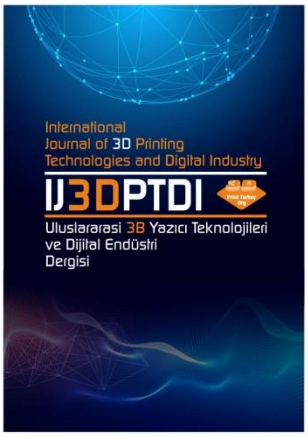

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DESIGN AND MANUFACTURING OF A TWO-STAGE REDUCTION GEARBOX WITH 3D PRINTERS

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ABSTRACT

3D printers, which have been used in recent years, enable the conversion of a digital model into a physical 3D object by placing the filament material layer by layer and can help a wide variety of industries. Digital models can be created using software such as Solidworks and Catia or data created by a 3D scanner. This study designed all parts of a two-stage reducer gearbox consisting of spur and helical gear pairs. The torques are calculated according to the input power. Shafts that can transmit torques are designed. Gear wheels were calculated according to the total reduction ratio and were designed to transmit torques. CAD software (Solidworks) designed the gearbox parts, assembled them, and simulated them. Thus a digital model has been created. CAD models were transferred to the 3D printer. The slicing was done precisely using Cura software. On the other hand, the Marlin software reads the G codes created with Cura software sent from the computer. PLA (Polylactic Acid) was used as the filament material. The digital model, in other words, the CAD assembly, has been checked with Solidworks simulation. It has been seen that the gears work in harmony with each other, and the shafts turn smoothly. On the other hand, the model produced with a 3D printer was checked by applying torque to the input shaft on a small lathe spindle. The tachometer was used to measure rotational revolutions. It was seen that the gears and shafts worked smoothly. Gearboxes made of PLA work silently, do not require lubrication with industrial machine oil, and are clean. PLA material is a plant-based plastic that is not harmful to human health.

Keywords: Gearbox, PLA Material, 3D printing, CAD, Additive Manufacturing.

1. INTRODUCTION

Gear systems used to reduce the input rotation speed to the desired output rotation speed in places where the rotational movement taken from the motor is higher than the need is called reducer. Gearboxes are independent elements added to the needed system.

Gearboxes can be used wherever there is force and movement. Walking grates, pumps, machine tools, elevators, cranes, textile machinery, sheet bending machines, rams, rotary drums, conveyors, etc. They are used where there are many rotational movements. Various designs are available, manufactured in different torque and sizes.

It is crucial to create a hygienic environment in the food, beverage, food industry, chemical, and pharmaceutical industries and sensitive product areas. In most cases, the climate should be completely free of bacteria. Machine lubricating oils are also harmful to human health. This problem has been solved with hygienic type special gear motors and gearboxes.

Previous studies investigated the effects of nozzle temperature and filler density on the mechanical properties of structures produced with polylactic acid (PLA), one of the commonly used 3D Printer materials. These studies evaluated three-dimensional printer product structures regarding mechanical properties, production time, and cost [1]. The gearbox of a belt conveyor carrying coal and operating in dusty environments in a thermal power plant has been investigated. The causes and solutions of significant faults in such gearboxes are explained [2]. Another study created a bolt and nut model using Solidworks software. Precise slicing was done using Cura software on the three-dimensional printer and directed to the print. PLA and ABS were used as printing materials [3]. The mechanical properties of the samples produced as layers from PLA and TPU materials were investigated. Tensile and compression tests were applied to the samples prepared with 20%, 60%, and 100% filling percentages.

1.1. Nomenclature

List of symbols.

