

Original Article

Design and Analysis of a Sweeping System for Cleaning Vehicles Using Two Circular Brushes and a Cylindrical Brush

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Abstract - Waste and other pollutants in the streets affect people's quality of life and health, as well as hinder pedestrian and vehicular traffic. In response to this problem, cleaning robots have been developed with different functions, methods of action, and forms of operation, but most of these robots only clean dust and are unable to clean in the corners, where most debris accumulates. That said, this study aims to design a cleaning system that is capable of cleaning objects larger than dust and smaller than a 500 ml bottle, which consists of 2 circular brushes and 1 cylindrical brush in the middle - front of the robot so that the garbage from the streets is directed to a container which is in the same robot, the design is carried out in a CAD/CAE software and subjecting them to simulations of stress and deformation in the same software to validate the feasibility of the design. As a result, the specifications of each of the elements of the system, the result of the simulations, and the materials with which the robot is built, as well as a comparison with another cleaning system and conventional cleaning, are used to validate the design of this cleaning system using brushes.

Keywords - Cleaning robot, Cylindrical and circular brushes, Simulation, CAD/CAE, Cleaning system.

1. Introduction

Street cleaning is crucial for human quality of life and health, as the accumulation of pollutants affects people [1]. Traditional manual sweeping is a risky job; cleaning staff are exposed to multiple hazards like traffic accidents, inhalation of particulate matter, and solar radiation. Additionally, their work postures are repetitive and not ergonomic [2]. To address these challenges, innovative technological solutions have been implemented worldwide to safeguard operators and optimize waste management [3]. Decades ago, more advanced tools and devices began to be used to make cleaning more efficient [4]. Over time, cleaning vehicles and robots have evolved, becoming more sophisticated, electric, and capable of operating autonomously [5]. The goal of these machines is to keep urban spaces clean to promote hygiene, public health, and improve city aesthetics, which contributes to overall social well-being [2]. While automation improves the quality of many activities, it also carries the risk of job loss and human obsolescence. Therefore, it is essential to establish policies that regulate the use of these new technologies to manage their social impact [6]. In this context, robotic technology and cleaning vehicles have proven to be highly effective. For example, Vanegas-Useche et al. [7] evaluated the concept of an oscillating brush and found that oscillations improve

sweeping efficiency for wet and compact debris. Similarly, Abdel-Wahab et al. [8] conducted tests to determine the effectiveness of gutter brushes on different types of dirt. They found that dry sludge on rough surfaces is the most difficult to sweep, requiring a large brush inclination angle and deep penetration. Xu et al. [9] concluded that continuous technological innovation will lead to the development of more intelligent cleaning vehicles.

Mukesh et al. [10] created a low-cost cleaning machine that uses the vacuum principle to collect heavy particles, while Khan et al. [11] developed a solar-powered sweeping machine with sensors to automate cleaning in small areas, offering an efficient alternative despite its initial cost. Wang et al. [12] created a finite element model to analyze brush deformation in a semi-autonomous sweeper, optimizing its control with an adaptive servo controller. Hayat et al. [13] introduced Panthera, a reconfigurable robot that adjusts its structure to pavement width and pedestrian density. In the same vein, Velez et al. [14] designed adaptable circular brush mechanisms for uneven terrain, demonstrating their feasibility through structural and dynamic analysis. In the field of simulation, Tassinari et al. [15] used SolidWorks to design a worm gear system, confirming the mechanism's reliability



with a safety factor of 2.4. Choudhary et al. [16] proposed an axial modification method for bevel gears that optimizes meshing and reduces transmission errors and stress through tooth end relief. Similarly, Choudhary modeled and simulated bevel gears for a gearbox, evaluating different materials to optimize selection based on stress resistance, a process ideal for off-road vehicles. The design of cleaning vehicles and their mechanisms should follow rigorous engineering methodologies to clearly define their characteristics. For instance, Liu et al. [17] used Fuzzy Quality Function Deployment (FQFD) and the ARIZ algorithm to define the performance of a sweeping vehicle in various environments. Similarly, Limachi et al. [18] applied the Quality Function Deployment (QFD) and Failure Mode and Effects Analysis (FMEA) methodologies to the design of an explosive ordnance disposal vehicle. Technical and economic analysis has demonstrated the importance of these design methodologies for defining key variables in vehicle development [18]. In the same vein, Author used a systematic design approach for a clearance vehicle, which allowed for a clear definition of requirements and the selection of main components. However, Reichelt et al. [19] point out that traditional machinery design models may be reaching their limits, as the automotive industry now requires new approaches. In response, the application of transdisciplinary engineering design processes that integrate tools from other disciplines is considered a viable alternative [20].

This study uses the city of Arequipa, Peru, as a case study due to its inefficient waste management system and the lack of modern equipment for urban cleaning [21]. For this reason, a sweeping system is proposed for cleaning vehicles, consisting of two circular brushes and one cylindrical brush. The Ganesan and Esakki systematic design approach will be used for this purpose. The project includes simulating the mechanisms in SolidWorks software to determine the safety factor, stresses, and deformations. Finally, a comparative analysis will be conducted between this proposed system, conventional cleaning, and the system proposed to validate its reliability.

2. Methodology

For the design of the Brush Sweeping System (BSS) of the cleaning vehicle, the Systematic Design Approach of Ganesan and Esakki [22] will be used, which consists of 4 steps. First, the task is clarified. Next, in the conceptual design, the functional structure of the task is determined, and options are evaluated based on both technical and economic factors. In order to choose the option that comes closest to the ideal solution or variant, the VDI 2225 standard is also used for the technical-economic evaluation. This is followed by the realization design process, during which architectural, structural, and energy analyses, if applicable, of the sweeping system are carried out. All this can be done through calculations or simulations in specialized software. Finally, drawings and TCM specifications are provided in the detailed

design. Additionally, dynamic simulations of the vehicle will be performed in software in order to build the cleaning system later, and some tests will be described to evaluate the system.

2.1. Task Definition

The purpose of a cleaning vehicle for the streets of Arequipa is to address the evident accumulation of small and medium-sized waste. Visits to various city points revealed that cleaning personnel face significant risks. On the one hand, they are exposed to potential accidents due to the large volume of vehicles, while on the other, the high levels of vehicular emissions, particulate matter, and intense solar radiation in Arequipa pose a threat to their respiratory and dermatological health. Additionally, workers experience ergonomic issues from performing their duties in uncomfortable positions for long periods. Therefore, there is an urgent need to implement technologies to improve cleaning activities. This study approaches the problem generically by defining it as a system that "will sweep and subsequently store" medium and small-sized waste. The proposed solution is a sweeping system that can be attached to any medium-sized vehicle, whether operated manually or automatically. To define the best design for this system, a list of assumptions and requirements is created to establish the necessary criteria and expectations.

1. The vehicle shall only pick up small and medium-sized debris such as bags, small bottles, cardboard, stone particles, and dust.
2. The maximum rotation speed of the circular and cylindrical brushes shall be 450 and 900 rpm, respectively.
3. The maximum travel speed of the system will be 1 m/s, considering that the vehicle will be manually operated and that this value is the average walking speed of a human being
4. The power defined for the energy source is 1.85 kW, since the vehicle will be manually operated, and this energy source will only drive the brushes.
5. Considering that the vehicle will work manually, the working day of a sweeper is 6 hours, so the autonomy of the machine should be 6 hours to cover a working day.
6. The system must conform to the proportions of the road shoulder, as specified in the Highway Manual: Geometric Design. Thus, the maximum width dimension of the system shall be 0.75 m.

