1}, F_{t2}	N	$\frac{2000T_1}{d_1}$	$F_{t1}\frac{cos\alpha cos\gamma - \mu sin\gamma}{cos\alpha sin\gamma + \mu cos\gamma}$	79.412	135.691
11	Axial force	F_x		$F_{t1}\frac{cos\alpha cos\gamma - \mu sin\gamma}{cos\alpha sin\gamma + \mu cos\gamma}$	F_{t1}	135.6907	79.412
12	Radial force	F_r		$F_{t1}\frac{sin\alpha}{cos\alpha sin\gamma + \mu cos\gamma}$		78.2085	
13	Efficiency	n_R	-	$\frac{tan\gamma F_{t2}}{F_{t1}}$		0.9045	
14	Output torque	T_2	Nm	-	$\frac{F_{t2}d_2}{2000}$	-	1.2212

The allowable tangential force (F_{ta}) kilogram force (kgf) at the pitch circle of nylon worm gear is obtained from the lewis formula.

$$F_{ta} = m_n y b \sigma_b f \quad \text{………….eq. 4.10}$$

Where m_n: Normal module (mm)

b: face width (mm)

σ_b: Allowable bending stress (kgf/mm^2)

f : speed factor

y: tooth profile factor at pitch point

$$m_n = \frac{d_2 cos\alpha}{z_2} = \frac{18*cos20}{12} = 1.41mm$$

b = 20mm

From tables

y = 0.415, f = 1 and $\sigma_b = 1.5$

Hence,

$$F_{ta} = 1.41 * 0.415 * 20 * 1.5 = 17.5545\text{kgf} = 172.21\text{N}$$

Factor of safety (FOS) = $\frac{\text{Allowable Tangential force}}{\text{Applied Tangential force}} = \frac{F_{ta}}{F_t} = \frac{172.21}{135.6907} = 1.269$

FOS = 1.269 >1 it is safe.

4.4 Design of Shaft

A shaft is the component of a mechanical device that transmits rotational motion and power. In this section there are two shafts, the one is to transmit motion from back wheels to spur gears (figure 4.9) and the other one is to transmit motion from pinion gears to the roller brush bristles which are attached on its surface in a row of clusters (figure 4.7).

Shaft design procedure:

Because of the simultaneous occurrence of torsional shear and normal stresses due to bending, the stress analysis of a shaft virtually always involves the use of a combined stress approach. The procedure to design a shaft is discussed below:

1. Determine the rotational speed of the shaft.
2. Determine the power or the torque to be transmitted by the shaft.
3. Determine the design of the power-transmitting components or other devices that will be mounted on the shaft, and specify the required location of each device.
4. Specify the location of bearings to support the shaft. Normally only two bearings are used to support a shaft. The reactions on bearings supporting radial loads are assumed to act at the midpoint of the bearings. Bearings should be placed on either side of the power-transmitting elements if possible to provide stable support for the shaft and to produce reasonably well-balanced loading of the bearings.
5. Propose the general form of the geometry for the shaft, considering how each element on the shaft will be held in position axially and how power transmission from each element to the shaft is to take place.
6. Determine the magnitude of torque that the shaft sees at all points. It is recommended that a torque diagram be prepared.
7. Determine the forces that are exerted on the shaft, both radially and axially.

8. Resolve the radial forces into components in perpendicular directions, usually vertically and horizontally.
9. Solve for the reactions on all support bearings in each plane.
10. Produce the complete shearing force and bending moment diagrams to determine the distribution of bending moments in the shaft.
11. Select the material from which the shaft will be made.
12. Determine an appropriate design stress, considering the manner of loading
    - Smooth
    - Shock
    - Repeated and reversed
    - Other
13. Analyze each critical region of the shaft to determine the minimum acceptable diameter of the shaft to ensure safety under the loading at that point. In general, the critical points are several and include those where a change of diameter takes place, where the higher values of torque and bending moment occur, and where stress concentrations occur.
14. Specify the final dimensions for each point on the shaft.

4.4.1 Design of Bristles Attachment Shaft

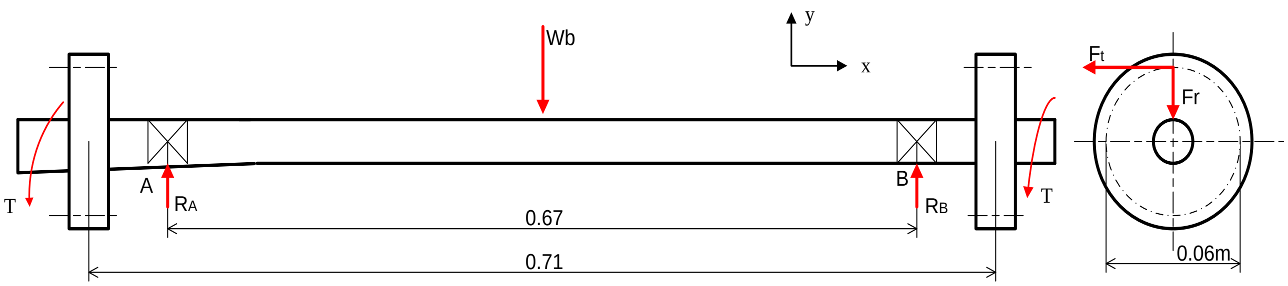


Figure 4.7 Free body diagram of bristles attachment shaft

The reaction forces at A and B are computed as follows:

$$\sum F_y = 0$$

$$R_A + R_B - (2F_r + W_b) = 0$$

$$R_A + R_B = 2F_r + W_b$$

W_b is the weight of shaft plus bristles which is equal to 11.234N and F_r is the radial force exerted by spur gears, from gear design section F_r = 21.55N. Hence,

$$R_A + R_B = 2 * 21.55 + 11.234 = 54.334N \text{.................eq 4.11}$$

$$\sum M_A = 0$$

$$0.67 * R_B + 0.02 * F_r - (0.335 * W_b + 0.69 * F_r) = 0 \text{ .... eq. 4.12}$$

Solving eq. 4.11 and eq. 4.12

$$R_A = R_B = 27.165N$$

The shear force, bending moment and torque due to the weight of shaft plus bristles and external load exerted by spur gear are shown in figure 4.8.

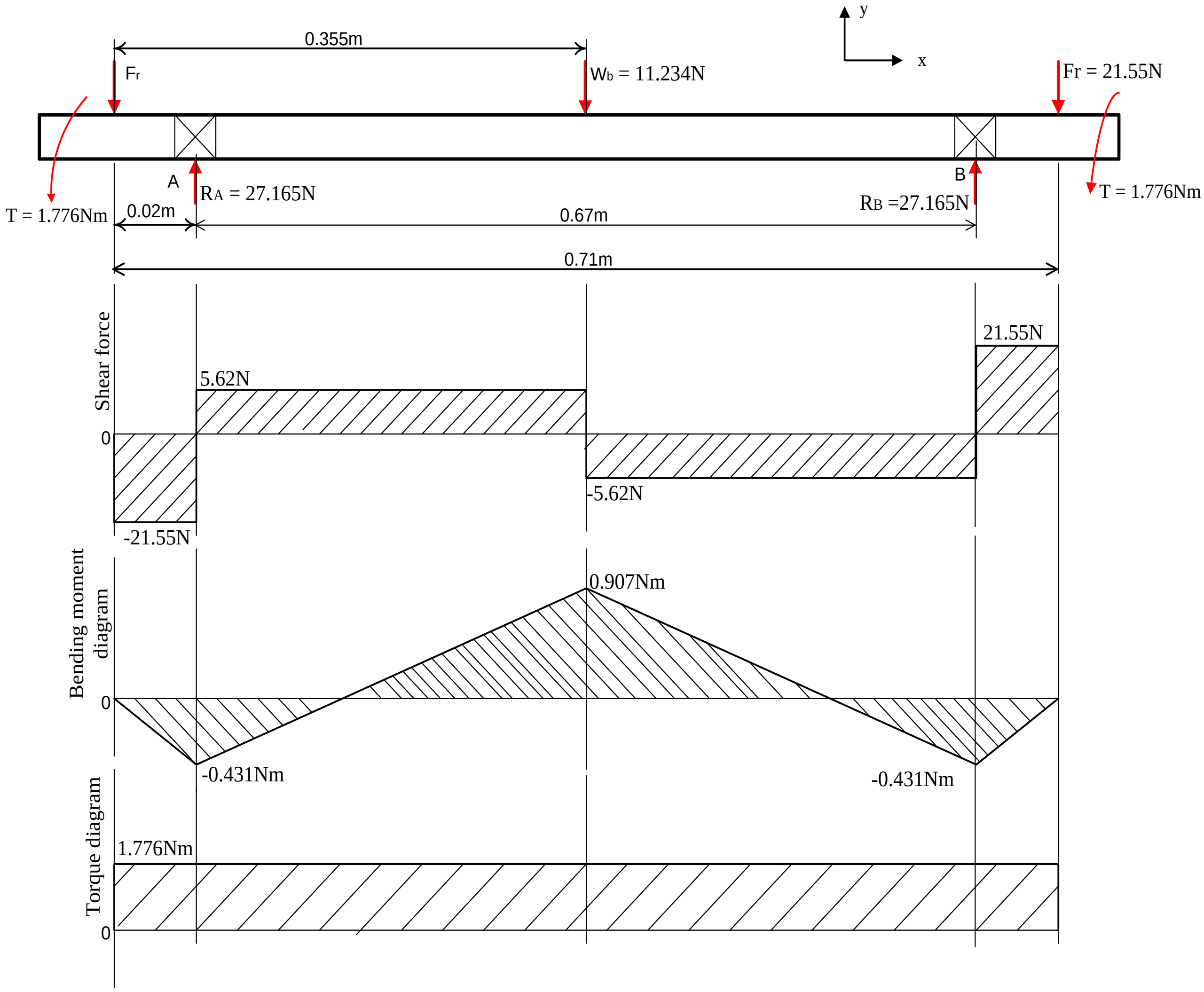


Figure 4.8 Shear force, bending moment and torque diagram of bristles attachment shaft

In the combined torsion and bending, the stress elements in the shaft are:

$$\text{Normal stress due to bending } (\sigma) = \frac{32M}{\pi d^3} \text{ ....eq. 4.13}$$

$$\text{Shear stress due to torque } (\tau) = \frac{16T}{\pi d^3} \text{ ....eq. 4.14}$$

The maximum shear stress is the significant stress in this situation and is given by the expression

$$\tau_{max} = \sqrt{\frac{\sigma^2}{2} + \tau^2} \quad \text{……………. Eq. 4.15}$$

Substituting eq. 4.13 and eq. 4.14 into eq. 4.15 yields the expression for maximum shear stress in terms of load and diameter of the shaft as shown below:

$$\boldsymbol{\tau_{max}} = \frac{\mathbf{16}}{\pi\mathbf{d^3}}\sqrt{\mathbf{M^2} + \mathbf{T^2}} \quad \text{………. eq. 4.16}$$

The yield strength in shear of nylon is predicted to be half the tensile yield strength by the maximum shear stress theory of failure, and the shear yield strength of this material can therefore be derived from the tensile yield strength.

Therefore $S_{sy} = \frac{S_y}{2}$

Design equation then becomes

$$\tau_{max} = \frac{16}{\pi d^3}\sqrt{M^2 + T^2} = \frac{S_{sy}}{f.s} = \frac{S_y}{2*f.s}$$

$$d^3 = \frac{16}{\pi}\sqrt{M^2 + T^2} * \frac{2*f.s}{S_y} \quad \text{………….. eq. 4.17}$$

Where

S_{sy}: shear strength of the material

S_y: yield strength of the material

f.s: factor of safety, and $\frac{S_{sy}}{f.s} = \frac{S_y}{2*f.s} = \tau_d$, the design or allowable shear stress

The torque and bending moment loads

T = 1.776Nm and M = 0.907Nm

Yield strength of chosen material and the factor of safety

S_y = 60MPa and f.s = 4

Substituting the above values into eq. 4.17

$$d^3 = \frac{16}{\pi}\sqrt{0.907^2 + 1.776^2} * \frac{2*4}{60}$$

d = 11mm

Select the shaft size to be used form the nearest size in the range of preferred metric sizes [20] (1,1.2,1.6,2,2.5,3,4,5,6,8,10,12,16,20,25,30,35,40,45,50,55,60,65,70,75,80,90,100 mm.)

The nearest shaft size selected is 12 mm.