P_1	(kW)	Input power
P_2	(kW)	Output power
n_1	(rpm)	Input speed
n_4	(rpm)	Output speed
i_T	(-)	Total reduction ratio
i_{12}	(-)	Reduction ratio between first and second gears
i_{34}	(-)	Reduction ratio between third and fourth gears
z	(-)	Number of teeth
η_t	(-)	The efficiency of the system
d_0	(mm)	Section circle diameter
m	(mm)	Module
m_n	(mm)	Normal module for helical gears
m_t	(mm)	Transverse module
M_t	(Nm)	Torque
s	(-)	Safety factor
d	(mm)	Shaft diameter

List of abbreviations

CAD	Computer-Aided Design
3D Printing	Three-Dimensional Printing
STL	Stereolithography
SD Card	Secure Digital Memory Card

It was observed that sample sizes and filler percentage significantly affect mechanical performance. Filling percentages are essential for designers using mechanical loading applications [4]. A single-stage reduction gearbox has been outlined. The gears, shafts, and gearbox casing have been optimized [5]. In this study, several simple CAD systems are examined. Thus, technical and economic criteria were evaluated. It has been shown how the designed models can be used in 3D printing. This work illustrates the possibilities and limitations that can be expected when using simple CAD systems. [6]. This study gives general information about 3D printing techniques, classification, materials used, and applications in various industries [7]. This article examines the wide variety of materials applied in 3D printing. The article also describes the applications of 3D printed products made of different materials and the different processes of 3D techniques. Advice has been given to people who will work on 3D printing. A study has emerged that will be useful to people who are interested in 3D printing [8]. This article is an experimental study of a Ganesh idol demonstrating its critical benefits such as additive manufacturing or 3D printing, rapid prototyping, flexible design, and waste minimization. Therefore, this article provides an overview of 3D printing and a survey. There are applications and information about how fast 3D printing technology is developing and globally focused research results [9]. Here the author reviews several standard simple CAD systems. Thus, he examined the technical and economic criteria. It also showed how models designed in this way could be used in 3D printing. This is a case study. It shows the possibilities and limitations of using basic CAD systems [10]. The author; First, three geometric models of rectangular, oblong, and ellipse are used at different nozzle distances and scan speeds. Then, using these geometric models, it created three new G-code programs for manufacturing. The difference between the CAD model and the oblong model showed that the oblong model is a better choice for controlled 3D printing of microchannels [11]. This article presents four new sabotage attacks for fused filament fabrication (FFF) based 3D printing: (1) spacing via filament kinetics, (2) density variation via filament state, (3) density variation via filament velocity, and (4) dynamic thermal manipulations were examined. In this study, small attacks that are difficult to detect are examined [12].

In this study, the top cover design and prototype production of a carpet washing machine was made. It aims to make a design change on the upper part of the device to increase export sales and produce a new model product at a low cost. For this purpose, three different designs were made. A design was selected by applying concept tracking/scoring matrices to the designs. A prototype of the selected design has been produced, aiming to make controls on the prototypes [18]. In this study, autonomous underwater vehicle design and application were carried out using 3D printing technology. The shell design of the autonomous underwater robot was carried out by observing creatures with high maneuverability underwater, and Computational Fluid Dynamics analyzes were carried out. After the shell design and manufacturing were completed, the propulsion system and electronic equipment were completed, and the physical structure of the autonomous underwater vehicle was completed [19]. In this study, high flame appearances of firearms, especially in night use, were investigated. The model to be developed was designed with SolidWorks, and internal airflow analyses were made with Solidflow. The prototype of a previously produced model was reproduced with a three-dimensional printer. The new design aims to increase night vision and conceal the wearer's position by minimizing the appearance of flame after a muzzle blast [20]. These studies aim to reduce the noise caused by gears in automobile transmissions. The geometric design parameters of the gearbox were optimized [21], [22]. The Real Coded Genetic Algorithm (RCGA) has been applied to obtain the optimum helical gear design. In this study, the volume of a helical gear pair is minimized by including the module, face width, and the number of teeth, as well as the profile shift coefficients as design variables using RCGA [23]. It is a review article and aims to provide an overview of the studies on gear optimization, as well as to summarize the results obtained by other researchers and to formalize the gear optimization process [24]. In this study, the author made multi-objective Optimization of the gear train design to improve efficiency and transmission error. It has realized the multi-purpose Optimization of the gear unit with a multi-scale approach from the gear main idea to the complete transmission. A genetic algorithm technique called Non-Dominant Sequence Genetic Algorithm II (NSGA-II) was used in the Optimization [25]. This study evaluated the effects of gear addendum and dedendum on the optimization results for gear macro geometry design. Gear mass, efficiency, and transmission errors were considered objective functions for Optimization. Optimization results were normalized to min-max, and mean values of total scores were compared [26]. This study presents a method for calculating root and contact stresses for metal, spur, and helical gears. The results are verified by finite element calculations [27]. In this study, the macro geometry of a helical gear pair is optimized for low weight, high efficacy, and low noise; Furthermore, optimal solution trends were analyzed for five combinations of the three goals [28]. This study investigated the effects of helix angle, mechanical errors, and coefficient of friction on the time-varying tooth-root stress of helical gears [29]. This work is a platform for 3D printers, additive manufacturing, and 3D printed structures of the future [30]. This study developed a new composite filament that can be used in low-cost 3D printers to produce complex ceramic shapes [31]. In this article, a study was carried out on optimizing effective design parameters for a five-speed automotive gearbox. During the Optimization, the tooth-bending stress was taken as the objective function [32].