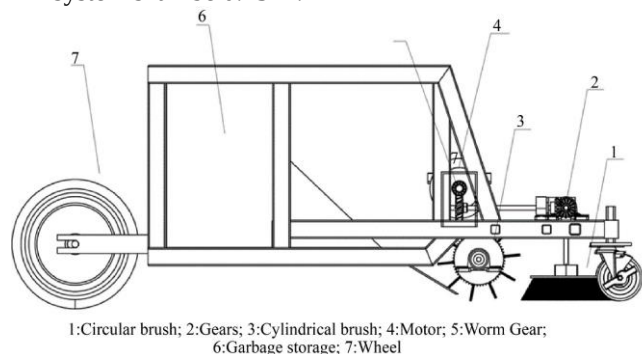


Fig. 1 Structural sketch of a cleaning vehicle

2.2. Conceptual Design

Generally, in the systematic design approach, it is appropriate to divide into sub-functions according to the subsystems that are operating in our equipment to be designed. However, in the present case, the sweeping system is considered a unitary system of the whole cleaning vehicle; moreover, it is considered a unique system in comparison to the subsystems of the vehicle due to its specific functionality and complexity.

Table 1 shows the morphological matrix identifying all the sections of relevance in the sweeping system, and three possible solutions for all the sections of the system. It is important to detail about each of these, in first instance in streets the use of circular brushes type “rotary brush” and “side broom” has been widely implemented in cleaning vehicles, the first one is mostly used to carry side debris towards the middle

part of the robot and the second one is used to rotate and remove loose debris from the floor, both are used for more massive debris because of their stiff bristles [12, 23]. Likewise, the use of cylindrical brushes, such as “cylindrical scrubber” and “main broom,” has been shown to be quite effective for less structured soils and abrasive environments [24]. Then, the energy source for this case can be an internal combustion engine or, with the use of an electric motor and batteries, with the internal combustion engine for its operation uses fuels that have higher energy efficiency than the batteries of electric motors, but electric motors have higher efficiency in converting chemical energy into mechanical energy compared to internal combustion engines [25]. The transmission system to the circular brushes and the cylindrical brush can be by chains, belts, and different types of gears given in Table 1; these are implemented to reduce the speed of the system, especially the bevel gears that serve for this speed variation [16].

Table 1. Morphological matrix

Sections	Sol. 1	Sol. 1	Sol. 1
Type of circular brushes	Rotary brush	Side broom	Rotary brush
Type of cylindrical brushes	Cylindrical scrubber	Cylindrical scrubber	Main broom
Energy source	I.C.E.	E.C.	I.C.E.
Transmission. Cir. B.	Belt + Miten gear	Belt helical gears + worm gear	Gears + Chain
Transmission Cyl. B.	Gears + Belt	Crown+ Chain	Gears + Chain
Brush drive	Differential	Differential	Independent

Table 2. Technical evaluation

Project Variants		Solution 1		Solution 2		Solution 3		Ideal Variant	
Technical Criteria	g	p	gp	p	gp	p	gp	p	gp
Ease of Manufacturing	3	3	9	3	9	4	12	4	12
Sweeping Efficiency	5	3	15	4	20	2	10	4	20
Sweeping Speed	4	2	8	4	16	2	8	4	16
Cleaning System Adaptability	4	3	7	4	16	2	8	4	16
Simplicity of Design	4	3	12	3	12	4	16	4	16
Energy and Noise Reduction	4	3	12	4	16	2	8	4	16
Maximum Score	23	17	60	22	86	16	58	24	92
Technical Value Xi		0.71	0.66	0.92	0.93	0.67	0.65	1.00	1.00

For the technical and economic evaluation of the conceptual versions proposed in the morphological matrix, the comparative evaluation of the VDI 2225 standard was used, because it is difficult to determine exact cost figures during the conceptual design phase. Recommendations proposed by the authors of the article incorporated as a fundamental basis for strengthening our analysis. Their approach offers valuable insights that complement the development of our research work. Tables 2 and 3 present the technical and economic evaluations, respectively. According to VDI 2225, each objective is assigned a score between 0 and 4. Zero implies

that the response is insufficient to achieve the desired result, while four indicates that it achieves the objective to the best of its ability. The absolute value scale allows a simple determination of whether a specific version is relatively close to or far from the theoretical ideal and is therefore often more appropriate for comparison. As a result, a score (p = score) is assigned to the variation considering each criterion and a weighted weight (g = weighted weight based on the importance of technical or economic factors). The degree of appreciation is calculated by dividing the total score of the variant by its ideal score, as shown in Tables 2 and 3.

Table 3. Economic evaluation

Project Variants		Solution 1		Solution 2		Solution 3		Ideal Variant	
Technical Criteria	g	p	gp	p	gp	p	gp	p	gp
Low material cost	4	4	16	4	16	4	16	4	16
Maintenance and replacement	5	2	10	3	15	1	5	4	20
Energy	5	2	10	3	15	2	10	3	15
Low manufacturing cost	4	4	16	3	12	3	12	4	16
Machine-hour cost	5	3	15	4	20	2	10	4	20
Maximum Score	23	15	67	17	78	12	53	19	87
Technical Value Xi		0.79	0.77	0.89	0.9	0.63	0.61	1.00	1.00

In Figures 2(a) and (b), it is observed that the ideal variable is the black rhombus, where the green point, which is solution 2, is the best option among all solutions.

presented in Figure 3. It is composed of five transmission systems: one chain, one worm gear, and three straight bevel gears. It also consists of six shafts.

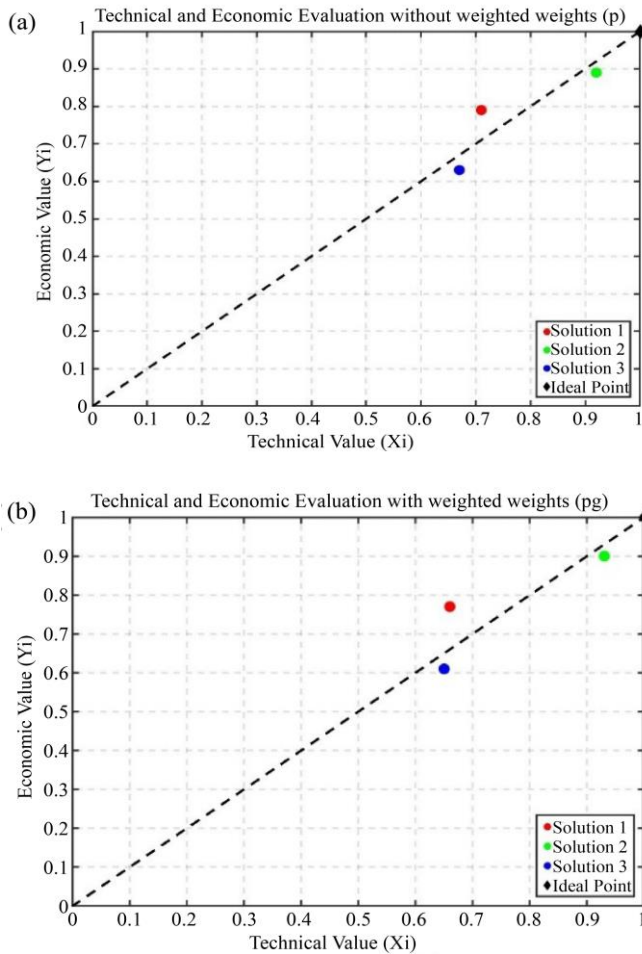


Fig. 2 Technical and economic evaluation according to VDI 2225, (a) Evaluation of concepts without weighted weights, (b) Evaluation of concepts with weighted weights

2.3. Embodiment Design

Before the engineering calculations and in accordance with the conceptual proposals of the previous section, a schematic of the sweeping system's mechanical components is

