Prediction and Optimization of Sustainable Production Processes for Automotive Components

Avinaash Jaganaa, Voonna Balakrishna Taruna, Koduri Naga Ganapathi Lakshmi Reshawantha, G. Rajyalakshmi, and K. Jayakrishna

Abstract This paper includes the study of power train components of an All-Terrain Vehicle. The research aims to optimize the designs and reduce the weight by iterating on different materials and designs using Finite Element Analysis. It also includes various studies of their manufacturing processes and compares them with additive manufacturing techniques to check the increase in sustainability and the reduction in material wastage. Reducing material wastage and reducing the carbon footprint using additive manufacturing techniques is the main target of the paper. In this work, a gearbox has been designed for a vehicle as an example. The loads have been calculated and the materials also have been selected for the gears and the casing. The materials selected are the materials that are commonly used in the present industry. Finite Element Analysis and optimization have been done to reduce the weight while maintaining a good safety factor at the same time. Sustainability analysis will further be done to compare the amount of carbon footprint by the two processes. From this study, the paper aims to create a process for machine design that takes sustainability, material usage, and carbon footprint into account apart from conventional considerations like weight, strength, size, etc. This will help promote a sustainable environment which is an increasing need. Finally, the work aims to create a process through an example of how to create a sustainable designing and manufacturing process.

Keywords Sustainability · Additive manufacturing · Automobile components · Carbon footprint · ANSYS

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1 Introduction and Literature

In the era of modern technology almost all optimization operations are taking place at a detailed design level that include optimizations of structures of metal gauges as well as beam cross-sections, topology optimization for the casted components, and calibration of engine. Even Though a lot of successes have been seen, optimization is rarely used and also has a lesser impact than expected for most of the researchers. The reason behind the lesser impact may be due to poor connection between CAD and CAE software, accuracy of computer simulations are predictively insufficient, difficulties occurred during automation and computer analysis iterations, larger simulation times, and less availability of data.

At the same time, sustainability has become a great word. Firstly, what is sustainability and what is the need for sustainability? Sustainability mainly refers to the economic value of any product or component which means that the economic value of the product should be the same or higher over a period of time. Sustainability is important because it improves the quality of our lives. It not only benefits us but the environment, if the sustainability of a component is more then the waste produced becomes less and hence more environmentally friendly.

Eckert et al. have performed a study on design of powertrain of electric hydraulic hybrid vehicle. The paper talks about an extensive strategy for optimizing an electric hydraulic mixture vehicle powertrain operating in series to control through the intelligent adaptive-weight hereditary algorithm technique. Factors of the hydraulic drivetrain and the electric framework have been considered advanced. Additionally, a fuzzy-logic regulator, that yields to the stage of the electric engine turn over stop and force that is applied to the siphon that compresses the gatherer, which is moreover thought to be in the detailing of the optimization issue to tune its membership capacities, rules, and weights. The results of the optimization show that electric hydraulic half and half vehicle powertrain structures can be an extremely alluring impetus innovation in regard to both manageable and conservative viewpoints, successfully lessening battery maturing by the utilization of a powerful thickness hydraulic gatherer, which goes about as a pinnacle power cradle unit [1].

Javorski et al. have made a study on gearbox design which is a multi-speed gearbox type and optimization of shifting control is also done so as to minimize the consumption of fuel and losses in mechanical. The authors of the paper focused on optimization of an ICEV drivetrain using the multi-objective optimization techniques, and stuff moving control focusing on the fuel utilization minimization, emanations of exhaust, and power of the gearbox misfortunes. The issue in optimization is addressed by the (I-AWGA) and includes various plan factors of the multi-speed transmission and differential framework, thinking about helpful constraints. The model of the vehicle is assessed with a consolidated driving cycle, accordingly hearty powertrain arrangements may be acquired by the interaction with optimization. The good compromise arrangement brings about the decrease of gas discharges in 2.32% HC, 3.44% CO, and 23.78% NOx, alongside the 15.6% fuel investment funds, confronting the standard vehicle [2].

Haishang et al. have made a work on AM of recycled plastics, many techniques were made for a more sustainable future. In this review, to alleviate any gamble brought about by creation speed, scaling, and speeding up the move towards the more limited recycling and assembling of plastic parts and parts, an assortment recycling-producing (CRM) model is worked to imagine the assessment of cycle stream as well as interaction joining. The review uncovers that AM sets out open doors, for example, prototyping, redoing, transportation cost decrease, and making of occupations in country regions, which might stop superfluous movement; and, above all, diminishing CO_2 discharges and plastic waste regardless of difficulties like abilities prerequisite and detriments in speed and scale creation [3].