2. GEAR DESIGN

2.1. Material Selection

PLA filament is a 3D printer material. PLA (Polylactic Acid) is a plant-based and biodegradable plastic. PLA is plastic produced from products such as corn starch and sugar cane. Since PLA is produced from organic materials, PLA filament is not harmful to human health.

In Figure 1, stress-strain curves of PLA material according to different filling densities. Table 1 shows the attributes and values of PLA filament.

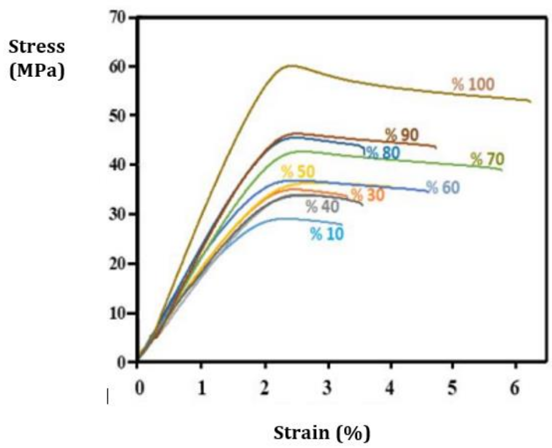


Figure 1. PLA material stress-strain values according to different filling densities [1]

Table 1. PLA material mechanical properties

Parameter	Attributes and values
Density	1.3 g/cm^3
Young's modulus	3.5 GPa
Elongation limit	6.0 %
Specific strength	38 kN-m/kg
Ultimate tensile strength	50 MPa
Shear modulus	2.4 GPa

2.2. Filament Consumption During Printing

Low filling density can be preferred in applications that require fast production and lightweight. On the other hand, high filler density could be preferred in cases where high-impact strength and flexibility are significant. (Table 2).

Table 2. PLA material filling ratios tensile stress.

Parts	PLA filling density %	PLA tensile stress MPa	Filling pattern
1st gear	60	36	grid
2nd gear	60	36	grid
3rd gear	60	36	grid
4th gear	60	36	grid
1st shaft	80	45	grid
2nd shaft	80	45	grid
3rd shaft	80	45	grid
Lover case	20	30	line
Upper case	20	30	grid

2.3. Gear Calculations

The design data was determined according to the stress values of the PLA material.

Input power P_1 is 0.3 kW, and the input revolution speed n_1=800 rpm. The total reduction ratio is i_T= 20.