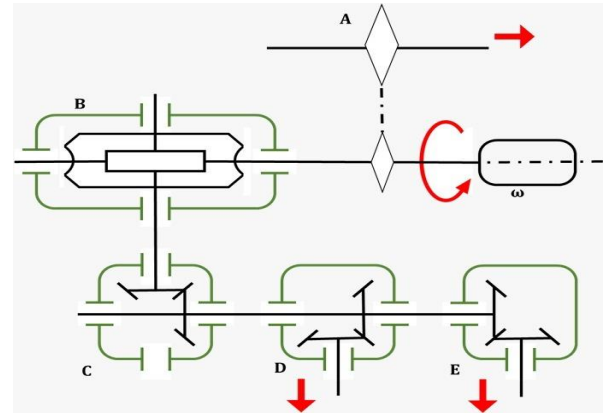


Fig. 3 Diagram of the sweeping system components

This geometry was developed using Autodesk Inventor software. The overall dimensions of the system are presented in Table 1, the circular brushes at the ends were created in such a way that they can clean and drag to the middle objects that are on the edges or in hard to reach places on the sides of the robot, all this so that the cylindrical brush can send all this garbage both that which comes from the circular brushes and the garbage in the middle to a container that is located at the rear of the robot. The selection of materials is given according to both economic and engineering aspects, so it was decided to use A36 steel for this system because the streets are a dangerous environment, where cars, people or animals can impact against the robot, so this robot must withstand forces provided by these and it is difficult for an external agent can deform the parts of the robot, in the manufacturing stage the A36 steel is easy to weld, work and form, also compared to other materials is relatively inexpensive. The brushes will be made of nylon, this material is more resistant to wear than polypropylene, because of this it will have a longer life, cleaning larger objects than dust, nylon also has a great flexibility, which makes it suitable for using the brushes in environments where the surface is not smooth as the streets, the nylon has a better grip on the garbage and despite the

different climatic changes, it maintains its structural integrity. Over time, the bristles will maintain their shape, thus improving the effectiveness of the cleaning robot. Table 4 below details the parts of the cleaning system with their respective materials.

Table 4. Description and materials of the cleaning system components

Item	Description	Material
Chassis	Dimensions: 0.6 x 1.05 m	A36 Steel
Shaft for the cylindrical brush	Diameter: 5/8" Large: 0.5 m	A36 Steel
Cover for the cylindrical brush shaft.	Diameter: 3.5" Large: 0.5 m	HDPE
Cylindrical brush	Diameter: 0.6m	Nylon
Circular Brush	Diameter: 0.3m	Nylon
Wheels	Diameter: 0.5m	Rubber
Caster wheel	Lead: caster wheel	Nylon/Metal
Gears	Shaft 2: 1 x 30 cm helical gear 2 x 20-tooth spur bevel gears Shaft 3: 25-tooth spur bevel gear 50-tooth spur bevel gear	A36 Steel
Chains	Roller chain 05B 2- 93 ISO 606:2004	7075 aluminum
Mechanical pinion	Pinion of 9 teeth Pinion of 48 teeth	7075 aluminum

2.4. Speed of the Components

After the analysis of the various matrices, the most appropriate solution for the proposed work is chosen, as can be seen in Figure 4. This mechanism is shown in its isometric view to give a better visualization of all its components, all designed in Inventor.

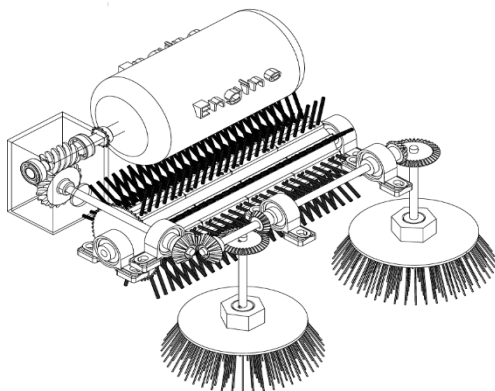


Fig. 4 Diagram of the cleaning system with its mechanical drives

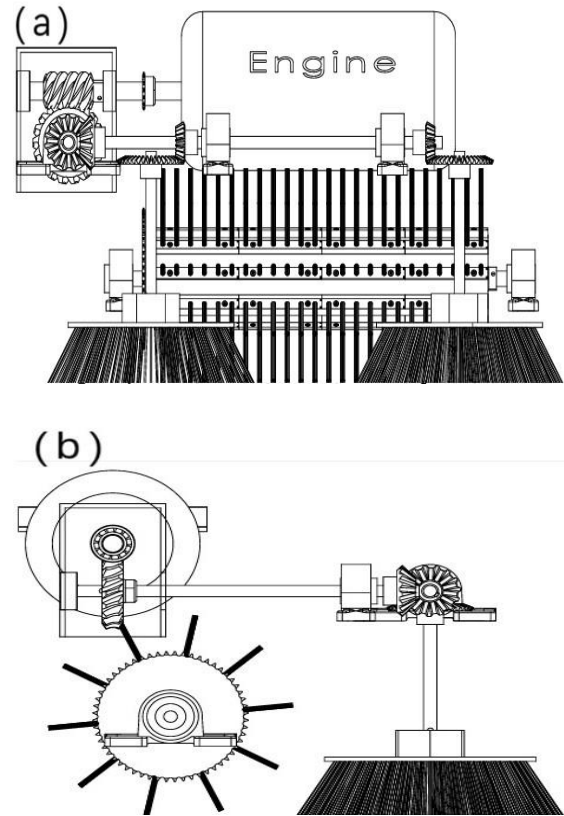


Fig. 5 Mechanical drive diagram, (a)Front view, and (b)Side view.

Our system has two circular brushes that direct the garbage to the middle, and the cylindrical brush is responsible for moving the garbage back to where the warehouse is located. For the analysis, we identify the components and the speed that each of them requires so that the 3 brushes have an adequate speed. These speeds are specified in Table 5.

Table 5. Description and materials of the cleaning system components

Component	Transmission ratio	Exit speed
Pinion (14 tooth) - chain - Crown (56 tooth)	1/4	900
Worm gear - Helical gear	1/4	900
15-tooth straight bevel gear	1/1	900
Straight bevel gear (20 tooth) - Straight bevel gear (40 tooth)	1/2	450

2.5. Static Analysis

Shaft 1 requires high-speed reduction mechanisms; that is why, for the transmission to shaft 2, the worm-screw-crown mechanism is used. However, chain transmission is used to transmit the cylindrical brush so that there is no loss of power. In Figure 6, you can see the mentioned mechanisms.

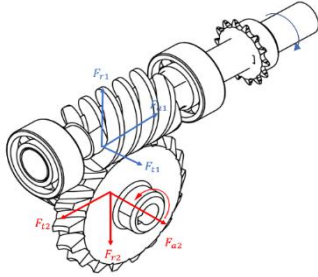


Fig. 6 Diagram of the mechanical drive of shaft 1

For shaft 2, high-speed reduction mechanisms are not required, as in shaft 1, which is why straight bevel gears are used for transmission to axis 3. The aforementioned mechanisms can be seen in Figure 7.

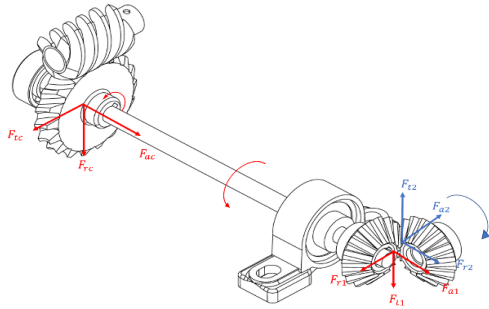


Fig. 7 Diagram of the mechanical drive of shaft 2

For shaft 3, speed reduction mechanisms are required since this transmits to the circular brush axes, which is why straight bevel gears are used for the transmission, but with different numbers of teeth. The aforementioned mechanisms can be seen in Figure 8.

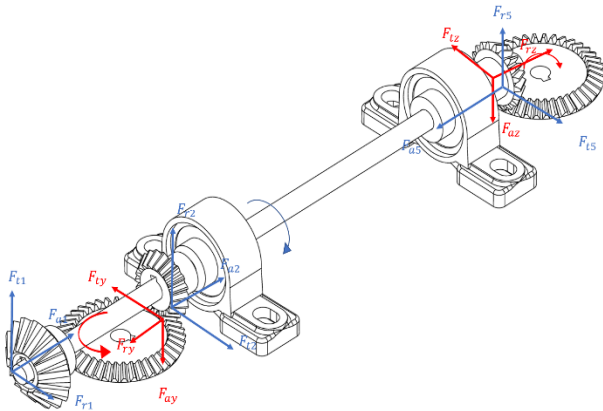


Fig. 8 Diagram of the mechanical drive of shaft 3

2.6. Shaft Sizing

2.6.1. Theoretical Foundations of the Goodman Criterion

The Goodman criterion is one of the most effective methods for fatigue analysis of mechanical components subjected to fluctuating loads. In the specific case of shaft design, the modified Goodman's fundamental equation

establishes a relationship between the alternating and mean stress components, expressed as:

$$\frac{1}{N_f} = \left(\frac{\sigma_m}{S_u} \right) + \left(\frac{\sigma_a}{S_e} \right) \quad (1)$$

Where σ_a represents the alternating stress, σ_m the mean stress, S_e the fatigue limit or resistance strength, S_u the ultimate tensile strength of the material, and N_f the safety factor.