4.4.2 Design of Spur Gears and Back Wheels Engagement Shaft

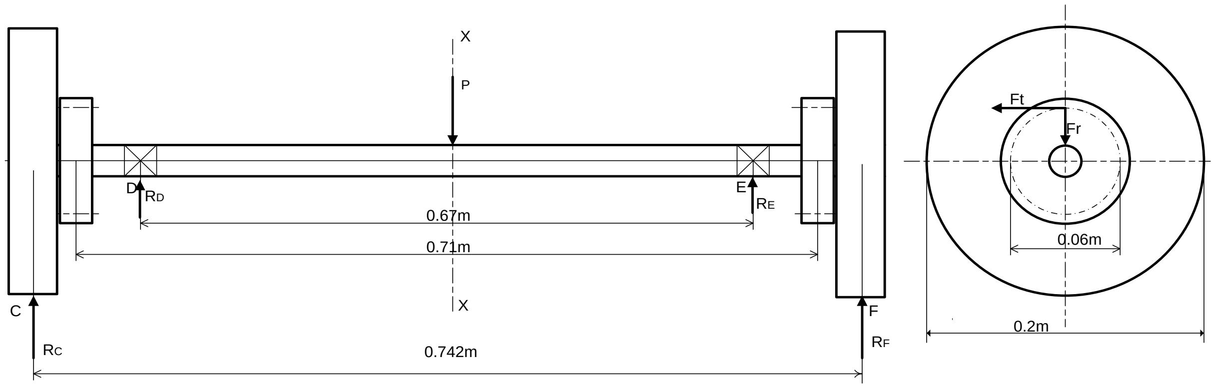


Figure 4.9 Free body diagram of spur gears and back wheels engagement shaft

The reaction forces at D and E are computed as follows.

$$\sum F_y = 0$$

$$R_C + R_F + R_D + R_E - (2F_r + P) = 0$$

From wheel design section $R_C = R_F = N_2 = 47.23N$

The geometry is symmetrical about X-X therefore, $R_D = R_E$

P is force due to weight of the machine which is equals 125N

$$2R_C + 2R_D - (2F_r + P) = 0$$

$$2 * 47.23 + 2R_D - (2 * 21.55 + 125) = 0$$

$$R_D = 36.82N$$

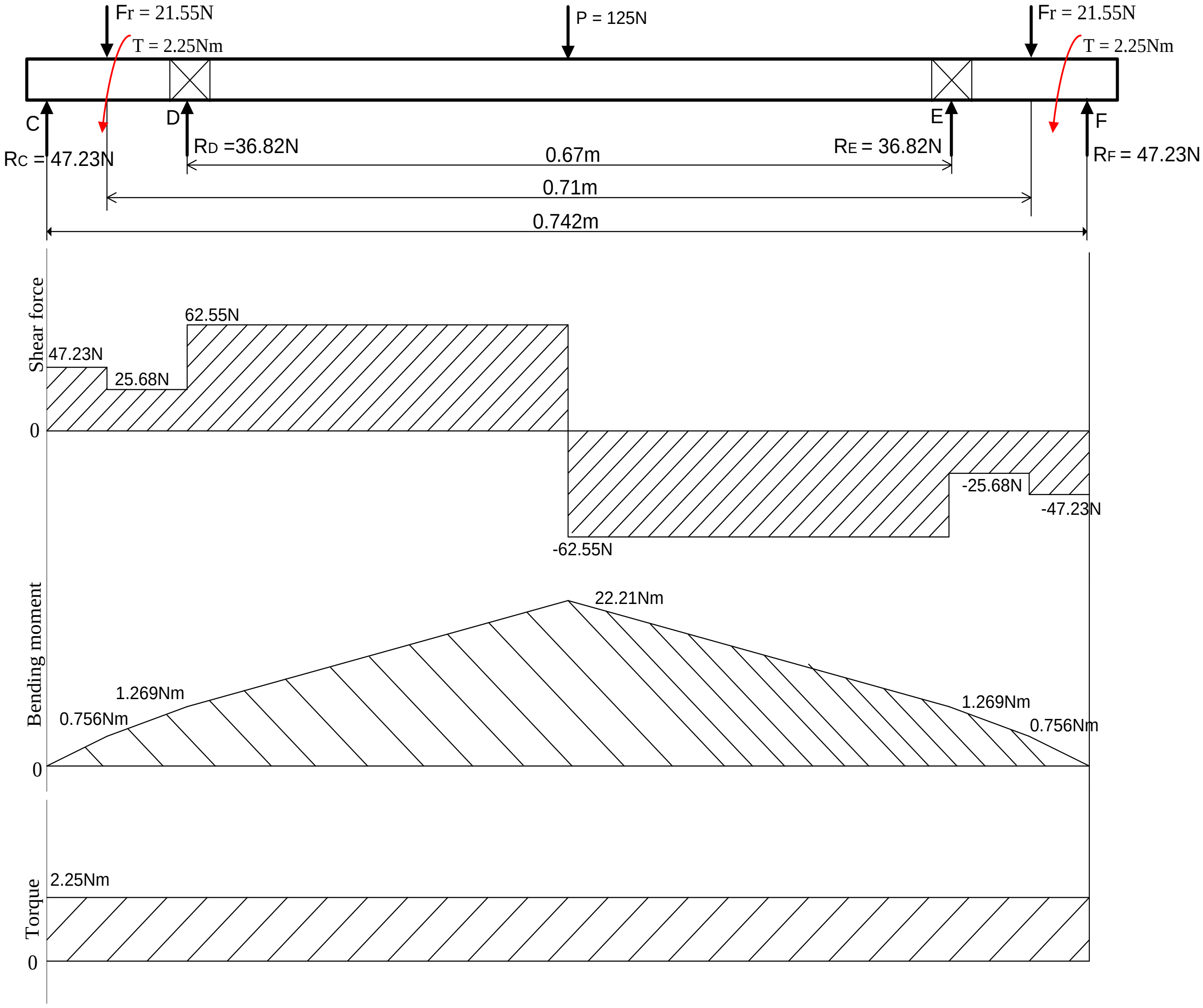


Figure 4.10 Shear force, bending moment and torque diagram of spur gears and back wheels engagement shaft

The torque and bending moment loads

T = 2.25Nm and M = 22.21Nm

Yield strength of chosen material and the factor of safety

S_y = 60MPa and f.s = 2

Substituting the above values into eq. 4.17

$$d^3 = \frac{16}{\pi}\sqrt{22.21^2 + 2.25^2} * \frac{2 * 2}{60}$$

d = 19.6mm

Select the shaft size to be used form the nearest size in the range of preferred metric sizes [20] (1,1.2,1.6,2,2.5,3,4,5,6,8,10,12,16,20,25,30,35,40,45,50,55,60,65,70,75,80,90,100 mm.)

The nearest shaft size selected is 20 mm.

4.5 Bearing Selection

4.5.1Ball Bearings

Because of their greatly reduced starting friction, when compared to the conventional journal bearing, they have acquired the common designation of “anti-friction” bearings. Although normally made with hardened rolling elements and races, and usually utilizing a separator to space the rolling elements and reduce friction, many variations are in use throughout the mechanical and electrical industries. The most common anti-friction bearing application is that of the deep-groove ball bearing with ribbon-type separator and sealed-grease lubrication used to support a shaft with radial and thrust loads in rotating equipment. This shielded or sealed bearing has become a standard and commonplace item ordered from a supplier's catalogue in much the same manner as nuts and bolts. Because of the simple design approach and the elimination of a separate lubrication system or device, this bearing is found in as many installations as the wick fed or impregnated porous plain bushing.

4.5.2 Selection of Ball Bearings

As compared with sleeve bearings, ball bearings offer the following advantages:

1) Starting friction is low;
2) Less axial space is required;
3) Relatively accurate shaft alignment can be maintained;
4) Both radial and axial loads can be carried by certain types;
5) Angle of load application is not restricted;
6) Replacement is relatively easy;
7) Comparatively heavy overloads can be carried momentarily;

4.5.3 Ball Bearing Rating Life

Even in bearings operating under normal conditions, the surfaces of the raceway and rolling elements are constantly being subjected to repeated compressive stresses which cause flaking of these surfaces to occur. This flaking is due to material fatigue and will eventually cause the bearings to fail. The effective life of a bearing is usually defined in terms of the total number of revolutions a bearing can undergo before flaking of either the raceway surface or the rolling element surfaces occurs.

The magnitude of the rating life L in millions of revolutions and L_h in hours, for a radial ball bearing application is given by the formula:

$$L = \left(\frac{C}{P}\right)^3 \quad \text{……………eq. 4.18}$$

$$L_h = \frac{10^6}{60n}\left(\frac{C}{P}\right)^3 \quad \text{…………. eq. 4.19}$$

Where C: dynamic basic load rating (N)

P: equivalent radial load (N)

n: revolution per minute (rpm)

Equivalent radial bearing load

$$P = XF_r + YF_a \text{……………….. eq. 4.20}$$

The values of X and Y factor is shown in table 4.3.

Table 4.3 Values of X and Y factor for deep groove ball bearing, single row, normal clearance.

Relative axial load Fa/C_0	e	If $Fa/Fr \leq e$ X	If $Fa/Fr \leq e$ Y	If $Fa/Fr > e$ X	If $Fa/Fr > e$ Y
0.014	0.19	1	0	0.56	2.30
0.028	0.22				1.99
0.056	0.26				1.71
0.084	0.28				1.55
0.110	0.30				1.45
0.170	0.34				1.31
0.280	0.38				1.15
0.420	0.42				1.04
0.520	0.44				1.00

Source: Adapted in part from [21]

The procedures to find X and Y values are discussed below:

- find value of C (dynamic load) and C_0 (static load) for given bearing from bearings catalogue.
- calculate value Fa/C_0
- read value of "e" factor
- calculate value F_a/F_r
- read value of X and Y factor from table 4.3.
- check if value $F_a/F_r \leq e$ or $F_a/F_r > e$

Table 4.4 Deep groove ball bearings, single row

Principal dimensions			Basic load ratings		Fatigue	Speed ratings		Mass	Designation
			dynamic	static	load limit	Reference speed	Limiting speed	Mass	Designation
d	D	B	C	C_0	P_u	N		m	* = SKF Explorer bearing
mm			kN			r/min		kg	
12	21	5	1,43	0,67	0,028	70000	43000	0,0063	61801
12	21	5	1,43	0,67	0,028	70000	36000	0,0063	61801-2Z
12	24	6	2,25	0,98	0,043	67000	40000	0,011	61901
12	24	6	2,25	0,98	0,043	67000	32000	0,011	61901-2Z
12	28	8	5,4	2,36	0,1	60000	38000	0,022	6001 *
12	28	8	5,4	2,36	0,1	60000	30000	0,022	6001-2RSL *
12	28	8	5,4	2,36	0,1	60000	30000	0,022	6001-2Z *
12	28	8	5,4	2,36	0,1	60000	38000	0,022	6001-RSL *
12	28	8	5,4	2,36	0,1	60000	38000	0,022	6001-Z *
12	30	8	5,07	2,36	0,1	56000	34000	0,023	16101
12	30	8	5,07	2,36	0,1	56000	28000	0,023	16101-2Z
12	32	10	7,28	3,1	0,132	50000	32000	0,037	6201 *
12	32	10	7,28	3,1	0,132	50000	26000	0,037	6201-2RSL *
20	32	7	4,03	2,32	0,104	45000	28000	0,018	61804
20	32	7	4,03	2,32	0,104	-	13000	0,018	61804-2RS1
20	32	7	4,03	2,32	0,104	45000	22000	0,018	61804-2RZ
20	37	9	6,37	3,65	0,156	43000	26000	0,038	61904
20	37	9	6,37	3,65	0,156	-	12000	0,038	61904-2RS1
20	37	9	6,37	3,65	0,156	43000	20000	0,038	61904-2RZ
20	42	8	7,28	4,05	0,173	38000	24000	0,05	16004 *
20	42	9	7,93	4,5	0,19	38000	24000	0,051	98204 Y

Source: Adapted in part from [22]

From bearings catalogue [22] and shown in table 4.4 above for bristles attachment shaft bearings-61801 and for spur gears and back wheels engagement shaft bearings-61804 were selected. The loads on the bristles attachment shaft were computed in shaft design section and the result was 27.165N on both bearing supports. Moreover, the rotation of this shaft was determined as 100rpm in gear design section. For spur gears and back wheels engagement shaft the loads were 36.82N on both bearing supports and the rotation of this shaft was 79.554rpm. There are no axial loads or loads along the shaft axis in both shafts. The rating life calculation for both shafts is done in this section.