Rajak and Vinodh et al. have made a study on application of fuzzy logic for social sustainability performance evaluation: a case study of an Indian automotive component manufacturing organization. This article presents a methodology for social sustainability execution assessment. The methodology has been tried and carried out in an Indian auto part fabricating association. The acquired record has been approved utilizing the traditional fresh method and the social sustainability file is viewed as 6.98. The methodology is productive in estimating the qualities and shortcomings of a singular local area or association concerning a point-by-point set of markers to recognize the more fragile traits. The outcomes utilizing the fuzzy methodology have been approved with the ordinary fresh methodology. 22 social sustainability ascribes out of 60 are viewed as more fragile and fitting activities were inferred to work on the more vulnerable qualities [4].

Sargini et al. have done a study on additive manufacturing of a brake pedal of an automotive vehicle using metal fused deposition modelling. The primary goal of the exploration is the investigation of another brake pedal considering additive manufacturing as an opportunity, combination of parts with decreased mass, new material for additive manufacturing, and utilization of metal-based additive manufacturing innovation. Finite Element Analysis (FEA) has been used to examine how feasible another brake pedal plan for additive manufacturing handling is. The model of the FDM-created metal brake pedal has been actually tried for approving the Finite Element Analysis results and also to check the unwavering quality in FDM innovations that are based out of metal [5].

Mani et al. have made a study on this paper that initially analyses the likely ecological effects of additive manufacturing. A procedure for the sustainability portrayal of additive manufacturing is taken into consideration to fill in an asset for the local area benchmarking additive manufacturing processes in attaining sustainability. The proposed diagram for a sustainability portrayal manual for fill-in as a source of perspective for the local area to benchmark AM processes for sustainability. The aide is still needed to be officially evolved by and by a functioning work thing inside the ASTM E60.13 council [6].

Niaki et al. have focused on reasons behind manufacturers adopting additive manufacturing technologies: The sustainability role in it. This paper aims to recognize and focus on the determinants of its reception and also to explain the benefits of sustainability as the choice to embrace. Thereafter, at that point, the examination tries to recognize the needs of various application areas through a study that is of multiple stages. The outcomes prove that natural sustainability benefits are scarcely applicable to reception choices by and by and this is conversely, with the writing expressing the enormous sustainability benefits. The outcomes demonstrate the significant job of financial thought processes in reception choices. The discoveries additionally demonstrate that the capacity of added substance fabricating for delivering practically any perplexing plan is the vital driver of its reception in all areas [7].

Wie et al. have made research on Failure analysis for a transmission gear used in an electric vehicle which is known as secondary driving helical gear. In this paper, the observed results were disappointing due to auxiliary driving helical stuff in the transmission arrangement of an EV being found to be dissected. The pressure conveyances of the tooth flank taken utilizing dynamic and static contact in finite elements was acquired again in view of ANSYS Workbench programming. The outcomes then showed that the surfaces that were cracked in the bombed gear begin from the roots of tooth and display the small granular fragile break, the fundamental explanation, solidifying and hardness profounding in the root area, various huge carbides on the network of martensite because of ill-advised hotness treatment, additionally FE reproduction results uncovered that more contact pressure in the root position and high effect force is acting in the underlying phase of cog wheels fitting while minimizing in assistance perhaps prompted the weakness disappointment [8]. Qingyong et al. have focused on contact mesh analysis and topology optimization of electric vehicle gearbox. Taking into account the NVH issue of car transmissions, the third pair of stuff sets of an electric vehicle gearbox is taken as the examination object. In view of the nonlinear unique model hypothesis of the stuff transmission framework, the stuff profile alteration and tooth direction are exhaustively used to choose a sensible shape change plot. Noticing the reproduction results, it tends to be seen that the stuff pair transmission blunder and the most extreme contact pressure after the shape alteration are altogether diminished contrasted and those before the shape change, and the contact pressure map circulation is more uniform [9]. Srikar and Mahato have made a study on design of two stage single speed gearbox used in terrain vehicles along with calculation and its analysis. In this paper, they zeroed in on the hypothetical investigation of planning and estimation, along with its analysis of gearbox which can be used in a BAJA SAE. The gearbox is further co-ordinated by CVT, i.e., constant factor transmission which is combined with ultraviolet joints for transmission of force to the wheels. The gearbox is laboured for 2 years and is considered with productive resilience [10].