2.6.2. Calculation of Moments and Load Diagrams

The analysis of a shaft begins with determining the reactions at the supports and constructing the shear force and bending moment diagrams. For a shaft subjected to transverse loads, the bending moment at any section is obtained by:

$$M(x) = \int V(x) dx \quad (2)$$

Where $V(x)$ represents the shear force at position x . The bending moments in the horizontal and vertical planes are calculated independently:

$$M_{xy} = \sqrt{M_x^2 + M_y^2} \quad (3)$$

Additionally, the torque diagram represents the distribution of the torsional moment along the axis, characterized by abrupt changes in the points of application of torsional loads.

2.6.3. Calculation of Nominal or Theoretical Stresses

Normal stresses due to bending and shear stresses due to torsion are calculated using the classical equations of mechanics of materials:

$$\sigma = \frac{32M}{\pi d^3} \quad (4)$$

$$\tau = \frac{16T}{\pi d^3} \quad (5)$$

Where σ represents the resultant bending moment, T the torsional moment, and d the shaft diameter. These nominal forces are the basis for determining the alternating and average components that will later be involved in the Goodman criterion. Considering that the shaft is rotating and the stresses

vary with respect to time, it is considered that a fluctuating stress of the pure alternating type acts.

$$\sigma_{xa} = \frac{32M}{\pi d^3}; \sigma_{xm} = 0; \sigma_{ya} = 0; \sigma_{ym} = 0 \quad (6)$$

Regarding the stresses due to torsion, they are considered constant with respect to time.

$$\tau_{xym} = \frac{Txc}{J} = \frac{Txd / 2}{\pi xd^4 / 32} \quad (7)$$

$$\tau_{xym} = \frac{16xT}{\pi xd^3} \quad (8)$$

2.6.4. Calculation of Fatigue Stress Concentration Factors

Stress concentrators (keyways, section changes, slots) locally amplify nominal stresses.

2.6.5. Calculation of Work Efforts

Working stresses consider the effects of stress concentration on nominal values. For a shaft with fluctuating loads, the alternating and mean components must be determined:

$$\sigma_a = K_f \frac{32M_a}{\pi d^3} \quad (9)$$

$$\sigma_m = K_f \frac{32M_m}{\pi d^3} \quad (10)$$

$$\tau_a = \frac{16xT_a}{\pi xd^3} \quad (11)$$

$$\tau_m = \frac{16xT_m}{\pi xd^3} \quad (12)$$

Where the subscripts a and m denote the alternating and mean components, respectively, and K_f is the fatigue stress concentration factor for torsion.

2.6.6. Calculation of Equivalent Stresses

To apply the Goodman criterion, it is necessary to obtain equivalent stresses that combine the effects of normal and shear stresses. Using distortion energy theory (von Mises), the alternating and mean equivalent stresses are calculated as follows:

$$\sigma_a^2 = \sigma_{xa}^2 + \sigma_{ya}^2 - \sigma_{xa} \sigma_{ya} + 3\tau_{ya}^2 \quad (13)$$

$$\sigma_m^2 = \sigma_{xm}^2 + \sigma_{ym}^2 - \sigma_{xm} \sigma_{ym} + 3\tau_{ym}^2 \quad (14)$$

2.6.7. Determining the Correct Fatigue Limit

The corrected fatigue strength limit S_e differs from the theoretical limit S_e' and is calculated by applying modification factors

$$S_e = K_a * K_b * K_c * K_d * K_e * S_e' \quad (15)$$

Where:

K_a = surface finish factor

K_b = size factor

K_c = reliability factor

K_d = temperature factor

K_e = factor of various effects

For steels, the theoretical value S_e' is estimated by

$$S_e' = 0.5S_u \text{ para } S_u \leq 1400 \text{ MPa} \quad (16)$$

Applying the Goodman criterion to the calculated equivalent stresses.

Due to fatigue:

$$\frac{1}{N_f} = \left(\frac{\sigma_m}{S_u} \right) + \left(\frac{\sigma_a}{S_e} \right) \quad (17)$$

Substituting the expressions for a and σ_m then clearing d, the diameter that guarantees a safety factor N_f against fatigue failure is obtained.
By yielding:

$$N_y = \frac{S_y}{(\sigma_m + \sigma_a)} \quad (18)$$

Where S_y represents the yield strength of the material. The final design must satisfy both the fatigue and yield criteria.

3. Results and Discussion

Results and a discussion can be made as a whole, including research findings and explanations.

Shafts

Table 6 identifies the nominal or theoretical stresses in each of the sections of axes 2 and 3 as a function of diameter. Tables 7 and 8 show the stress concentration factors for fatigue in each of the sections of axes 2 and 3. Table 9 shows the working forces in each of the sections of axes 2 and 3 as a function of the diameter that will later be calculated.

Table 6. Nominal or theoretical stresses of axes 2 and 3

Section	Axis 2		Axis 3	
	σ_{xa}	τ_{xym}	σ_{xa}	τ_{xym}
Section 1	0	0	0	$43.188 / d^3$
Section 2	$40922.47733 / d^3$	$45.07766743 / d^3$	$541521.394 / d^3$	$43.188 / d^3$
Section 3	$346543.8227 / d^3$	$45.07766743 / d^3$	$770856.132 / d^3$	$21.594 / d^3$
Section 4	0	$45.07766743 / d^3$	$127562.5649 / d^3$	$21.594 / d^3$
Section 5	-	-	0	$21.594 / d^3$

Table 7. Nominal or theoretical stresses of axes 2 and 3

Section	K_{ff}	K_{ff}	K_{ff}	K_{ff}	Factor Total
1	1	1	1	1	1
2	1	1.6	1.9	1	3.04
3	1	1	1	1	1
4	1	1.6	1.9	1	3.04

Table 8. Nominal or theoretical stresses of axes 2 and 3

Section	K_{ff}	K_{ff}	K_{ff}	K_{ff}	Factor Total
1	1	1.6	1.9	1	3.04
2	1	1.6	1.9	1	3.04
3	1	1	1	1	1
4	1	1	1	1	1
5	1	1.6	1.9	1	3.04

Table 9. Work efforts of axes 2 and 3

Section	Axis 2		Axis 3	
	σ_{xa}	τ_{xym}	σ_{xa}	τ_{xym}
Section 1	0	0	0	$43.188 / d^3$
Section 2	$124404.3311 / d^3$	$45.07766743 / d^3$	$1646225.039 / d^3$	$43.188 / d^3$
Section 3	$346543.8227 / d^3$	$45.07766743 / d^3$	$770856.132 / d^3$	$21.594 / d^3$
Section 4	0	$45.07766743 / d^3$	$127562.5649 / d^3$	$21.594 / d^3$
Section 5	-	-	0	$21.594 / d^3$

The Critical Section of Axis 2

Analyzing it is observed that the critical section is located in the preferred section 3

Axis 2 Section 3 Equivalent Stresses:

$$\sigma_a = 234830.252 / d^3, \quad \tau_m = 78.077 / d^3$$

The Critical Section of Axis 3

Analyzing it is observed that the critical section is located in the preferred section 2

Axis 2 Section 2 Equivalent Stresses:

$$\sigma_a = 1646225.04 / d^3, \quad \tau_m = 74.804 / d^3, \quad S_e' = 250 \text{ MPa}$$

Modification factors were considered for the correct fatigue limit.

$$S_e = K_a * K_b * K_c * K_d * K_e * S_e' = 126.18 \text{ MPa}$$

Shaft Diameter

Table 10. Diameter of axes 2 and 3

	Axis 2		Axis 3	
	Due to fatigue	By creep	Due to fatigue	By creep
Diameter [mm]	11.15	12.55	18.25	20.55

The final design must satisfy both the fatigue and creep criteria. Shaft 2 obtained a diameter of approximately 5/8" inch, and for shaft 3 a diameter of approximately 13/16". Figure 9 shows the results of the simulations made on the axes.