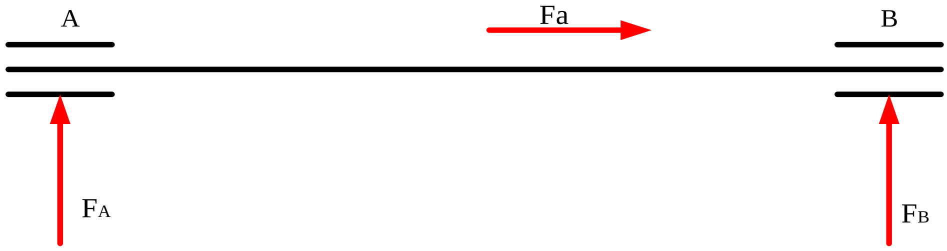


Figure 4.11 Shaft load sketch

For bristles attachment shaft, from table 4.4 C = 1430N

From table 4.3 X = 1; since $Fa/Fr = 0/27.165 = 0 \leq e$

Bearing equivalent load (P) = F_r = 27.165N,

Rating life in millions revolutions and hours

$$L = \left(\frac{1430}{27.165}\right)^3 = 145{,}874 \text{ Millions revolution}$$

$$L_h = \frac{10^6}{60 * 100}\left(\frac{1430}{27.165}\right)^3 = 14{,}070 * 10^3 \text{ hours}$$

For spur gears and back wheels engagement shaft, from table 4.4 C = 4030N

Bearing equivalent load equals (P) = F_r = 36.82N

Rating life in millions revolutions and hours

$$L = \left(\frac{4030}{36.82}\right)^3 = 1{,}311{,}184 \text{ Millions revolution}$$

$$L_h = \frac{10^6}{60 * 100}\left(\frac{4030}{36.82}\right)^3 = 218{,}530 * 10^3 \text{ hours}$$

As shown in the calculation above, the bearings seem over dimension because the diameter of the shaft is determined based on loads and material properties.

4.6 Design of Brush for Street Cleaning

Brushes have to be very specialized in order to meet all of the unique requirements of the road cleaning purpose. They are shaped and sized for cleaning of coarse and fine debris. Proper bristle selection is also extremely important. Longer bristles offer greater flexibility when compared to the same material in a shorter trim. The key to efficiency is maximum bristle tip contact to surface and the proper type of bristle for the surface to be cleaned. Proper selection is extremely important for making the cleaning process as easy and efficient as possible.

Brooms are ideal machine attachments to clean and remove debris from streets, parking lots, sidewalks and factory floors. There are two key factors to determine which type of broom needed: downward force and/or hopper bucket.

Table 4-5 Types of brooms

	downward force	hopper bucket
Angle broom	Yes	No
Utility Broom	Yes	Yes
Pickup Broom	No	Yes

Angle, Utility and Pickup Brooms are ideal work tools for cleaning and removing debris from streets, parking lots, sidewalks and factory floors in a variety of construction, industrial and landscaping settings. Brooms perform well on many types of surfaces, including concrete, asphalt and turf. Different types of brushes are available to maximize productivity on various types of surfaces: Polypropylene brushes, mixed polypropylene/steel wire brushes and solid steel wire brushes. Angle Brooms are designed to operate best during forward machine travel. They use a windrowing action to move loose debris forward and to the side of the surface being swept. Angle brooms can be oriented straight or angled to optimize the windrowing action. Pickup Brooms sweep and deposit material into an integrated hopper bucket for easy removal and dumping. These often have a guide wheel on the front of the broom to prevent the bristles contacting the surface with significant force. Pickup brooms often have the guide wheel in the front to minimize the broom down force, but the hopper and broom are hinged to make dumping easier. Utility Brooms sweep and collect light debris on smooth or rough surfaces. They can be adjusted for greater bristle down-force in tough applications.

4.6.1 Analytical Model for Particle Removal Mechanisms

In order to properly use a brush to sweep debris, it is necessary to investigate the debris removal mechanisms. Unfortunately, scientific studies on outdoor sweeping are rarely seen. A large area that can be related to the current interest is cleaning small particles from semiconductor wafers, which is also known as post-CMP (chemical–mechanical planarization) cleaning process. Many researchers (e.g., Roy [23],Visser [24], and Moumen [25]) have investigated the particle removal mechanisms because semiconductor devices need ultra clean environments, but a fabrication process such as CMP often leaves thousands of micron-size particles on wafer surfaces. One of the methods for post-CMP cleaning is mechanical cleaning, which often uses a brush tool in conjunction with some chemical liquids to provide a combination of hydrodynamic effect and contact effect to remove particles. The analytical methods for post-CMP cleaning using brushes may be extended to analyse road sweeping problems. Many studies (e.g., Dugger [26] and Estragnat [27]) have suggested that using combined chemical–mechanical cleaning leads to the highest removal ability. Zhang [28] have performed experiments to prove that the removal rate depends on several parameters of the cleaning tool, such as the pressure of the brush, the brush rotational speed, and the cleaning time. Similarly, Moumen [25] have suggested that the cleaning results could be improved by optimizing the liquid flow, the brush pressure, and the brush rotational speed. A typical particle removal model has been presented by Soltani and Ahmadi [29], and it has been utilized by many other researchers (e.g., Cooper [30] and Burdick [31]). Figure 4.13 shows the model for a particle adhering to a rough surface in a hydrodynamic flow field. There are three forces applied to the particle: the dragging force (F_D) due to the hydrodynamic and contact effect, the lifting force (F_L) caused by the adhesion between the particle and the brush tool, and the adhesion force (F_A) between the particle and the wafer surface. The chemical flow not only produces an average dragging force but also generates an external moment (M). The moment potentially enables the particle to roll around a support point A, on a rough surface, or to roll around a contact point B, if the surface is flat.

This model was used to show that particle removal theoretically depends on three mechanisms: lifting, sliding, and rolling. According to Burdick [31], the removal criteria can be derived from the force and moment balance. On a rough surface, sliding is unlikely to happen before rolling, but rolling may occur when

$$M + F_D l_1 + F_L l_3 \geq F_A l_3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{ eq. 4.21}$$

On a flat surface, rolling occurs when

$$M + F_D\, l_2 + F_L a \geq F_A a, \quad \ldots\ldots\ldots\ldots\ldots\ldots\text{eq. 4.22}$$

and sliding occurs when

$$F_D \geq \mu(F_A - F_L \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{eq. 4.23}$$

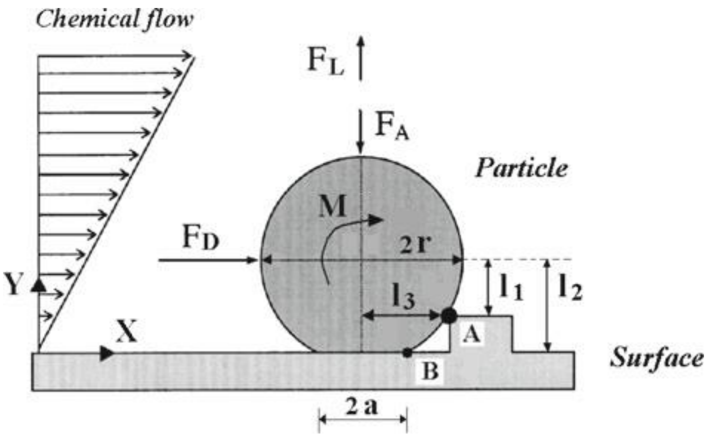


Fig. 4.12 A particle removal model for post-CMP cleaning [31]

In eq 4.21–4.23, a is the radius of the particle-surface contact area, l_1, l_2, and l_3 are three lever arms, as shown in Figure 4.12, and μ is the static coefficient of friction. As for the lifting criterion, it has been assumed that lifting occurs, regardless the surface roughness, when

$$F_L > F_A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{eq. 4.24}$$

In these criteria, the adhesion (F_A) is the major factor determining the difficulties of particle removal. Since the particles in post-CMP cleaning are of micron size, most researchers (e.g., Larios [32] and Busnaina [33]) have assumed that, in the absence of chemical bonding, the predominate adhesion forces are the electrostatic forces and the van der Waals forces, which mainly depend on the particle size and the contact geometry.

As the particles in post-CMP cleaning are of micron sizes, and brush filaments are comparatively much larger, most researchers have not considered the deformation characteristics of brush filaments. A large amount of particles, in fact, do not have physical contact with the filament tips; therefore, many researchers (e.g. Cooper [30]) have used hydrodynamic theories to calculate the external loads, F_D, F_L, and M, applied to the particles. Regarding real contact problems, some researchers (e.g., Busnaina [33]) have assumed that the exerted forces are linear functions of the brush pressure, rotational speed, and power. In many more studies, the required forces to remove particles are calculated, but they have not explicitly suggested how to use a brush tool to produce these forces.

The particle removal model represented in Figure 4.12 may be modified to investigate the debris removal problems in road sweeping applications. Since debris is much larger than the CMP particles, the van der Waals forces and the electrostatic forces are negligible. Instead, dry friction, weight, and the adhesion caused by bounding mud may be the major factors affecting debris removal. Besides, the removal forces are mainly caused by direct brush-debris contact; hence, the interaction between the brush filaments and debris must be investigated. Despite these differences, the dragging, lifting, and rolling criteria should be applicable to debris removal problems. Brush-debris interaction models will be presented in the next section to assess sweeping effectiveness.

4.6.2 A Simplified Sweeping Model

The basic Conditions for Debris Removal:

Before exploring the complex real sweeping mechanisms, let us first consider the simplest case for which the object removal problem can be described in a 2-D plane. Such a simplification needs several basic assumptions as follows: (a) the tines deflect only in a plane vertical to the ground; (b) the object to be swept has a regular and symmetric shape; (c) the interaction between the object and the ground is even in the whole contact area, and it can be described by general mechanics theory; and (d) the ground surface is flat. As an example for these assumptions, Figure 4.13 shows a simple 2-D model for a flicking tine sweeping an object on a flat surface. The object considered here is large in size, so that the roughness of the road surface plays a less significant role. It is very difficult to idealize the object shape because in reality many stones and gravels often have irregular shapes. It has been shown that it is not very realistic to use sphere or oval models, because most road debris has sharp edges. Herein, it is assumed that the object cross-section is rectangular, whilst a cubic object can be defined as that with aspect ratio of the cross-section of one.

There are uncertain factors in the interaction between the object and the road surface. In dry conditions, Coulomb's law may be used to calculate the road friction. However, in many situations it is likely to see a bonding layer between the object and the road surface, such as wet mud, condensed clay, etc. Hence, the object friction has to be analysed using different criteria. If the frictional load given by the road can be described by a parameter f_R, then the total sweeping loads on the object can be represented as in Figure 4.13. Assuming that an initially straight flicking tine moves in the X direction, when sweeping occurs, the tine surface should contact the object front surface, P_2P_3. As the tine top moves, the tine deflects in its weaker plane, thus the surface contact problem very likely becomes a point contact problem. Since the object has a sharp corner, the contact point on the object should be fixed at the left-top corner, P_3. As shown in Figure 4.13, the loads applied to the object include a normal tine contact force N_T, tine friction force f_T, road friction and normal forces f_R and N_R, as well as the object weight mg. Note that the combination of N_T and f_T does not align with f_R. The external forces generate a rolling moment M_{roll}, and the object is likely to roll about its right-bottom corner, P_1.

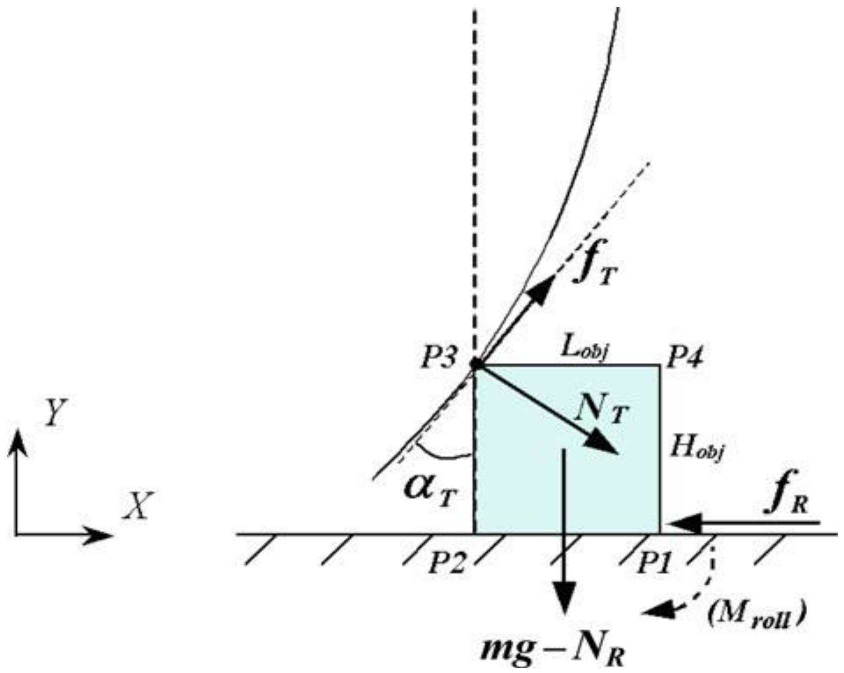


Figure 4.13 A schematic 2-D model for a flicking tine sweeping a rectangular object

Since the deflected tine has a large curvature, a parameter α_T may be used to define the angle formed by the tine tangent at P_3 and the object front edge P_2P_3. For convenience, the total sweeping force applied by the tine may be named as F_S. F_S is the combination of N_T and f_T, and it should be represented in the form

$$F_{SX} = N_T \cos \alpha_T + f_T \sin \alpha_T \quad \text{……….. eq. 4.25}$$

$$F_{SY} = f_T \cos \alpha_T - N_T \sin \alpha_T \quad \text{…………… eq. 4.26}$$

The rolling moment generated by F_S can be written as

$$M_{roll} = F_{SX} H_{obj} + F_{SY} L_{obj}, \quad \text{…………… eq. 4.27}$$

Where H_{obj} and L_{obj} are the object height and object length, respectively. Theoretically, the object removal depends on three factors, namely, the dragging force F_{SX}, the lifting force F_{SY}, and the rolling moment M_{roll}. However, F_{SY} is normally negative, thus the dragging force and the rolling moment are more important factors. It is assumed that the object removal occurs when either of these two factors exceeds a certain value. From the object equilibrium, the minimum removal conditions can be given by

$$\sum F_X = F_{SX} - f_R > 0 \quad \text{.................................eq. 4.28}$$

or $$\sum M_{roll} - mg.\frac{L_{obj}}{2} > 0 \quad \text{.................................eq. 4.29}$$

Note that the normal force is not introduced in the second part of eq. 4.29. This is because if the object tended to rotate about P_1, N_R would act at this point and would not produce a moment about P_1. Although the aforementioned model greatly simplifies the sweeping problem, it is not easy to be solved analytically. A major reason is that the tine curvature is unknown so that α_T is an unknown parameter. Besides, as the tine is sliding on the object, the contact point on the tine surface is moving, and the boundary conditions for different tine positions are different.