The total reduction ratio,

$$i_T = \frac{n_1}{n_4} \tag{1}$$

$$i_T = i_{12} \cdot i_{34} \tag{2}$$

Reduction ratio between first and second gears,

$$i_{12} \cong 1.2\sqrt{i_T} \tag{3}$$

$$i_{12} = \frac{n_1}{n_2} = \frac{z_2}{z_1} \tag{4}$$

Reduction ratio between third and fourth gears,

$$i_{34} = \frac{n_2}{n_3} = \frac{z_4}{z_3} \tag{5}$$

Output power and total efficiency,

$$P_2 = P_1 \cdot \eta_t \tag{6}$$

Pitch circle diameter of spur gears,

$$d_0 = m\, z \tag{7}$$

Transverse module,

$$m_t = \frac{m_n}{Cos\beta} \tag{8}$$

Pitch circle diameter of helical gears,

$$d_0 = m_t\, z \tag{9}$$

Torque,

$$M_t = 9550\frac{P_1}{n_1} \tag{10}$$

In this gearbox, the input speed is the speed of the first shaft and the output speed is the speed of the third shaft. The pressure angle between cooperating gears is taken as α=20^o, and the helix angle in helical gears is taken as β=15^o. The calculated values of the gears are given in Table (3).

Table 3. Gear calculations.

Gear number	Type	Number of teeth, z	Module m, mt (mm)	Pitch circle d_0, (mm)	Face width, b (mm)
1	spur	15	1.25	18.75	10
2	spur	81	1.25	101.25	10
3	helical	18	1.75	31.50	15
4	helical	67	1.75	117.25	15

2.4. Shaft Calculations

Shafts are machine elements used in power and motion transmission. The shafts in this study are rod elements of circular cross section and enable the gears on them to rotate. They are forced by torsional and bending stresses due to the gear forces that occur depending on the input speed and torque.

$$\tau_{te} = \frac{M_t}{W_t} \tag{11}$$

τ_{te} is the torsion stress as (N/mm^2), M_t is the torsion moment as (Nmm), and W_t is the bending strength moment as (mm^3).

$$M_t = 9.55.10^6\ \frac{P}{n} \tag{12}$$

P is the power as (kW), and n is the number of shaft revolutions as (rpm).

$$W_t = \frac{\pi d^3}{16} \tag{13}$$

The maximum bending stress (σ_{max}) took as 45 MPa.

$$\sigma_e = \frac{\sigma_{max}}{s} \tag{14}$$

σ_e is the safe stress, s is the safety factor, and s= 1.2 is chosen. The shaft diameter calculates as follows.

$$d = \sqrt[3]{\frac{32 \quad M_t}{\pi \ \sigma_e}} \tag{15}$$

Table 4. Calculated values of shafts

Shaft number	Number of revolutions, n (rpm)	Torques, M_t (Nm)	Shaft diameters, d mm
1	800	3.581	11
2	149	19.228	18
3	40	74.645	28

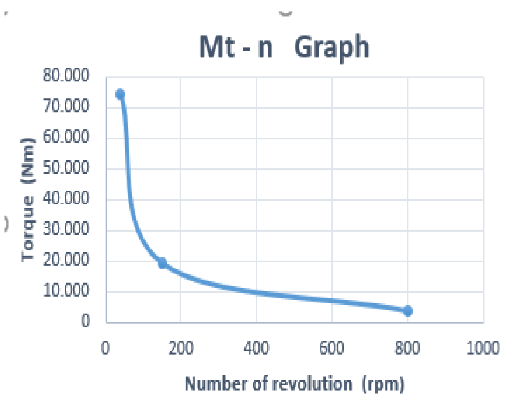


Figure 2. Torque-number of revolution diagram

The number of revolutions in Table 3 is calculated from equations (1), (4), (5), torques are calculated from equation (10), and shaft diameters are calculated from equation (15). During operation, radial and tangential forces occur in the gears. These forces are usually calculated in the 2D plane. These are transmitted to the rolling shaft bearings as a reaction force. In this way, bending moments occur in the shafts. This study calculated bending moments for each of the three shafts. The sections dangerous against breakage were depicted. The locations and diameters of the steps on the shafts were determined. At all stages of calculations, toot bending stresses and toot contact stresses are considered.

In order to make gear strength calculations, basic calculations, and geometric measurements must be made and known. If these values are changed due to strength calculations, the calculations are made again with new values. Strength calculations are iteration on the one hand and vicious circle calculations on the other. The processes continue until the calculations and measurements match each other. This study is used in the ISO 6336 standard for strength and dynamic calculations. Especially in the calculations of bending stresses and gear contact stresses. Although we take ISO 6336 as a guide in this study, it has always been considered that the material we use is Poly Lactic Acid. In order to prevent tooth root fractures filling ratio of PLA material is kept high, and the tightest fill pattern is used.