Table 11. Von Mises stress and axis shift

Section	Von Mises tension [N / m ²]	Maximum displacement [mm]
5/8" Shaft	302936896	5.26
13/16" Shaft	133006104	4.19

Figure 10 shows the results of the analysis of the 14 and 56-tooth ladybugs, which are part of the transmission to the cylindrical brush.

Figure 11 shows the results of the analysis of the worm gear and the worm wheel, which are part of the transmission to the circular brush.

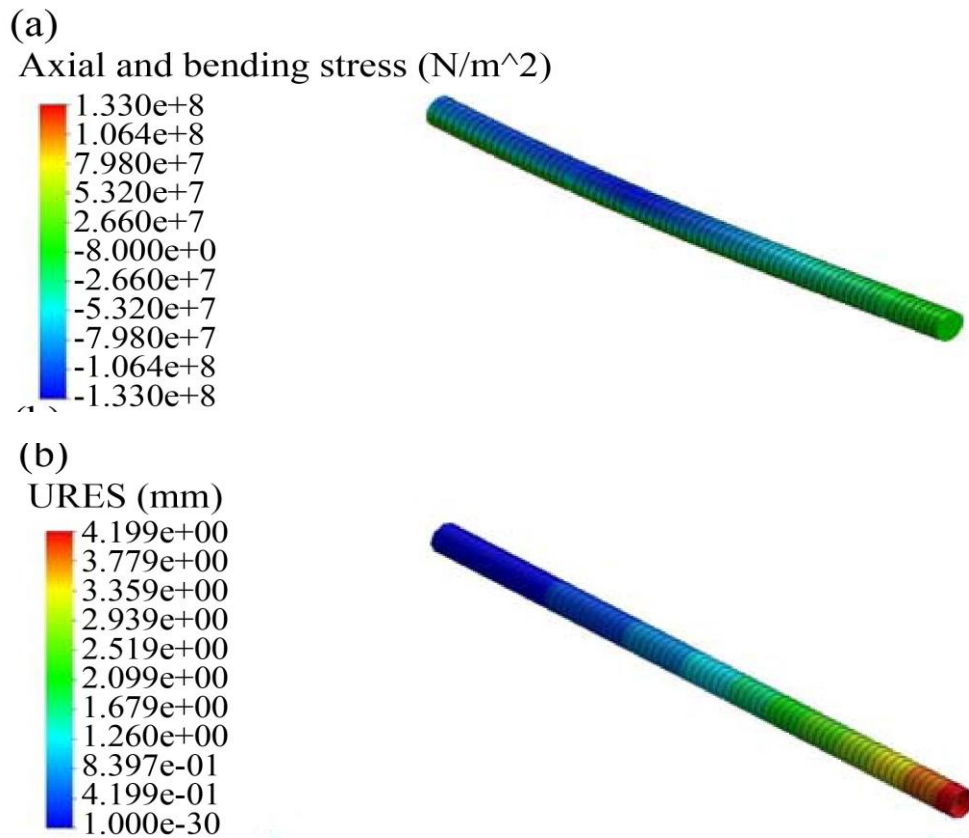
Figure 12 shows the analysis of the 14-tooth spur bevel gear, used on axis 2 to transmit motion to axis 3 without reducing revolutions.

Figure 13 shows the 20 and 40-tooth spur bevel gears, used in the circular brush shaft, which play a crucial role in reducing speed during system operation. Von Mises tension and displacement are analyzed for each of these gears, providing a detailed understanding of the state of stress they experience under load. The 40-tooth gear provides greater speed reduction by offering adaptability to situations that demand more torque and control.

In the simulation, the load conditions are modeled, and the voltage distributions in the components during operation are analyzed. Table 12 contains the results of the analysis to identify critical areas where stress can reach dangerous levels,

ensuring that the design is capable of withstanding the operating loads without compromising structural integrity. The results of the displacement allow us to observe the deformations experienced by the components under the applied loads, identifying possible points of failure or excess flexibility that could affect the operation of the system.

To strengthen the evaluation, a quantitative comparison was performed between the proposed sweeping system, a conventional manual cleaning method, and a previously reported automated model. The proposed design achieved an estimated 25% improvement in sweeping efficiency and a 15% reduction in energy consumption due to the combined use of circular and cylindrical brushes. These findings are consistent with those reported by author, who observed that multi-brush mechanisms and optimized brush positioning significantly enhance debris collection performance. From an urban application perspective, these results indicate that the proposed system can improve cleaning productivity, reduce human exposure to dust, and minimize noise and emissions during street maintenance operations [26]. Such improvements directly contribute to sustainable urban development and cleaner environments in medium-sized cities such as Arequipa, where manual sweeping remains predominant.



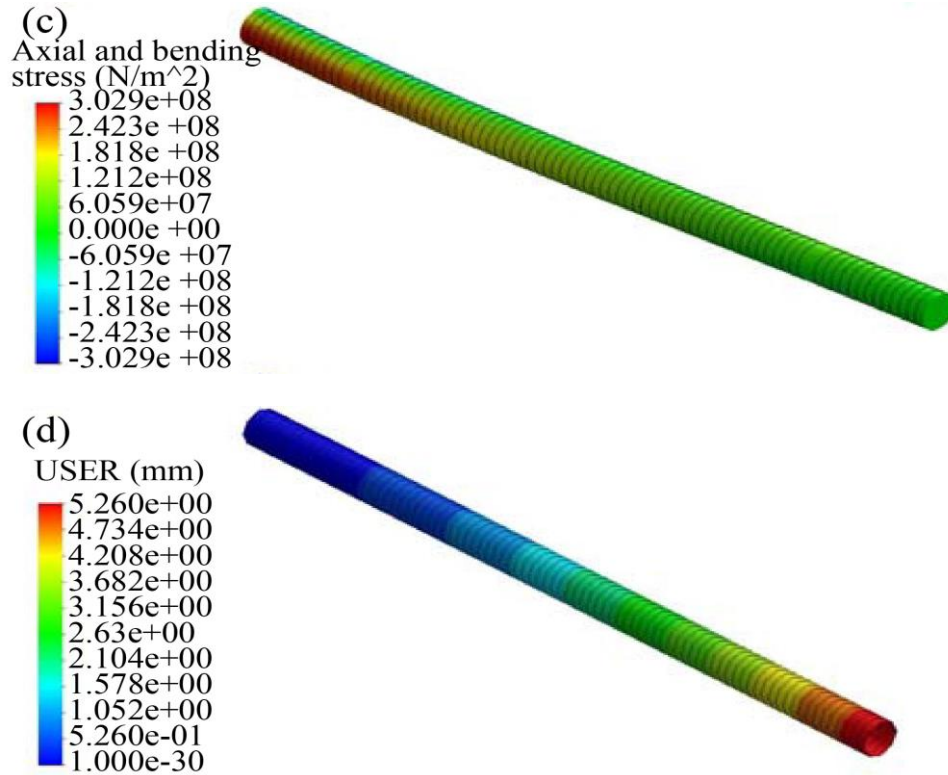


Fig. 9 (a)13/16" Shaft Von Mises Tension, (b)13/16" Shaft Displacement, (c)1/2" Shaft Von Mises Tension, and (d)1/2" Shaft Displacement.