4.6.3 A 3-D Finite Element Sweeping Model

The 2-D sweeping model has explored some fundamental mechanisms of debris removal. However, in reality, rotary brush sweeping is not a two-dimensional problem. This is largely because a brush tine often has an inclined mounting angle φ, (Figure 4.14) spinning on a conic surface; thereby the debris motion is not in the same plane of that of the tine deflection. Considering a flicking tine, for example, a schematic description of a 3-D sweeping problem is given in Figure 4.14. In such a situation, the loads applied to the object include two horizontal friction vectors f_X and f_Z , a combined tine contact force f_S, a normal force N_R, and gravity mg. The external loads also generate rolling effects, which may be described by three moments, M_{Xroll}, M_{Yroll} and M_{Zroll}. The directions of the three rolling moments should be defined using the right-hand rule in the 3-D coordinate system. The values of the rolling moments depend on the sweeping force F_S. However, it is very difficult to predict the tine-object contact point, as well as the main components of F_S, because they highly depend on how the tine surface contacts the object. Unlike the 2-D model, in the 3-D model, the motion of a rotating tine is not in a single plane. Consequently, unless the object width W_{obj} (P_1P_2) is very large, the tine tip can slip away from a side of the object.

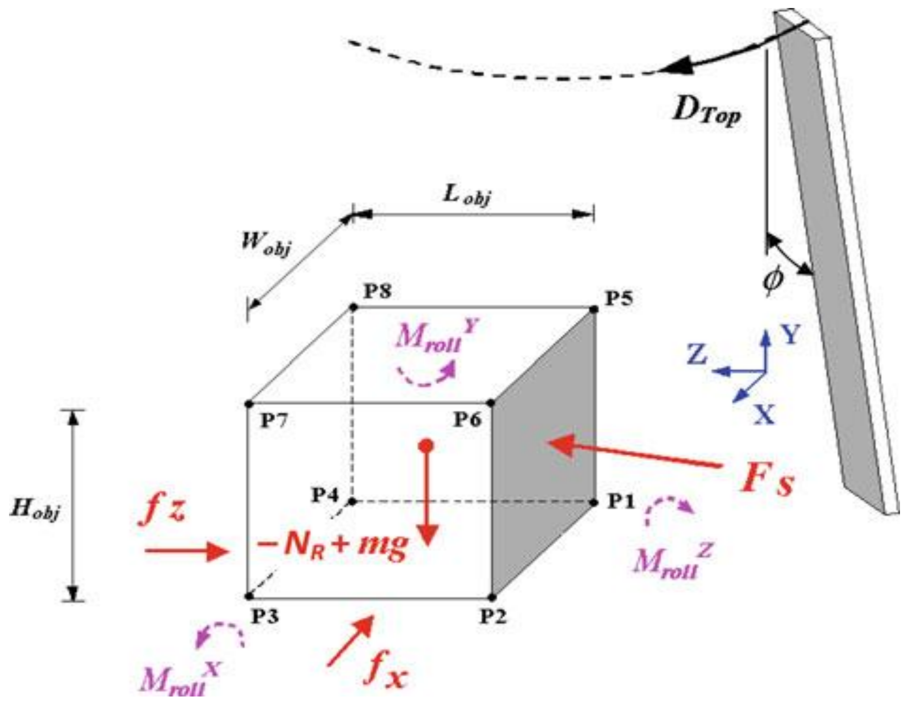


Figure 4.14 A schematic 3-D model for a flicking tine sweeping a rectangular object

The total sweeping load consists of three forces and three rolling moments about the coordinate axes. The total forces can be described by

$$F_{xs} = \sum F_x\, i;\ F_{ys} = -mg + \sum F_y\, i; F_{zs} = \sum F_x\, i$$

where $F_x i$, $F_y i$, and $F_z i$ are the forces at the constrained point Pi . According to Figure 4.14, the total rolling moments should be written as

$M_{Xroll} = (F_{y1} + F_{y2} - F_{y3} - F_{y4})L_{obj}$; $M_{Zroll} = (F_{y2} + F_{y3} - F_{y1} - F_{y4})W_{obj}$;

$M_{Yroll} = (-F_{x1} - F_{x2} + F_{x3} + F_{x4})$ Lobj2 + $(F_{z1} - F_{z2} - F_{z3} + F_{z4})W_{obj2}$.

According to the coordinate system in Figure 4.14, it can be concluded that the object mainly slides and rolls in the brush tangential direction. Considering that F_{XS} is positive, the object also tends to move outwards in the brush radial direction. Besides, since M_{yroll} is positive whilst M_{zroll} is negative, the object also tends to roll anti-clockwise about its own central axis, and rolls outwards about its bottom edge P_2P_3. The vertical force has actually a negative effect on object removal since the lifting force F_{yS} is less than zero.

4.6.4 Geometric and Operating Parameters of Brushes

The performance of the brushes depends on several variables, which may be classified as material properties, geometric parameters, and operating variables. The brushes consist of bristles of circular cross section, which are arranged into one or more rows of clusters. The main geometric and operating parameters are presented in table 4.6. The bristle mount angle is that between the bristle axis and the mounting board normal. The bristle mount orientation angle defines the action of the brush: cutting, flicking, or intermediate action. In the cutting brush, the cross section of the bristle is orientated so that it deflects mainly in the brush radial direction. This brush provides a stiff bristle–debris collision (cutting action). The bristles of the flicking brush deflect predominantly in the tangential direction, flicking through debris.

The operating variables, introduced in table 4.6, are those that can be controlled during the operation of the street sweeping. The orientation of the brush with respect to the direction of travel of the machine is defined by the offset angle (ξ) and the angle of attack (β).The penetration, Δ, is defined by the first cluster, which is represented by a single bristle that would make contact with the road surface when a stationary (non-rotating) brush is lowered. The penetration can be considered as the vertical distance between the surface and the tip of that bristle if it could penetrate the road without deflection.

Table 4.6 Geometric and operating parameters of the brushes

Geometric parameter	**Symbol**	**Disc brush**	**Roller brush**
Bristle mount orientation angle	γ	15	15
Bristle length	l_b	90mm	70mm
Number of bristles per cluster	n_{bc}	28	28
Number of clusters per row	n_c	50	8
Number of rows of clusters	n_r	1	41
Bristle mount angle	$\emptyset$	15^0	90^0
Outer mount radius	r_{A1}	130mm	30mm
Inner mount radius	r_{A2}	125mm	27mm
Bristle diameter	b_d	0.6mm	1mm

Operating parameter	**Symbol**	**Unit**	**Value**
Brush offset angle	ξ	degree	180
Brush angle of attack	β	degree	15
Brush rotational speed	ω	rpm	100
Machine speed	V	m/s	0.833
Brush penetration	Δ	mm	0 -10

4.7 Solid Modeling and Finite Element Packages

4.7.1 Solid Modeling

Solid modeling is geometrical representation of a real object without losing information the real object would have. It has volume and therefore, if someone provides a value for density of the material, it will have mass and inertia. Unlike the surface model, if one makes a hole or cut in a solid model, a new surface is automatically created and the model recognizes which side of the surface is solid material. The most useful thing about solid modeling is that it is impossible to create a computer model that is ambiguous or physically non-realizable [34].

4.7.2 Motion Analysis of SCM by SolidWorks Motion

SolidWorks motion is an add-in module that comes with SolidWorks. Apart from being 3-D CAD Design Software, SolidWorks also used to evaluate and analyze the design in motion prior to moving on to the prototyping stage. It also useful to determine specific aspects related to design such as the interference of moving parts and the forces related to surfaces in contact. SolidWorks Motion allows one to analyze two major types of problems pertaining to the motion of solid bodies. The first is kinematic, which refers to the study of the motion of a rigid body without considering the forces that result in the motion of the body. The second is dynamic, which refers to the study of the motion of a rigid body as a result of the applied external forces on the body.

The motion study of SCM was achieved in three stages: In the first stage parts are assembled to make sub assembly for coarse debris cleaning mechanism. The assembled parts were animated to see if there are interferences or collision between parts. In the second stage, fine debris cleaning mechanism sub assembly was animated in the same manner as for coarse debris cleaning mechanism. In the final stage the sub assemblies were assembled together to make the entire assembly. The entire assembly was tested to ensure that all components work together as required.

4.7.3 Finite Element Packages and Static Analysis of SCM Components

Finite-element analysis (FEA) is useful in predicting a model's response to various influences such as forces, torques, periodic excitations, and heat. It is used to analyze large or complicated models where analytical solutions are not possible. FEA software breaks the model into thousands of small tetrahedral elements and solves numerically for each one individually.

Some of the leading commercial FEA tools include COMSOL, Ansys, and SolidWorks Simulation. SolidWorks Simulation is primarily applicable to mechanical and thermal models. COMSOL specializes in multiphysics problems involving interaction between mechanical, thermal, and electrical behavior. Ansys also addresses mechanical and thermal simulations and has advanced capabilities required in certain fields. Among these FEM packages, in this work SolidWorks simulation was preferred to perform the analysis.

The following Steps are used to perform finite element analysis in SolidWorks simulation:

1. The geometry of the part or assembly to be analyzed is modeled in SolidWorks or imported from other 3CAD systems.
2. Selecting study type. In SolidWorks there are many types of studies for instance static analysis, Dynamic analysis, Fatigue analysis and Drop test.
3. Applying material type. When specify material type the software displays all properties of the material such as Young's modulus, Poisson's ratio, yields strength, density etc.
4. Applying constraints (Fixtures) to specify boundary conditions.
5. Meshing the three-dimensional model.
6. Applying external loads (force, torque, pressure).
7. The solution is generated based on the previous input parameters.
8. Finally, the solution is viewed in a variety of displays.

Static Analysis of Components:

The final stage of the research incorporates analysis of stresses on components based on the applied loads and boundary conditions. The results of stress analysis are included in Appendix A.

When loads are applied to the machine, it may deform and the effect of the load is transmitted throughout the components. The external load induces internal forces and reactions to render the body into a state of equilibrium. Static analysis calculates displacements, strains, stresses, and reaction forces under the effect of applied loads.

Static Assumption:

All loads are applied slowly and gradually until they reach their full magnitudes. After reaching their full magnitudes, loads remain constant (time-invariant). This assumption allows us to neglect inertial and damping forces due to negligibly small accelerations and velocities. Time-variant loads that induce considerable inertial and/or damping forces may warrant dynamic analysis. Dynamic loads changes with time and in many cases induce considerable inertial and damping forces that cannot be neglected. In this research the dynamic loads are neglected by assuming that the machine is driven on smooth surface with constant speed and applied force.

An important benefit of performing stress analyses is the ability to determine design sensitivities and to conduct trade studies. Thus, effective optimization of the components can be achieved, enhancing reliability while reducing cost and weight.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Debris on street and sidewalks are main problem of cities and towns, especially in the developing countries like Ethiopia in which the cleaning process is conducted manually using brooms, shovels and handcarts. Developing countries can't afford purchasing mechanical broom sweepers and high-efficiency vacuum-assisted machines because of the associated costs and maintenance facilities.

The street cleaning process has to be mechanized by implementing machines which help street cleaners to improve the street cleaning quality and efficiency. For this purpose manually driven street cleaning machine was developed.

To facilitate the design process of SCM, debris characteristics, types and distributions on street and sidewalks was analysed by taking samples where varieties of debris found. After analyzing debris on streets and sidewalks, fundamental requirements of the machine were proposed. Based on the requirements product specification was determined.