3. CAD MODELLING

Solidworks, a CAD software, is used in various industries for product designs. It provides a fast, economic and efficient study. In this study according to the calculated measurements, shafts, keys, and upper and lower casings were drawn with Solidworks software. Spur and helical gears, ball bearings, bolts, screws, and nuts were created according to ANSI metric standards in the design library in Solidworks software.

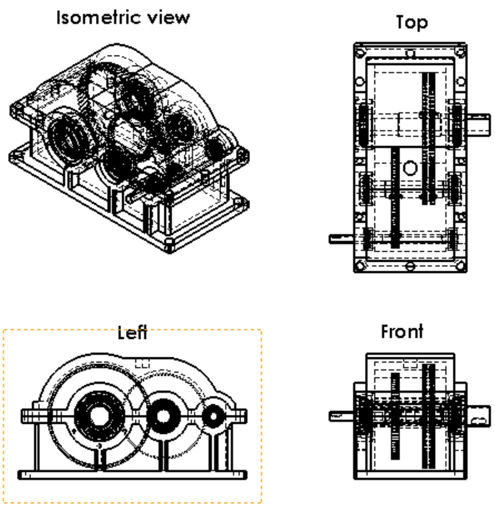


Figure 3. Reducer gearbox assembly modelling

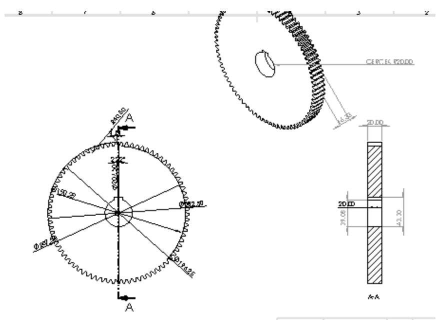


Figure 4. An example of a dimensional part.

4. PRINTING

Cura software is a three-dimensional slicing program. In this study, the STL file format was used in Cura software. On the other hand, the Marlin software reads the G codes created with Cura software sent from the computer and provides the printer's control.

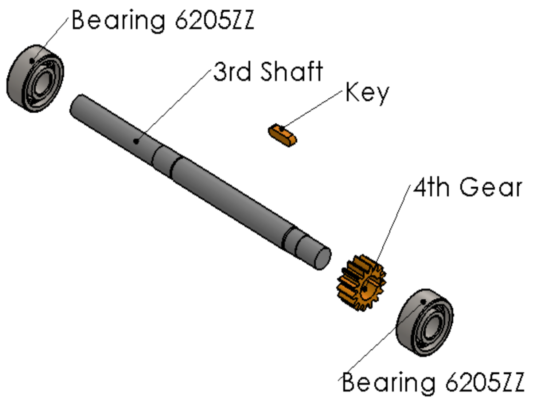


Figure 5. CAD modelling of the first shaft

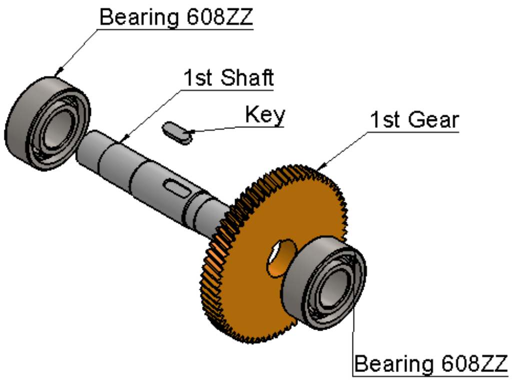


Figure 6. CAD modeling of the intermediate shaft.