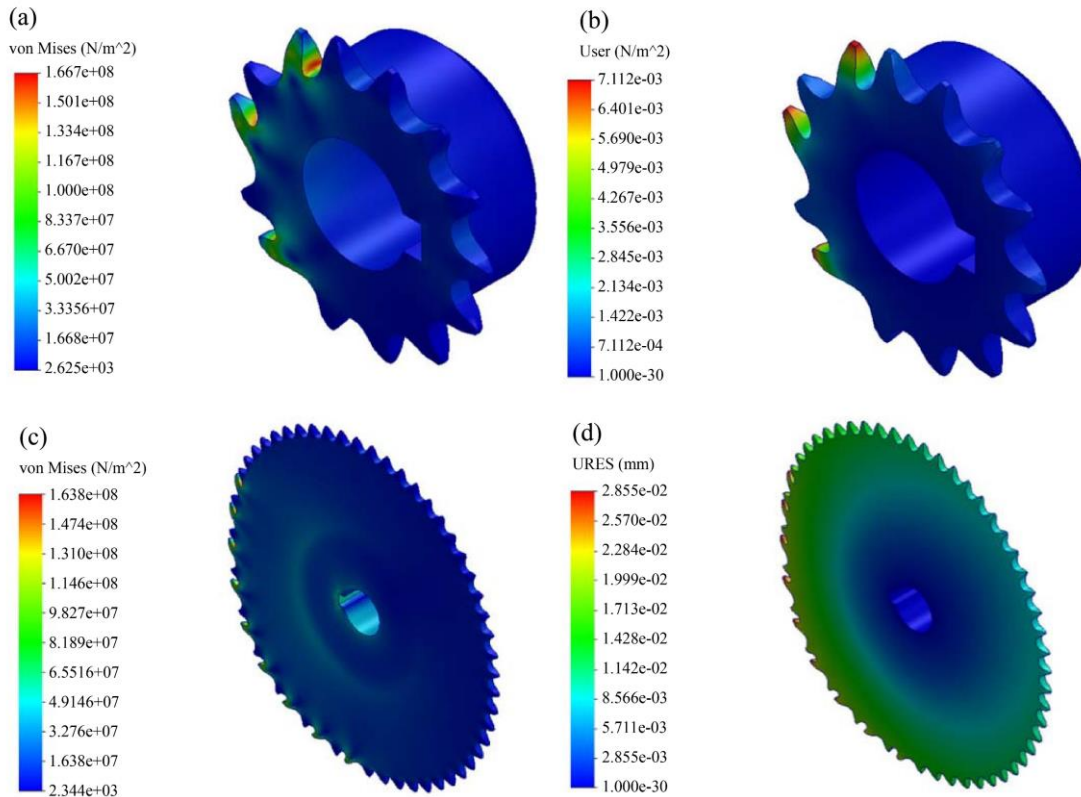


Fig. 10 (a)Von Mises Tension of 14-Tooth Sprocket, (b)Offset of 14-Tooth Sprocket, (c)Von Mises Tension of 56-Tooth Sprocket, and (d)Offset of 56-Tooth Sprocket.

Table 12. Von Mises Stress and Displacement of Transmission System Components

Component	Von Mises tension [N / m^2]	Maximum displacement [mm]
Pinion (14 tooth)	166735824.00	0.00711242
Crown (56 tooth)	163782720.00	0.028553043
Worm gear	6442448.50	0.000751018
15-tooth straight bevel gear	27955754.00	0.002402417
Straight bevel gear (20 tooth)	36570992.00	0.002337811
Straight bevel gear (40 tooth)	51807048.00	0.00135837

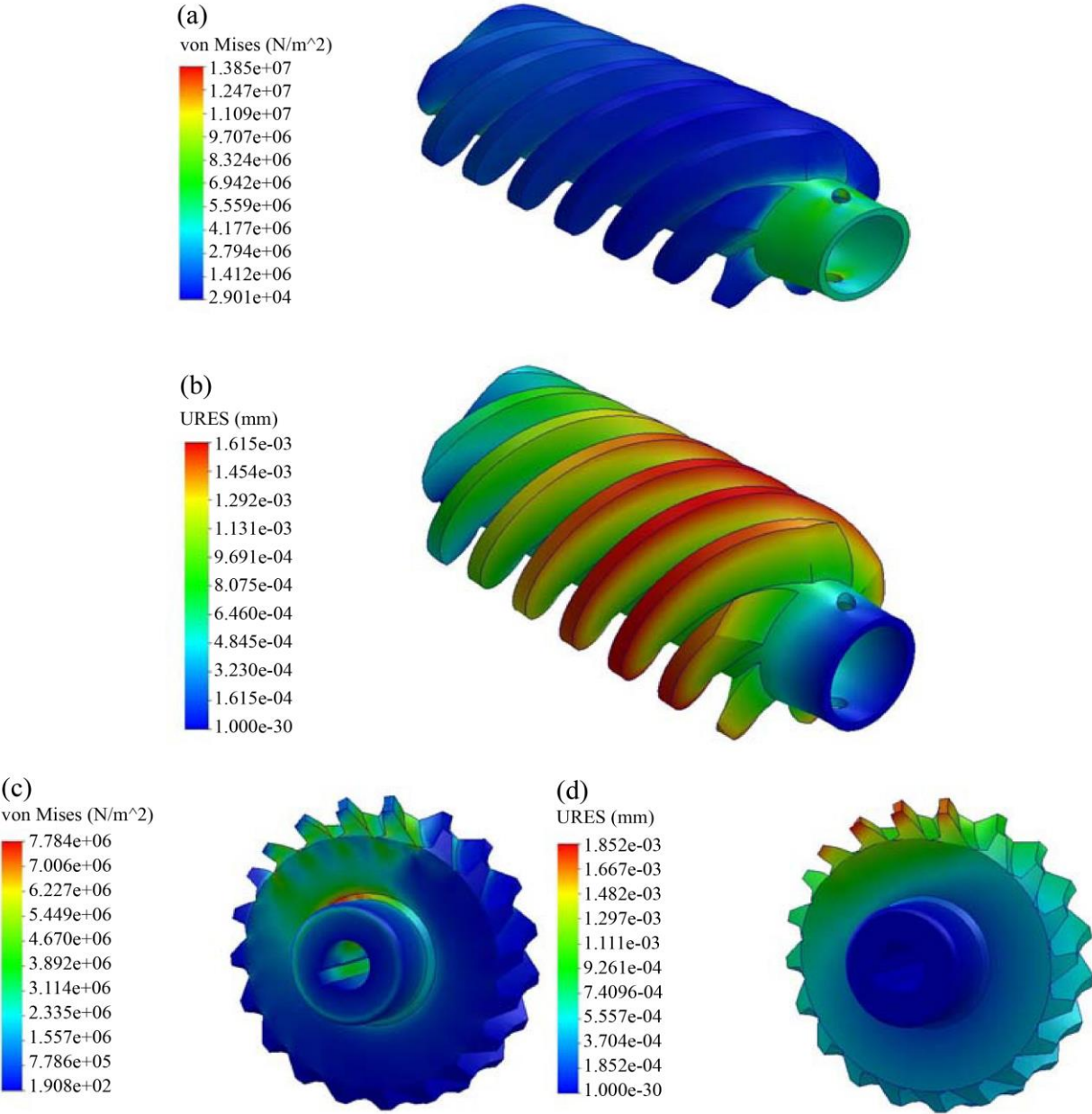


Fig. 11 (a)Worm screw von Mises tension, (b)Worm screw displacement, (c)Von Mises tension of the worm gear, and (d)Helical gear displacement.