During concept development stage, various concepts were generated by employing concept generation methods. Among these concepts the best concept was selected by setting criteria. The principle solution was specified by establishing function structures, searching for appropriate working principles and combining these into a working structure; the basic solution path was laid down through the elaboration of a solution principle. Based on the specified principle solution, the basic physical building blocks of the product in terms of what they do and what their interfaces are to the rest of the device was done. The 3-D part design was done in SolidWorks 2012 CAD software.

Kinematic study of the SCM was performed to determine the configuration and motion of motion transfer components by looking at the geometry during the motion. Therefore, the kinematic study makes possible to determine and design the motion characteristics of SCM. After completing the kinematic analysis the mechanical design of components was carried out to make the design to be safe.

Parts, sub assemblies and assembly of SCM were simulated using SolidWorks motion and SolidWorks simulation tools to ensure that all the parts work together as intended.

5.2 Recommendation

This thesis paper can be an interest for researchers, instructors and postgraduate students who have great enthusiasm to work more on human powered machines. It may motivate to design and develop other mechanism which can be driven manually to solve social problems. Furthermore this study contributes to a better and innovative product design, assist technological institutions and all those who are interested in product design.

In addition, it is suggested that a mass production of the product will reduce the manufacturing cost, so any interested person or company may have a better job opportunity with attractive profitability.

References

[1] Flintoff, F. (1976), Management of Solid Wastes in Developing Countries. WHO Regional Publications, South-East Asia Series No. 1, World Health Organization, New Delhi, India.

[2] Tchobanoglous, Theisen and Vigil (1993), Integrated solid waste management; Engineering principles and management issues. McGraw-Hill, Inc.

[3] Babayemi J. O., Dauda K. T.(2009), Evaluation of Solid Waste Generation, Categories and Disposal Options in Developing Countries: A Case Study of Nigeria

[4] Samuel Shimelis Teka (2006), Commercial Solid Waste Generation And Composition Analysis: Arada Subcity, Addis Ababa. M.sc. thesis environmental science program, Adis Ababa University, Ethiopia.

[5] Urban Development Sector Unit East Asia and Pacific Region. (1999). What a Waste: Solid Waste Management in Asia. Washington DC: World Bank.

[6] R. Chandrappa and D. B. Das (2012), Solid Waste Management, Environmental Science and Engineering, DOI: 10.1007/978-3-642-28681-0-2, Springer-Verlag Berlin Heidelberg.

[7] Schilling, J.G. (2005), Street Sweeping – Report No. 1, State of the Practice. Prepared for Ramsey-Washington Metro Watershed District (http://www.rwmwd.org). North St. Paul, Minnesota.

[8] Takele Tadesse (2004), Solid Waste Management Lecture Notes, University of Gondar, Gondar

[9] Lluis Boada, Esperanza Haya (2003), Solid waste management in the mediterranean region. made by isr/ewc and medcities, as an activity of the mediterranen urban waste management project.

[10] Anthony G, Elizabeth G (1981) Microbiology for environmental scientists and engineers. McGraw-Hill International Book Company, New York

[11] Edson J. (1875), Improvement in street sweeping machine. US Patent No. 6659, Boston, USA.

[12] Osborne M.L. (1917), Street cleaning Machine. US Patent No. 1229127, Oklahoma City, USA.

[13] Hanson H.I. et al (1962), Road cleaning machine. US Patent No. 3036326, Ohio, USA.

[14] Roger C. Sutherland (2011), Using street sweepers to improve water and air quality. AMEC Earth & Environmental in Tigard.

[15] G. Pahl andW. Beitz J. Feldhusen and K.-H. Grote (2007), Engineering Design: A Systematic Approach. 3rd English edition, Springer.

[16] Rawesak Tanawongsuwan, Aaron Bobick (2002), A Study of Human Gaits across Different Speeds. Georgia Institute of Technology, Atlanta, GA 30332-0280 USA.

[17] Eugene A. Avallone et. Al (2007), Marks' Standard Handbook for Mechanical Engineers 11th Edition. Mc-Graw Hill, New York ISBN 0-07-142867-4 page 9-4

[18] Magd M. Abdel-Wahab, Chong Wang, Libardo V. Vanegas-Useche, Graham A. Parker (2005), Experimental determination of optimum gutter brush parameters and road sweeping criteria for different types of waste. Ghent University, B-9000 Gent, Belgium.

[19] Kohara Gear Industry CO. LTD (http://www.khkgears.co.jp/english/index.html.), Gear technical reference.

[20] Shigley Joseph, Mechanical Engineering Design, First Metric Edition, McGraw Hill, 1986, page 660

[21] By erik Oberg, Franklin D. Jones, Horton, and Henry H. Ryffel (200), Machinery's Handbook 26th edition, Industrial Press, New York.

[22] http://www.skf.com/skf/productcatalogue/jsp/viewers/productTableViewer.jsp?&lang=en&newlink=1&tableName=1_1_1&presentationType=3&startnum=15

[23] Roy, S.Y., Ali, I., Shinn, G., Furusawa, N. (1995), Post chemical-mechanical planarization cleanup process for interlayer dielectric films. J. Electrochem. Soc. 142(1), 216–226

[24] Visser, J. (1995), Particle adhesion and removal- a review. Particle Sci. Technol. 13, 169–196

[25] Moumen, N., Gueerera, M., Piboonturn, C., Busnaina, A.A. (1999), Post-CMP cleaning of oxide silicon film. Megasonic and/or brush. In: Proc. IEEE/SEMI ACMC, pp. 250–253.

[26] Dugger, M.T., Adkins, C.L.J., Resnick, P.J. (1997), Particle-surface interaction in chemical mechanical polishing. Precis. Eng.20(2), 149–150.

[27] Estragnat, E., Tang, G., Liang, H., Jahanmir, S. (2004), Experimental investigation on mechanisms of silicon chemical mechanical polishing. J. Electron. Mater. 33(4), 334–339

[28] Zhang, G., Burdick, G., Dai, F., Bibby, T., Beaudoin, S. (1998), Assessment of post-CMP cleaning mechanisms using statistically designed experiments. Thin Solid Films 332(1), 379–384.

[29] Soltani, M., Ahmadi, G. (1994), On particle adhesion and removal mechanisms in turbulent flows. J. Adhesion Sci. Technol. 8(7), 751–834

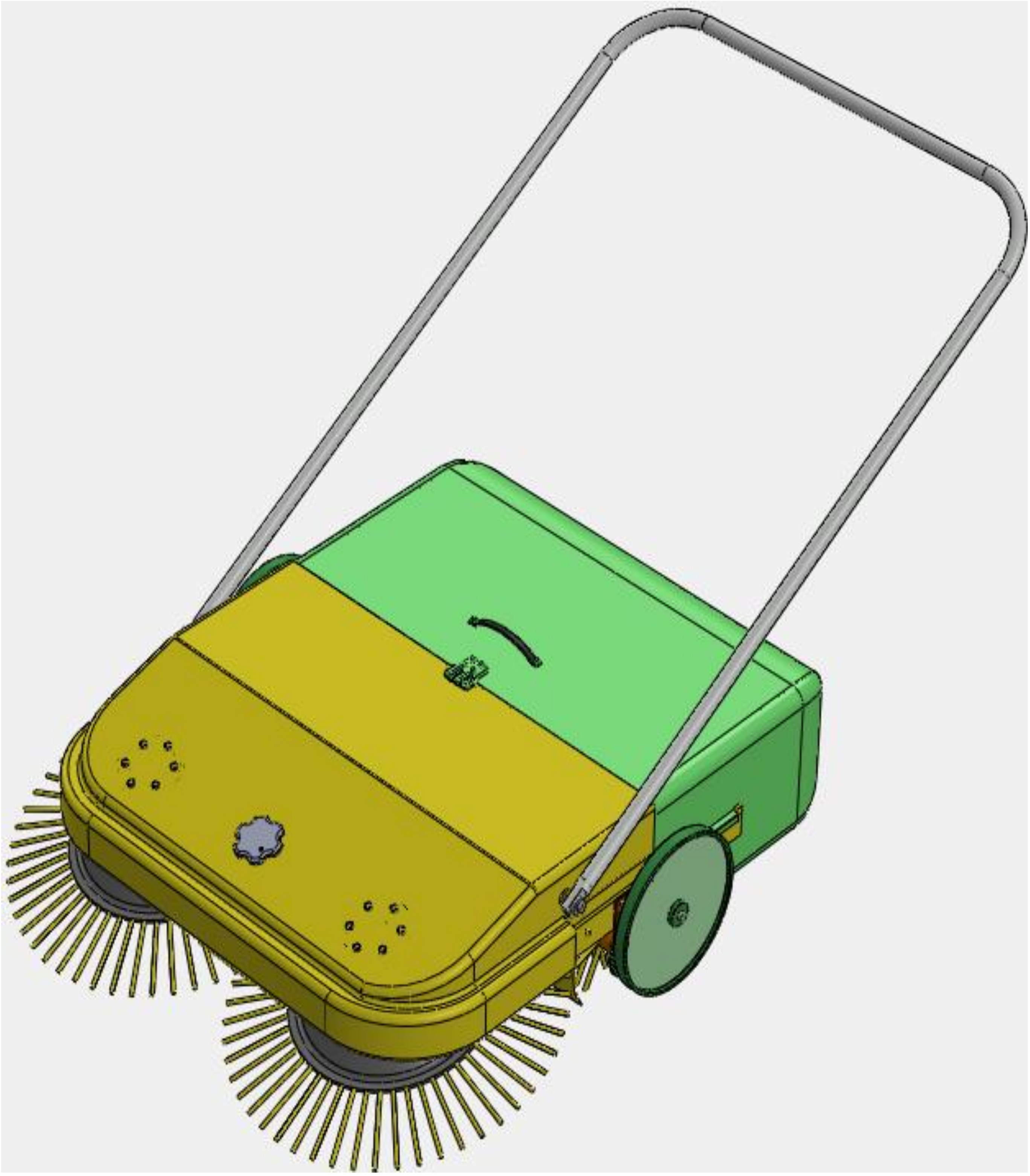
[30] Cooper, K., Ohler, N., Gupta, A., Beaudoin, S. (2000), Analysis of contact interactions between a rough deformable colloid and a smooth substrate. J. Colloid Interface Sci. 222, 63–74

[31] Burdick, G.M., Berman, N.S., Beaudoin, S.P. (2001), Describing hydrodynamic particle from surfaces using the particle Reynolds number. J. Nanopart. Res. 3, 455–467

[32] Larios, J.M., Zhang, J., Zhao, E.,Gockel, T., Ravkin, M. (1997), Evaluating chemical mechanical cleaning technology for post-CMP applications. Micro. Mag. 15, 61 18.

[33] Busnaina, A.A., Lin, H.,Moumen, N., Feng, J., Taylor, J. (2002), Particle adhesion and removal mechanisms in post-CMP cleaning process. IEEE Trans. Semicond. Manufact. 15(4), 374–382

[34] Negash Alemu (2007), Analysis of stresses in helical gears by finite element method. M.Sc. Thesis, Dept. of Mechanical Engineering, Addis Ababa Technology Institute.