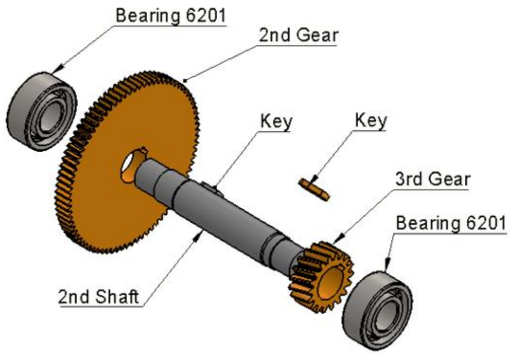
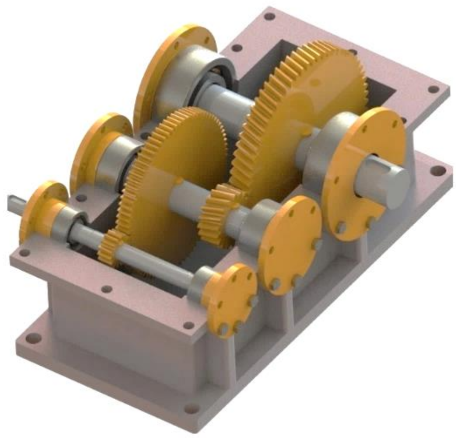
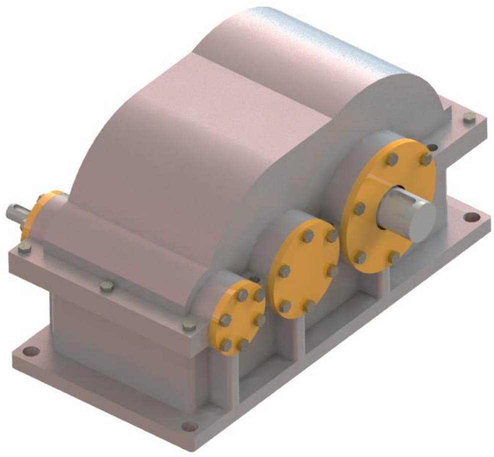


Figure 7. CAD modeling of the output shaft.



(a)



(b)

Figure 8. (a), (b) CAD modeling of the gearbox.

This study converts each part drawn with CAD software to STL format. The part to be produced was extruded along the z-axis. The printing parameters in Table 6. were entered for this study. After the printing parameters, the slicing software was started. The slicer software converted the STL file and printing parameters into G-codes and sent them to the printer control software.

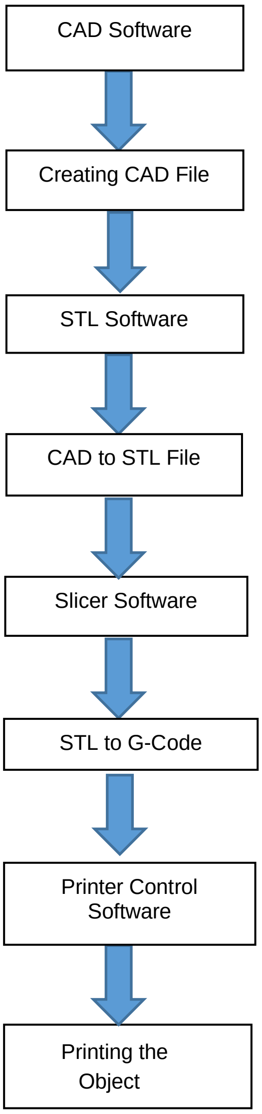
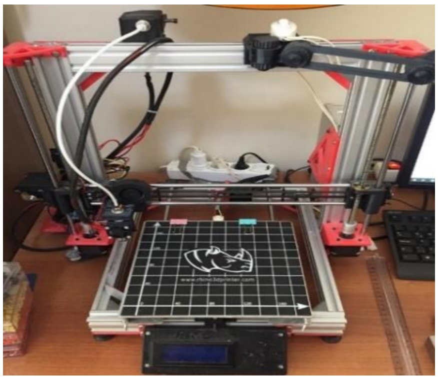
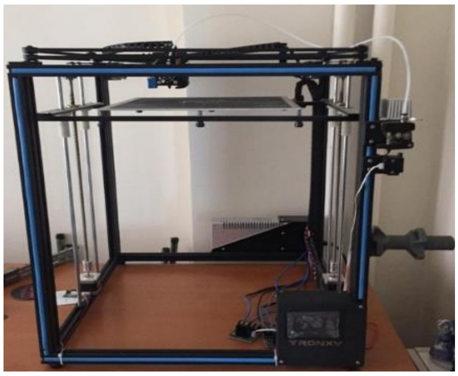


Figure 9. 3D printing process flow chart.