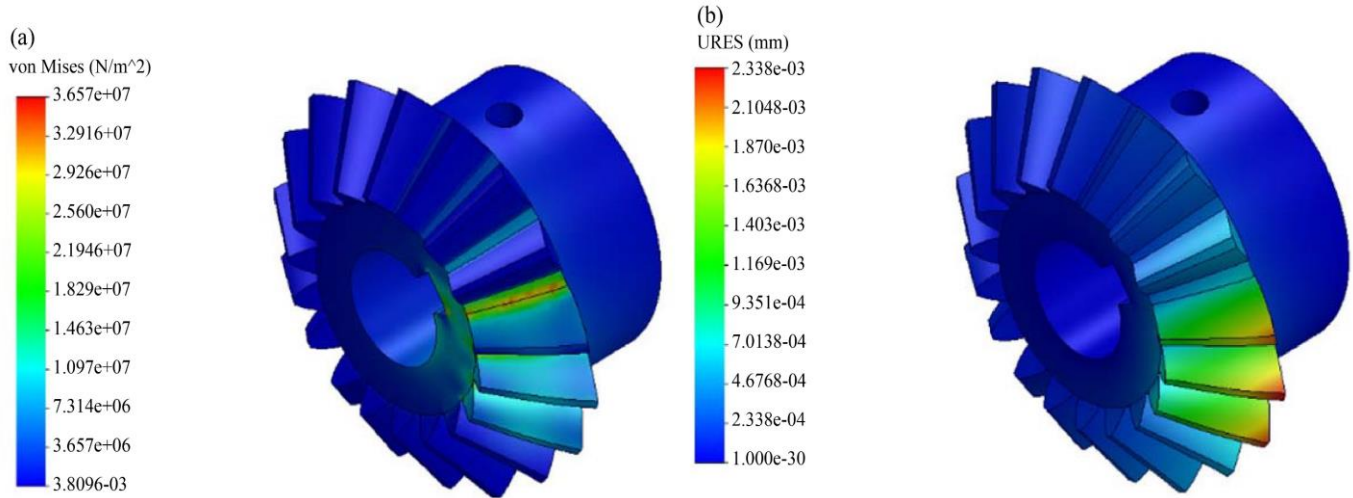


Fig. 12 (a) Von Mises Tension of 15 Teeth Spur Bevel Gear, and (b) Displacement of 15 Teeth Spur Bevel Gear.

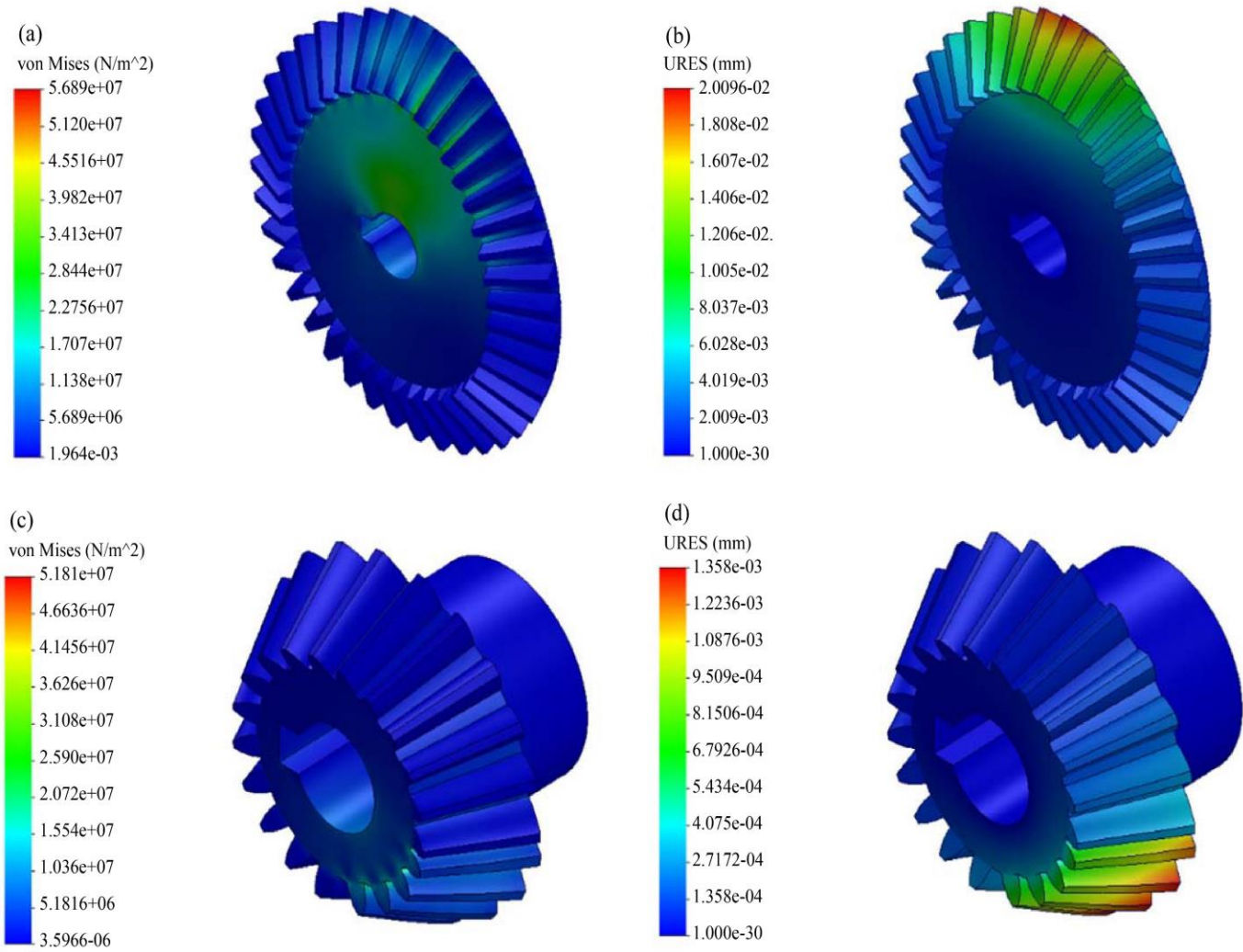


Fig. 13 (a) Von Mises tension of the 50-tooth spur bevel gear, (b) 40-tooth spur bevel gear displacement, (c) Von Mises tension 20-tooth spur bevel gear, and (d) 25-tooth spur bevel gear displacement.

The simulations performed for the various components of the drive system have provided a comprehensive view of the mechanical behavior under specific loading conditions. The von Mises stress analysis, as well as studies on displacements and safety factors, have allowed us to identify critical areas and optimize the design to ensure the robustness and durability of the components. All this helps us to ensure the efficient and safe operation of the circular brush system, especially in terms of speed reduction, which is required to maximize the effectiveness of the cleaning process. Based on these results, improvements can be implemented and informed decisions can be made to improve the overall performance of the system, ensuring long life and reliable operation.

3.1. Comparison with Other Cleaning Systems using the VDI 2225 Standard

In this section, a comparison is made between the conventional cleaning method in Arequipa, with the garbage collection machine (TCM) system, and with the Brush Sweeping System (BSS) proposed in this article. Using VDI 2225 to compare and evaluate conventional, TCM, and BSS cleaning.

3.1.1. Description of Conventional Cleaning

The number of people involved in this task varies from year to year, but about 200 people are in charge of this work, which begins with the collection of larger solid waste, to continue with the sweeping of smaller waste and dust accumulated on the roads of the city where they use straw brooms and appropriate clothing for this type of area and work, along with masks, appropriate shoes, gloves and hat. Cleaning on Arequipa's roads can vary, for example, on roads where there are many vehicles, safety cones should be placed to protect the well-being of the cleaning personnel. Also, in some areas with high levels of waste contamination, such as the historic center of Arequipa, a disinfection process must be carried out using tanker trucks for the proper cleaning of these places, since they generate a bad smell and can lead to diseases.

3.1.2. Description of TCM Cleaning

This machine is towed to the place where its services are needed, to then use its dragging mechanism, where the waste is swept from the tracks to the mechanism's conveyor belt, which in turn transports the waste to a container located at the back of the mechanism.

3.1.3. Description of Cleaning with BSS

This innovative mechanism is constituted by 2 circular brushes on the sides that will serve for the garbage located on the side of the robot to be taken to the central part where there is a cylindrical brush which will direct the waste to a container that will be located at the back of the robot, these lateral cylindrical brushes will also serve so that the waste that is inside small channels or sinks of the tracks can be cleaned by this mechanism.