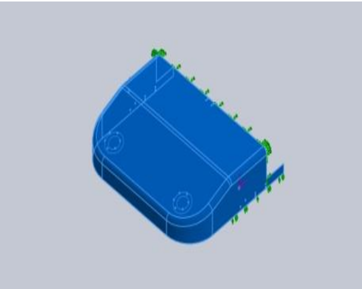


Manually driven street cleaning machine

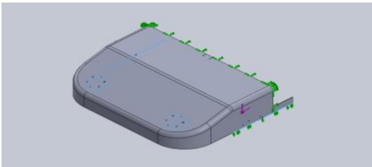
APPENDIX A: STATIC ANALYSIS RESULTS

A-1 Front Enclosure

Material Properties

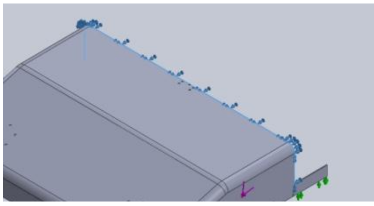
Model Reference	Properties	Components
	Name: Nylon 101 Model type: Linear Elastic Isotropic Default failure criterion: Max von Mises Stress Yield strength: 6e+007 N/m^2 Tensile strength: 7.92897e+007 N/m^2 Elastic modulus: 1e+009 N/m^2 Poisson's ratio: 0.3 Mass density: 1150 kg/m^3 Thermal expansion coefficient: 1e-006 /Kelvin	SolidBody 1(Ø5.0 (Ø5.0 (Ø5.0 (Ø5.0 (Ø5.0 (Ø5.0 (Ø5.0 (5) Diameter Hole2)(Front enclosure)

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Roller/Slider-1		Entities: 4 face(s) Type: Roller/Slider

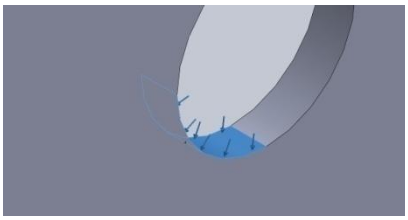
Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	0	57.9331	-0.0559592	57.9332

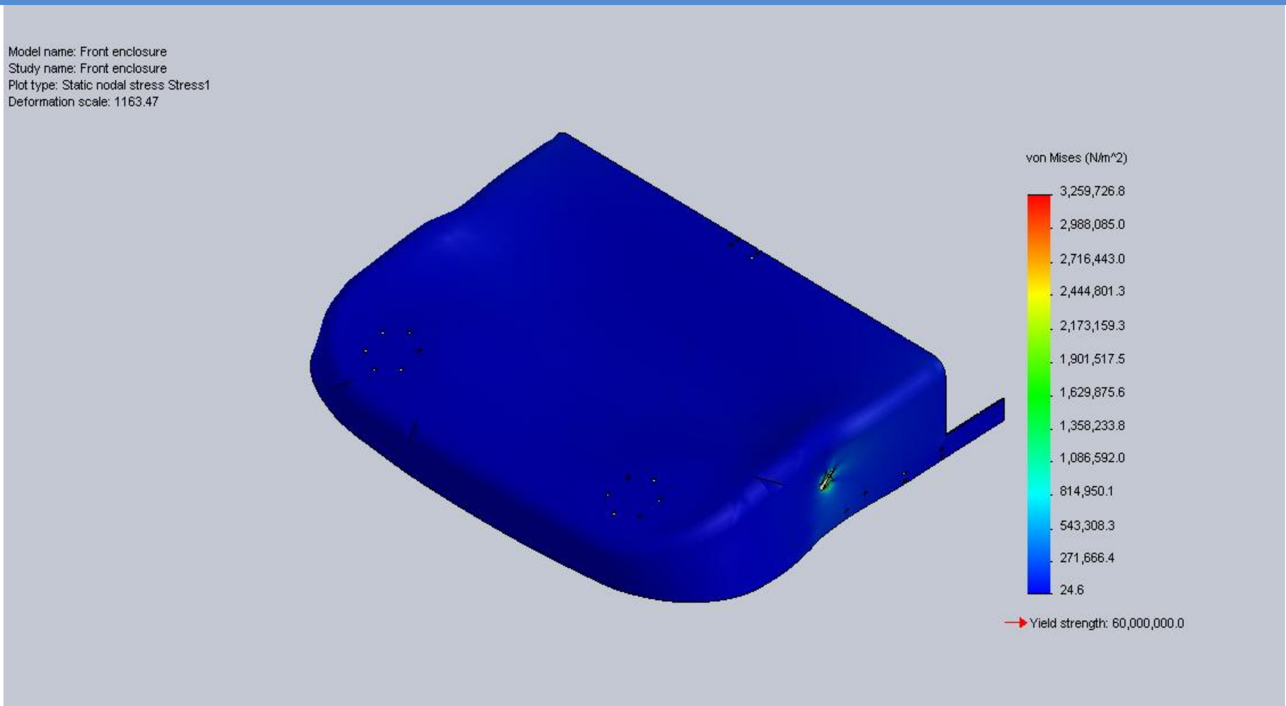
Fixture name	Fixture Image	Fixture Details
Fixed-3		Entities: 1 face(s) Type: Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	7.15256e-007	8.32833	-66.2055	66.7273

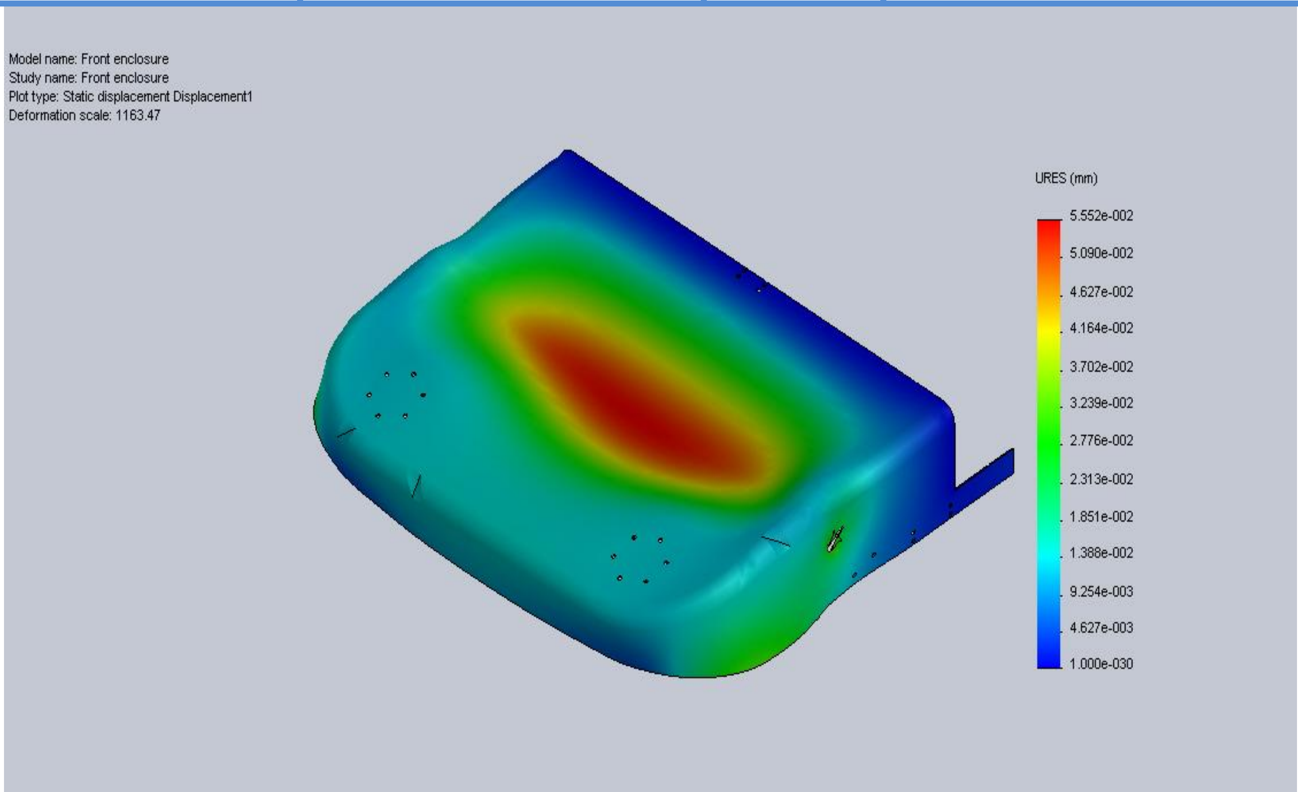
Load name	Load Image	Load Details
Force-1		Entities: 1 face(s) Type: Apply normal force Value: 51.965 N

Name	Type	Min	Max
Stress	VON: von Mises Stress	24.5708 N/m^2 Node: 8927	3.25973e+006 N/m^2 Node: 11820



Front enclosure stress

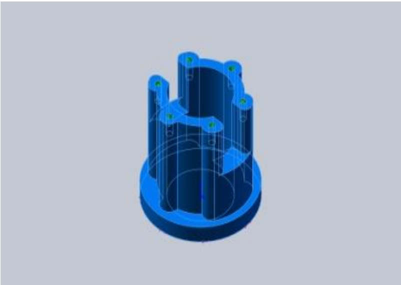
Name	Type	Min	Max
Displacement	URES: Resultant Displacement	0 mm Node: 407	0.0555238 mm Node: 13690



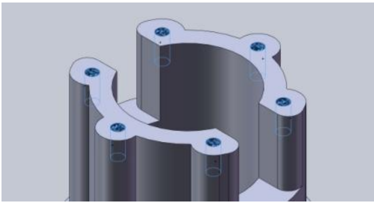
Front enclosure displacement

A-2 Disc Brush Holder Frame

Material Properties

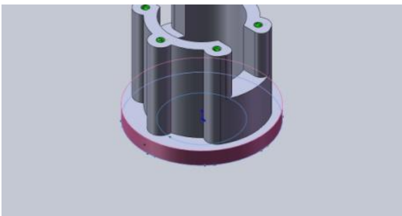
Model Reference	Properties		Components
	Name: Model type: Default failure criterion: Yield strength: Tensile strength: Elastic modulus: Poisson's ratio: Mass density: Thermal expansion coefficient:	Nylon 101 Linear Elastic Isotropic Unknown 6e+007 N/m^2 7.92897e+007 N/m^2 1e+009 N/m^2 0.3 1150 kg/m^3 1e-006 /Kelvin	SolidBody 1(Fillet1)(DHF 3)

Loads and Fixtures

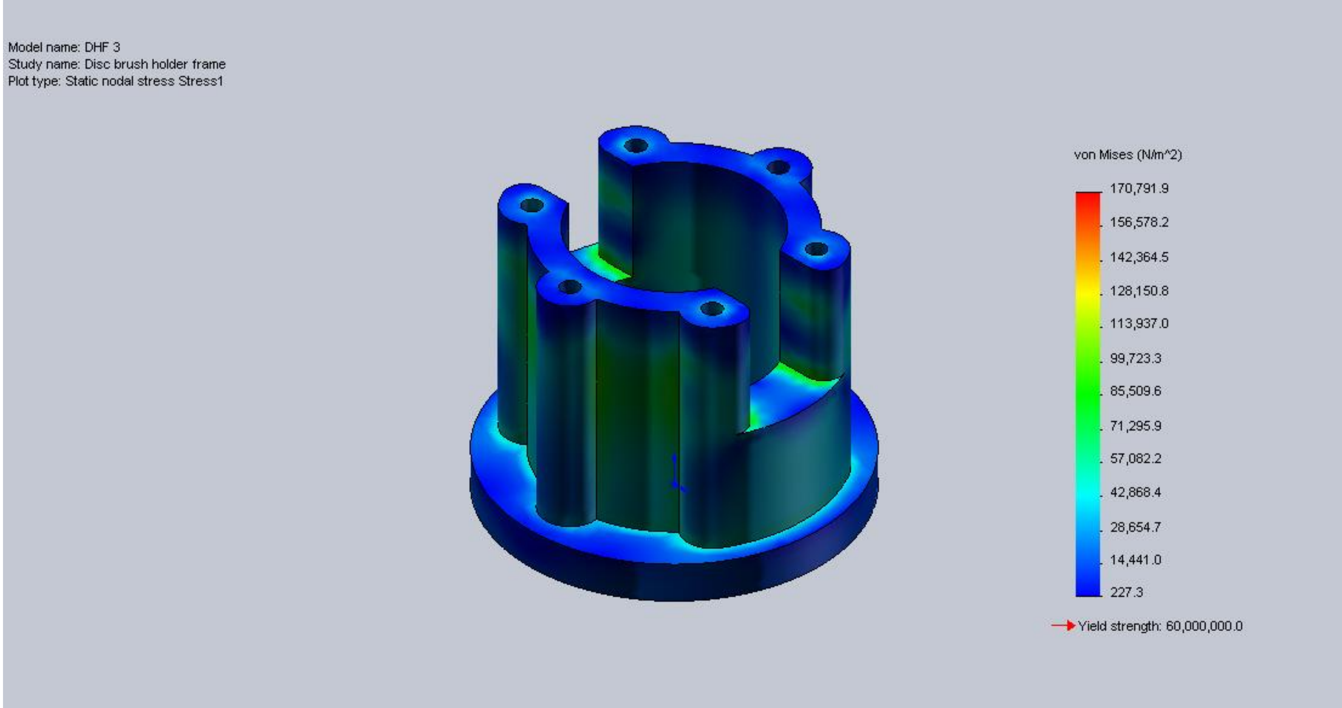
Fixture name	Fixture Image	Fixture Details	
Fixed-1		Entities: Type:	6 face(s) Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	0.00148418	6.50734e-005	-0.000202358	0.00149932