Figure 9 shows the flowchart for the 3D printer. Solidworks software was used as CAD software. In this study. Four different toot wheels, three different shafts, four different keys, six different covers, and two different gearbox case solid models were drawn for this reducer gearbox, and CAD files were created. Each file was imported into the slicer software as an STL file. Ultimaker Cura was applied as the slicer software. G-codes were generated by entering operating voltage, extruder structure, nozzle temperature, table temperature, nozzle diameter, layer thickness, and filament diameter. G code files SD card was loaded printer separately. The parts produced with 3D printers were assembled. Moreover, the assembly used six different bearings, many screws, and nuts. In this study, the PLA material filling rate was 60% for gears and 80% for shafts, and 20% for the lower and upper boxes. A 1.2 mm diameter nozzle was used for the upper and lower boxes. The lower box was printed in one go, the upper box piecemeal. The printing time for the boxes was in the range of 14-20 hours. A 0.6 mm diameter nozzle was used for gears and shafts. Due to the high number of walls in the gears, much filling was not required. The printing time for the gears was in the range of 4-8 hours. Printing time for shafts was in the range of 2-4 hours. There are hundreds of setting options in Cura software, and changing even one of these options changes the printing time**,** weight, and amount of filament. The printing time can be significantly reduced by using the appropriate options.



(a)



(b)

Figure 10. (a), (b) Printers used in production.

Table 5. Features of printer 1.

Parameter	Printer 1
Print volume	200x200x190
Model	(mm)
Software	Anet A8
Operating voltage	(current)
Extruder structure	Marlyn
Maximum nozzle	24 V DC, 20A
temperature	Bowden
Maximum table	Extruder
temperature	275º
	130º

Table 6. Features of printer 2.

Parameter	Printer 2
Print volume	300x300x400
Model	(mm)
Software	Tronxy X5SA
Operating voltage	Default
Extruder structure	software
Maximum nozzle	24 V DC,
temperature	30A
Maximum table	Bowden
temperature	Extruder
	265º
	90º

Table 7. Print parameters.

Parameter	Attributes and values
Nozzle diameter	0.6 mm
Layer thickness	0.4 mm
Wall number	2
Print temperature	210°C
Table temperature	60°C

Table8. Filament properties.

Parameter	Attributes and values
Amount of filament	1000 gr.
Filament type	PLA+
Filament diameter	1.75 mm

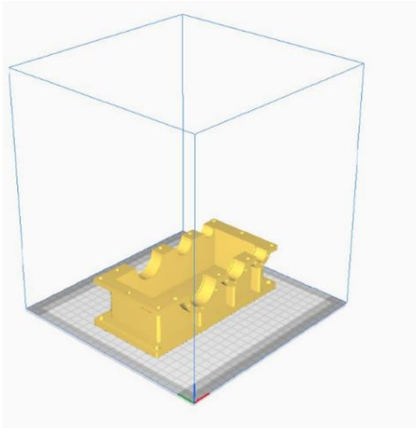


Figure 11. Gearbox case in Cura slicer software.

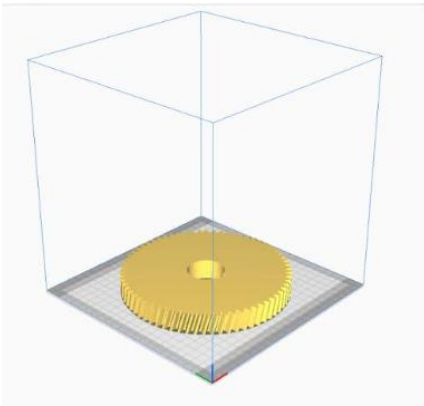


Figure 12. Helical gear wheel in Cura slicer software.