3.1.4. Evaluation of the Mechanism with BSS

Several indicators of the technical evaluation are analyzed, and some more indicators are added as needed for a good analysis. All the indicators shown will be evaluated and weighted in a qualitative way from 1 to 5 (g) according to the importance of the indicator, also a score is used in relation to the VDI 2225 scale that goes from 1 to 4 (p), all this in order to find the most appropriate cleaning method, all this represented in Table 13, these indicators will be presented below with a brief description and explanation of the reason for each score.

Sweeping Efficiency

This indicator tells us how effective the mechanism is at removing debris from the roads. For this indicator, a weighting of 5 in g is given since it is an important parameter. For p in conventional cleaning a score of 2 is given because a single person covers little cleaning space, and cleans little waste in a given time, but sometimes there is more than one person cleaning the tracks, TCM will be given 3 and SS will be given an efficiency of 4 given that this mechanism can clean large waste, can access waste in places that are difficult to clean such as channels or small holes in the tracks and this mechanism works alone and does not need a broom to be able to clean the waste. The mechanism works alone and does not need a broom to clean up the debris.

Collection Capacity

This indicator gives us understand the amount of waste that the mechanism can collect in one cycle. It is given a g-weighting of 4 since it is not as important as the previous indicator, but still retains its degree of importance. For "p", conventional cleaning is given a score of 1 as the dustbins are very small and every now and then people have to go to a larger container and deposit the waste. In the case of the TCM and the BSS, they are designed to have a container somewhere on the robot and deposit the waste there, but the TCM has better collection capacity than the BSS, because its corrugated conveyor belt is larger, so it will be given 4 and 3 points, respectively.

Time x Working Area

This indicator tells us how long it takes to clean a certain area of the roads. For the weighting g, we give 5, because it is an important aspect in the cleaning process. For the "p", we are going to give an evaluation that is not as it really is, but that is very close to it, because there are many external factors in each area that can affect the work time, such as breaks, the capacity of the person, accidents, or other inconveniences that occur in the work area.

Therefore, for conventional cleaning a score of 1 will be given because only 1 person covers very little area in a given time, although sometimes there is more than 1 person in a given area, for the TCM, which has a mechanism that makes the area it covers larger, a score of 4 will be given, and for the

BSS, which has less cleaning area but this is rewarded with the higher speed of its brushes, even so a score of 3 will be given.

Versatility of the Cleaning System

This indicator shows whether the mechanism is able to adapt to any work environment, such as irregularities in the roads or different types and sizes of waste. In the roads of Arequipa, there are many irregularities and various sizes and types of waste, hence the importance of this indicator, which is placed with a weighting g of 5. For the “p”, it is known that the 3 types of systems can collect waste of any type and sizes larger than dust, so it will take more into consideration if the mechanism is able to work on various types of surfaces or irregularities in them. It is seen that the conventional cleaning is able to adapt to any terrain or adversity, leaving aside its safety (this indicator will be evaluated later), that is why it is given a score of 4, for the TCM it is given a score of 3 and for the BSS seeing that its side brushes are appropriate for cases where irregularities are present, due to the fact that this mechanism is designed and its side brushes are correctly positioned for this time of terrains, that is why it is given the maximum score of 4.

Security

This indicator tells us the state in which a person is protected against risks or damages during road cleaning activities, understood as risks or damages to possible collisions with cars on the roads, ergonomic positions, extreme fatigue, and solar radiation, all of which can affect people's health. For all these reasons, a “p” score of 2 is given to conventional cleaning, despite having PPEs, hats, and safety cones for vehicles in transit, they are exposed to many dangers. Both TCM and BSS are given a score of 4, as these mechanisms are designed to mitigate these hazards. This

indicator is given a g-weighting of 5 since safety is the most important and the main reason we want to keep it in this article.

Simplicity of Design

This indicator tells us the simplicity of the mechanism to be able to clean the tracks with the same efficiency, this helps us to spend less inputs and money to manufacture the mechanism, as well as reduces the complication at the time of being used the cleaning mechanisms. A weighting g of 4 is given since the manufacturing part is important. For p, the conventional cleaning will be given a score of 3 since it does not have to manufacture anything, and only the cleaning workers have to be paid. However, it cleans less than a mechanism. For the TCM, it is given a score of 2. Even though its design is very interesting, it is very difficult to manufacture; on the other hand, the mechanism with 3 brushes is efficient. A simple mechanism to manufacture, which is why it is given a score of 4.

Energy and Noise Reduction

This indicator shows the energy consumption required by their cleaning mechanisms and the annoying noise they can generate. A g weighting of 4 will be given because lower energy consumption is important in several aspects, such as cost, efficiency, and environmental impact, but is not indispensable; noise is important. For conventional cleaning, a “p” score of 3 is given, since it requires physical energy and people get tired quickly, but it does not make as much noise as a mechanism. For the TCM a score of 4 is given, given that between its dragging mechanism and its conveyor belt it uses 2 motors each of 1HP, which consume little energy with respect to the BSS, which will be given a score of 3 given that its entire mechanism is driven by a single 2.5HP motor that consumes 1.865 kW and makes more noise due to the brushes.

Table 13. Technical evaluation of VDI 2225

Project Variants		Conventional cleaning		TCM		BSS		Ideal Solution	
Technical Criteria	g	p	gp	p	gp	p	gp	p	gp
Sweeping Efficiency	5	2	10	3	15	4	20	4	20
Collection capacity	4	1	4	4	16	3	12	4	16
Time x working area	5	1	5	4	20	3	15	4	20
Versatility of the cleaning system	5	4	20	3	15	4	20	4	20
Security	5	2	10	4	20	4	20	4	20
Simplicity of design	4	3	12	2	8	4	16	4	16
Energy and noise reduction	4	3	12	4	16	3	12	4	16
Maintenance	4	4	16	2	8	3	12	4	16
Maximum Score	36	19	85	25	114	29	131	32	144
Technical Value		0.63	0.62	0.81	0.82	0.88	0.88	1	1

Maintenance

This indicator tells us which mechanism needs more maintenance, which would therefore incur more costs, downtime, and replacement of parts. It is given a g-weighting of 4 because it is not indispensable. For conventional cleaning, we will give it a “p” score of 4 because its brooms, dustpans, or tanks rarely need maintenance or replacement. The TCM is given a score of 2 because it has a conveyor belt that is more prone to failures that increase in these dust environments, and therefore, more maintenance is needed the BSS will be put in the middle ground with a score of 3 since its mechanisms do not need as much maintenance as the TCM but need more maintenance than the conventional cleaning items. From a sustainability perspective, the proposed sweeping system contributes to environmental and social benefits. By integrating electric-driven mechanisms and efficient brush configurations, the system reduces energy consumption and minimizes dust re-suspension during operation. The use of durable materials such as A36 steel and nylon extends the service life of the equipment, lowering maintenance frequency and material waste. Furthermore, automating street cleaning reduces worker exposure to harmful particles and extreme weather, improving occupational safety. Overall, the system supports the development of cleaner, safer, and more sustainable urban environments, particularly in medium-sized cities where waste management resources are limited.

4. Conclusion

The development of an innovative cleaning system, based on a cleaning vehicle that integrates circular and cylindrical

wiper blades, provides an effective solution to address the debris problem on Arequipa's roads, where traditional methods have proven to be insufficient. Through Ganesan and Esakki's systematic design approach, various subsystems and vehicle components were identified and evaluated, ensuring that each technical choice was based on criteria of functionality, efficiency, and economic feasibility. Simulations of von Mises stress, displacement, and safety factors supported the robustness of the design, evidencing the system's ability to operate under various loading conditions in an urban environment. Through benchmarking using VDI 2225, key indicators were identified that highlight the advantages of the proposed sweeping system compared to conventional cleaning and the TCM mechanism.

A marked improvement in sweeping efficiency, collection capacity, and system versatility was highlighted, key factors for effective performance under varying working conditions. The design of the BSS promotes not only greater efficiency in cleaning debris, including debris in hard-to-reach locations, but also incorporates safety considerations, minimizing personnel exposure to hazards associated with working on the tracks. The choice of materials, such as A36 steel and nylon, ensures the robot's durability against adverse conditions, while the simplicity of the design ensures its economic viability and ease of manufacture.

Acknowledgements

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