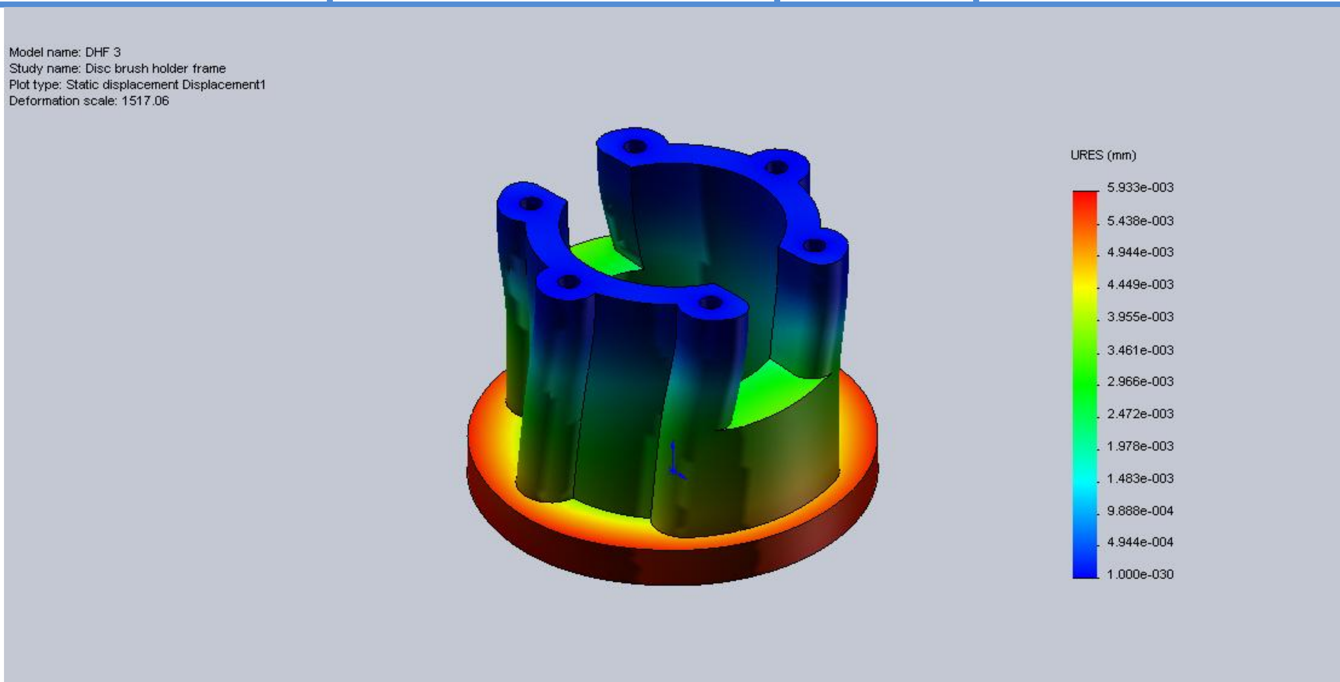
Load name	Load Image	Load Details	
Torque-1		Entities: Reference: Type: Value:	1 face(s) Face< 1 > Apply torque 1.2212 N-m

Name	Type	Min	Max
Stress	VON: von Mises Stress	227.259 N/m^2 Node: 30469	170792 N/m^2 Node: 32370



Disc brush holder frame stress

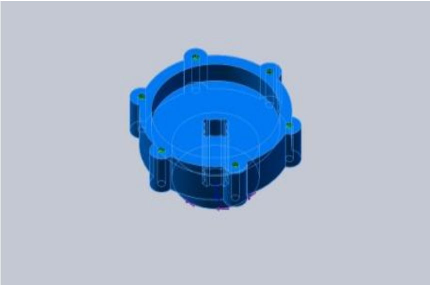
Name	Type	Min	Max
Displacement	URES: Resultant Displacement	0 mm Node: 141	0.00593251 mm Node: 31140



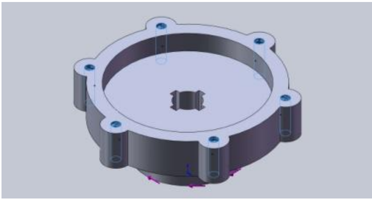
Disc brush holder frame displacement

A-3 Disc Brush Holder

Material Properties

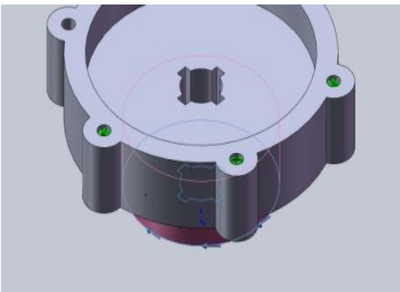
Model Reference	Properties	Components
	Name: Nylon 101 Model type: Linear Elastic Isotropic Yield strength: 6e+007 N/m^2 Tensile strength: 7.92897e+007 N/m^2 Elastic modulus: 1e+009 N/m^2 Poisson's ratio: 0.3 Mass density: 1150 kg/m^3 Thermal expansion coefficient: 1e-006 /Kelvin	SolidBody 1(Cut-Extrude3)(DHF & D C bottom 3)

Loads and Fixtures

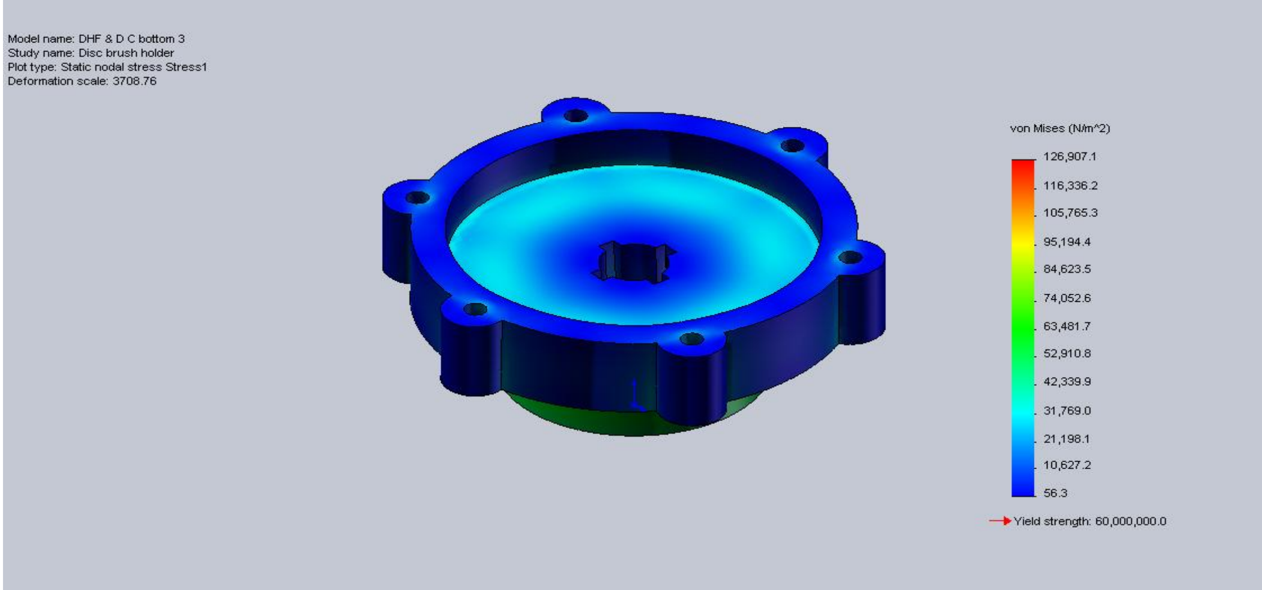
Fixture name	Fixture Image	Fixture Details
Fixed-1		Entities: 6 face(s) Type: Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	0.00126188	-4.03431e-006	0.000237801	0.0012841

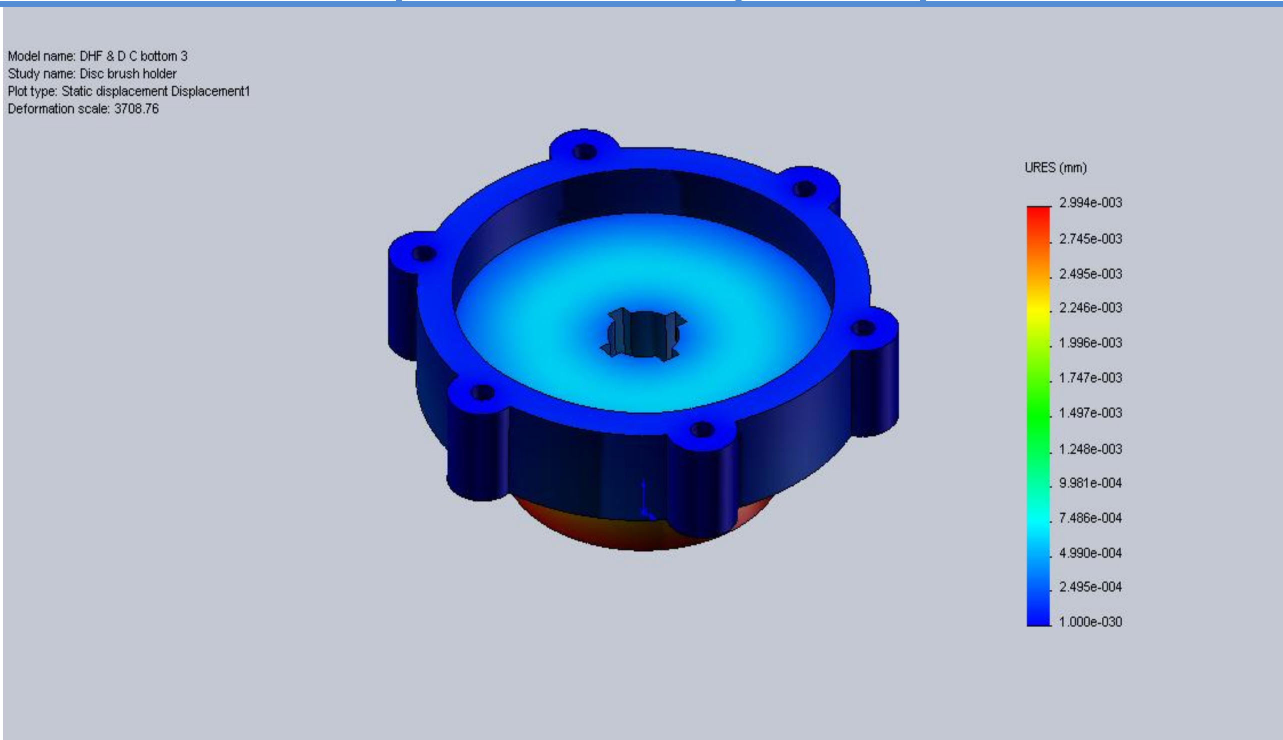
Load name	Load Image	Load Details
Torque-1		Entities: 1 face(s) Reference: Face< 1 > Type: Apply torque Value: 1.2212 N-m

Name	Type	Min	Max
Stress	VON: von Mises Stress	56.2667 N/m^2 Node: 61739	126907 N/m^2 Node: 73943



Disc brush holder stress

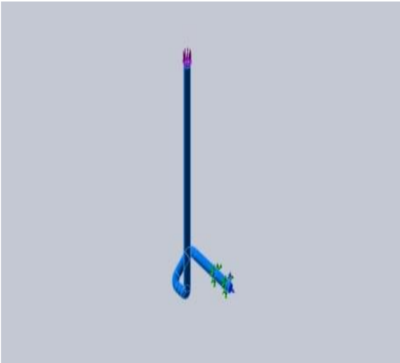
Name	Type	Min	Max
Displacement	URES: Resultant Displacement	0 mm Node: 271	0.00299426 mm Node: 613



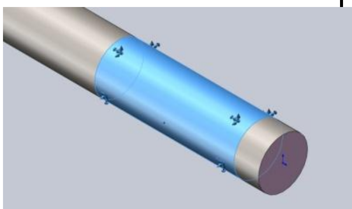
Disc brush holder displacement

A-4 Connector

Material Properties

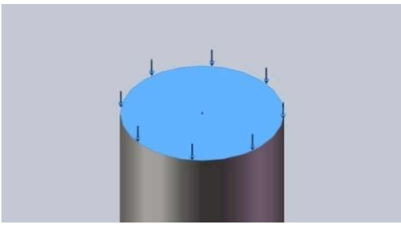
Model Reference	Properties	Components
	Name: ASTM A36 Steel Model type: Linear Elastic Isotropic Default failure criterion: Max von Mises Stress Yield strength: 2.5e+008 N/m^2 Tensile strength: 4e+008 N/m^2 Elastic modulus: 2e+011 N/m^2 Poisson's ratio: 0.26 Mass density: 7850 kg/m^3 Shear modulus: 7.93e+010 N/m^2	SolidBody 1(Split Line1)(Left side connector)