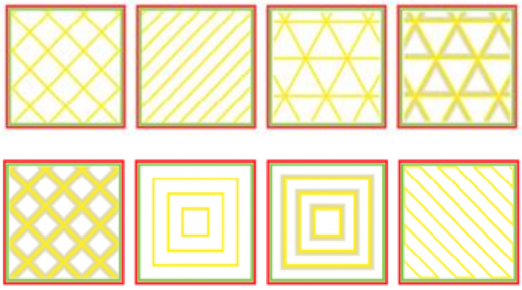


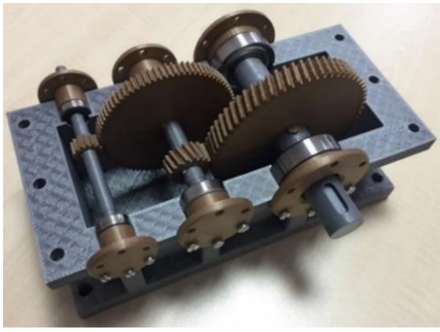
Figure 13. Cura 3D fill pattern [17].

If this model is used for mechanical purposes, the best option is to choose a 2D pattern such as Grid, Lines, or Triangles. The grid pattern consumes more material but is more rigid. The printing time of the grid pattern is also longer. The line pattern prints quickly and consumes less material. The triangular pattern provides good wall strength in thin structures This study mainly used the grid pattern as a filled form. A small amount of line pattern was also used.

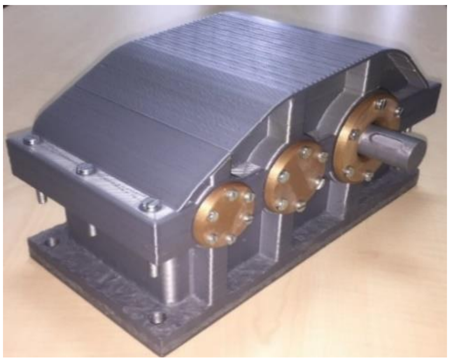
5. RESULTS

Figure 14 shows the gearbox prototypes, the parts of which were 3D printed and then hand-assembled. Bearings, screws, and nuts are purchased as standard parts. The outer dimensions of the gearbox are 280×135×160 cubic millimeters. The total reduction ratio of the system is 1/20. The reduction ratio has been reduced from n1= 800 rpm to n3 =40 rpm (Figure 2). For example, this reducer can be attached to the belt conveyor motor to transport lightweight and hygienic goods. In the food industry, chemical and pharmaceutical industries, and sensitive products areas.

However, the box casing can be redesigned in Solidworks software according to the geometric situation of the place where it will work and can be printed on a 3D printer. Similarly, gears can be redesigned and printed according to the desired speed and torque value. So everyone can make their design.



(a)



(b)

Figure 14. (a), (b) Prototypes of the gearbox manufactured with a 3D printer.

In this study, a 100% filling rate of PLA material was not preferred to shorten the long printing times of solid parts. This preference negatively affected the strength of the elements. In particular, the small cross-section of the input shaft means that it is subject to rapid breakage.

Therefore, we intend to manufacture this reducer as in figure 15.

Figure 15. A new design to work on [33].

In the new study, the shafts will be steel. This time, we will use a helical gear pair in the 1st stage because the first drive comes to the first-stage gears via the input shaft. However, helical teeth grasp each other more strongly. Gears and box cases will be made of PLA material using a 100% fill rate. Shafts and box cases will have a long life. Lifetime calculations of gears will be made, and their spare parts will be produced. For gears, colors in white and light gray tones will be preferred. For the box case, light pink and yellow colors will be preferred. In this way, reducers will have a clean appearance. After these experiences, gearboxes with different planes of input and output shafts can also be produced.

6. CONCLUSIONS

Our main goal is to convert a digital model (CAD drawings) into a 3D physical object. Since the density of PLA material is low, the weight of the produced parts is lightweight. It is economical and easier to manufacture. However, it is not resistant to high temperatures and abrasions. The reducer-gearbox made of PLA can be used at low temperatures (less than 60 degrees Celsius).

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