Loads and Fixtures

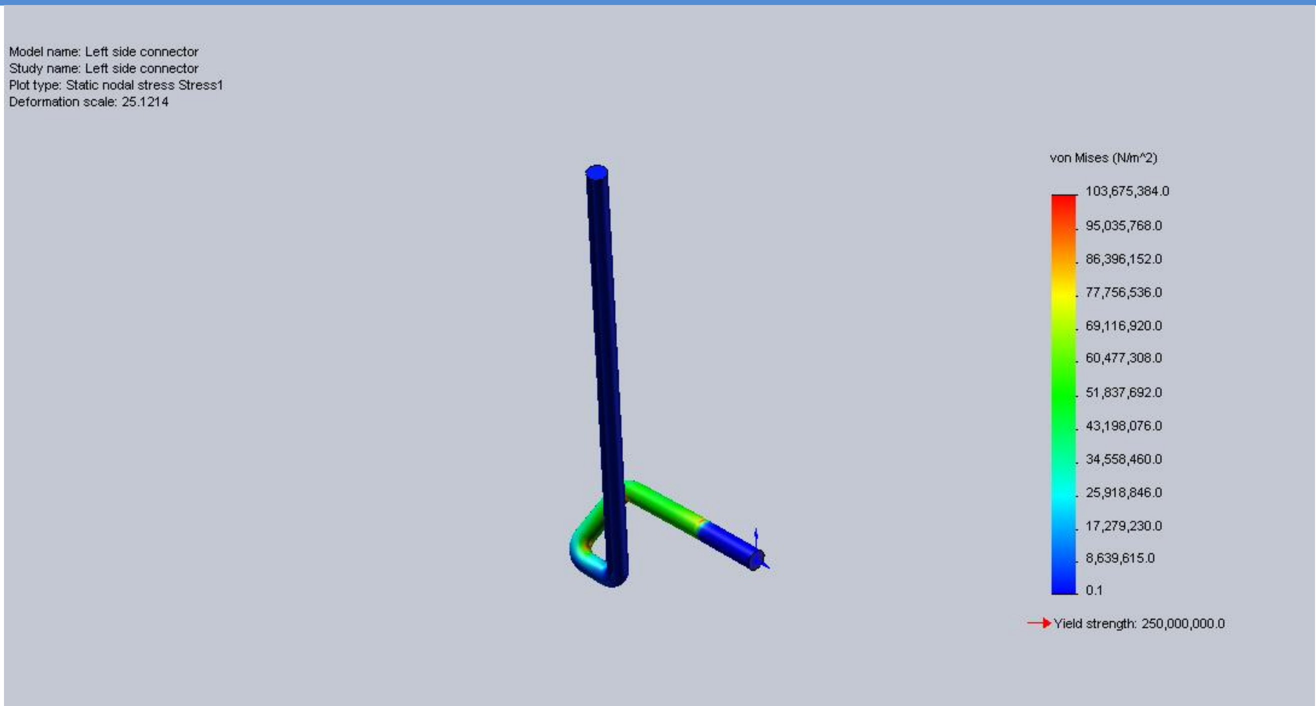
Fixture name	Fixture Image	Fixture Details
Fixed-2		Entities: 1 face(s) Type: Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	-0.00292873	68.631	0.00320482	68.631

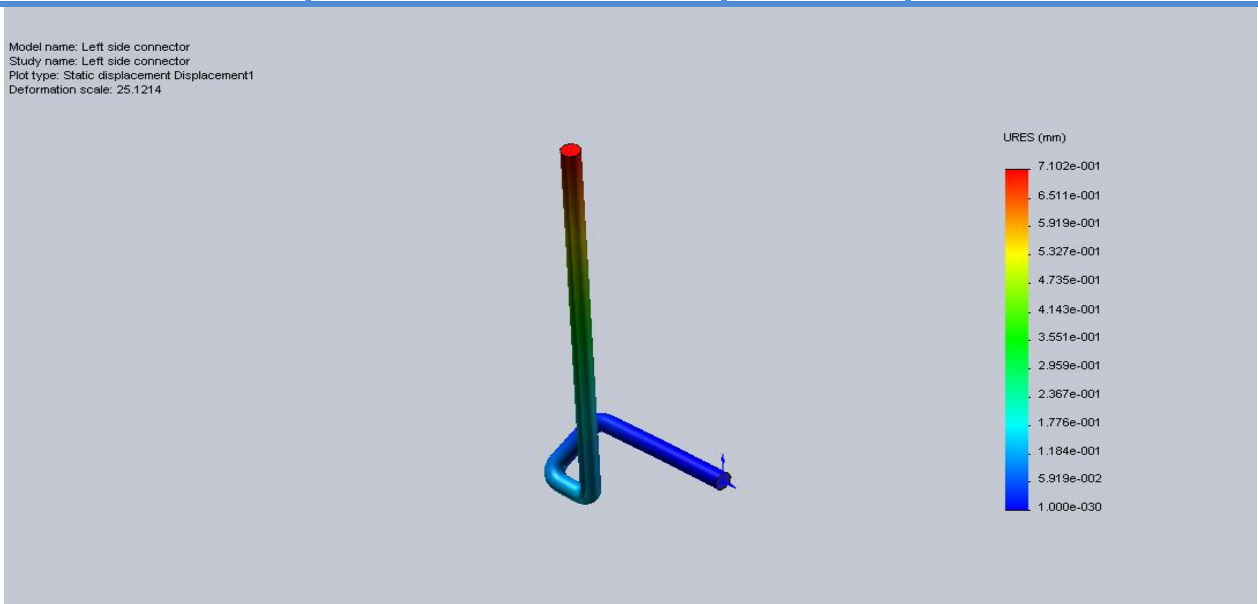
Load name	Load Image	Load Details
Force-1		Entities: 1 face(s) Type: Apply normal force Value: 68.82 N

Name	Type	Min	Max
Stress	VON: von Mises Stress	0.0641869 N/m^2 Node: 22616	1.03675e+008 N/m^2 Node: 37511



Connector stress

Name	Type	Min	Max
Displacement	URES: Resultant Displacement	0 mm Node: 284	0.710242 mm Node: 28662



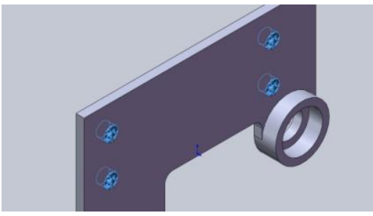
Connector displacement

A-5 Shaft Holder

Material Properties

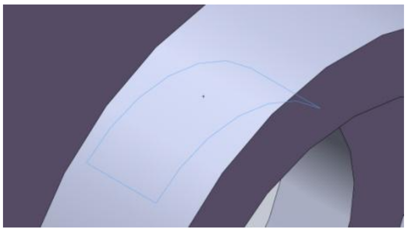
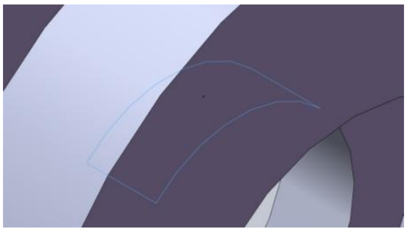
Model Reference	Properties	Components
	Name: Nylon 101 Model type: Linear Elastic Isotropic Default failure criterion: Unknown Yield strength: 6e+007 N/m^2 Tensile strength: 7.92897e+007 N/m^2 Elastic modulus: 1e+009 N/m^2 Poisson's ratio: 0.3 Mass density: 1150 kg/m^3 Thermal expansion coefficient: 1e-006 /Kelvin	SolidBody 1(Cut-Extrude2)(roller & axle holder left side)

Loads and Fixtures

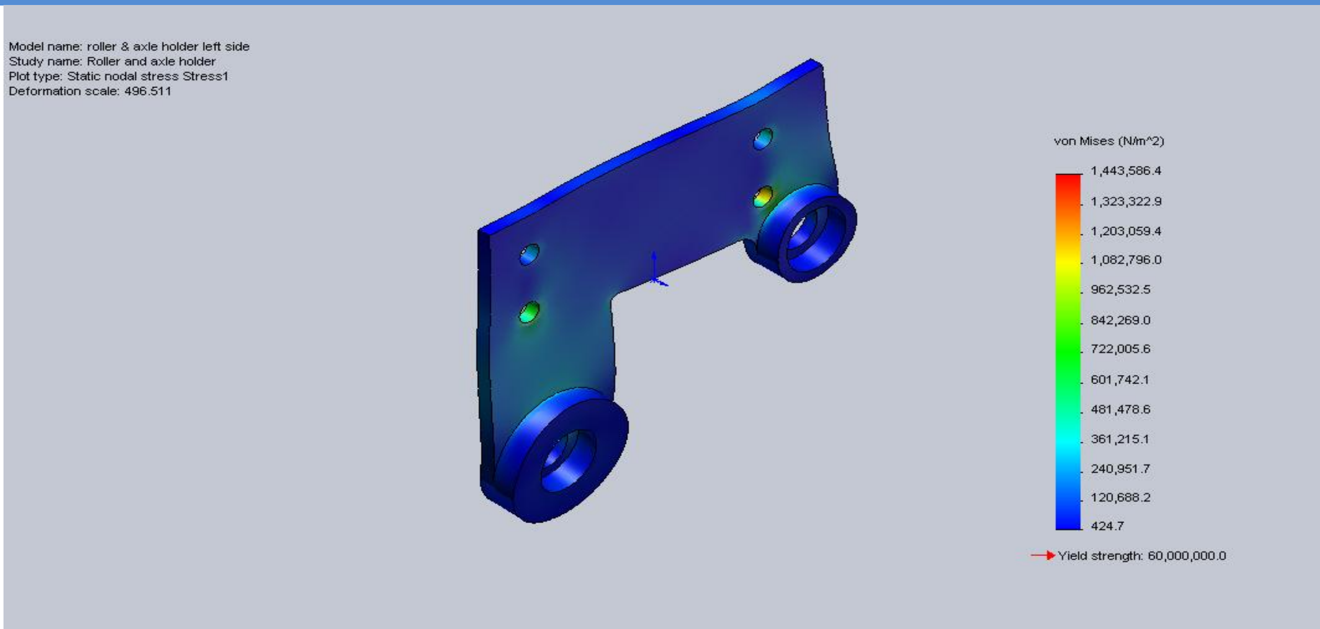
Fixture name	Fixture Image	Fixture Details
Fixed-1		Entities: 4 face(s) Type: Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	5.81816e-005	-44.9378	4.22206e-005	44.9378

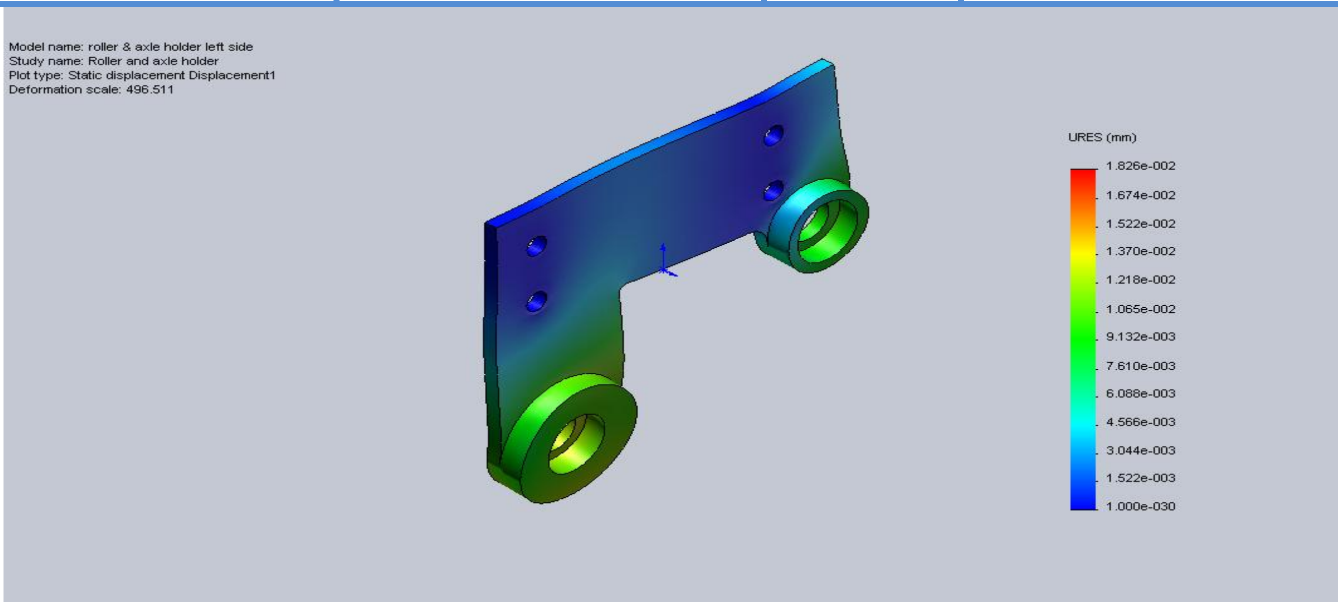
Load name	Load Image	Load Details
Force-1		Entities: 1 face(s) Type: Apply normal force Value: 22.748 N
Force-2		Entities: 1 face(s) Type: Apply normal force Value: 27.165 N

Name	Type	Min	Max
Stress	VON: von Mises Stress	424.719 N/m^2 Node: 15416	1.44359e+006 N/m^2 Node: 598



Shaft holder stress

Name	Type	Min	Max
Displacement	URES: Resultant Displacement	0 mm Node: 427	0.0182644 mm Node: 599



Shaft holder displacement