Feucht et al. have analysed how 3D printing can be used for components made with steel in additive manufacturing. They focused mainly on preliminary strength investigations that were carried out during the process, and also the sequence of processes that are required for homogeneous manufacturing. Author's focus is especially around the starter strength examinations completed and the interaction groupings expected for homogenous assembling. The paper finishes up with a thought of the execution on location [11].

In the present world reducing the weight of an automotive component is of great requirement without getting induced stresses to it. Reduction of body weight of automotive components also helps in getting a good mileage for a car or a bike. The authors

M. R. Idris, S. A. Syed Ahmed, E. Sujatmika, and W. M. Wan Muhamad, showed that 24% mass reduction can be done for the design of the rear spindle. In the same way we can try for other vehicle components which will help us contribute towards environmental sustainability, better conserving the world's metal resources and reducing carbon emission through improved overall vehicle fuel efficiency [12]. Considering additive manufacturing techniques such as 3D printing and CNC machining the production of automotive components becomes much easier with less wastage, possibility of producing every form and function. But the authors Enrico Dalpadulo, Fabio Pini, and Francesco Leali gave a conclusion that there is no added advantage in replacing the integrated platform with a stand-alone tool, rather than implementing the whole method and the workflow into a platform [13].

As common people these days are aware of buying sustainable products, the plastic industry is doing drastic changes in their manufacturing processes by considering 3D printing and other techniques of production in the industry. They also developed a methodology that demonstrates the advantage in comparing the existing subjective optimization research processes [14]. In order to analyse the sustainability in industry there are so many factors and variables needed. Some of the variables that are generally considered are consumption of energy, consumption of water, waste management, environment preservation, equality in society, and noise and emission management. Waste that is generally generated in the automotive manufacturing industry are classified as machine lubricants, coolants, Solvent cleaning, paint and scrap metals, and plastics. The authors C. Torcătoru and D. Săvescu stated that the above-mentioned variables accounted for a lot of variation in sustainability and also showed that an 83% variation in sustainability can be achieved which is shown using the statistics based calculation such as using the multiple regression, etc. [15].

It can also be used as a list of KPIs proposed by the authors Vikas Swarnakar, A. R. Singh, and Anil Kr Tiwari in their paper which is based on AHP (Analytical Hierarchy Process) in order to know the expert's opinion. They also proposed that few of the sustainability parameters are economic, social, and environmental. And the KPIs that come under economic are operational cost, the rate of acceptance of the product, effectiveness of overall equipment, inventory level work process, performance of equipment and machine, cost of facilities, efficiency in transportation; KPIs under social are satisfaction of employees, relation with the labour, society contribution, rate of accidents, opportunities in training, absenteeism ratio, volunteer sustainability initiatives, and gender ratio; and KPIs under environmental conditions are toxic water discharge rate, impact on green area, releasing harmful gases, consumption of water and fuel and also the materials, and overall solid waste generation [16].

A case study is presented by C. Torcătoru and D. Săvescu in which the authors chose a product which is analysed with SOLIDWORKS Sustainability and they also generated the sustainability report provided by SOLIDWORKS which is saved and used for the adoption of the right decision by the whole organization [17].

Process optimization parameters that are considered for manufacturing a spur gear as these fears are of different types which are most likely to be used in all types of power transmission systems. The design is further analysed theoretically and through finite element analysis and both the theoretical and practical results were compared.

The comparison showed that the theoretical results were far better than the finite element analysis results [18].

The authors have done AIP Conference Proceedings. Vol. 2347. No. 1. AIP Publishing LLC, 202 re-designing a bluetooth speaker which is more compact and sleeker looking and it should also be a water-resistant bluetooth speaker. For the purpose of designing, DFMA is used for minimization of quality required, and SOLIDWORKS Sustainability is used for evaluating for comparing different materials with four environmental factors such as carbon footprint, water eutrophication, total energy consumption, air acidity, and as well as material financial impact too [19, 20]. Jones, F. tried generating a simulation tool which is capable of predicting properties of heat-treated by the processes called carburizing-quenching-tempering, and finally display the results to the user in an understandable manner of comparison between real and simulation-based results of surface hardening of automotive components have been done [21].

After going through the various research papers, a lot has been learnt regarding the area of study. Literature regarding optimization of different components has been studied which mainly includes gearbox optimization. Structural analysis has been learnt from various research papers. The various parameters of gears such as the gear ratio, number of teeth, helical angle, face width, etc., can be iterated to get the best combination of strength and weight. The loads have been applied using static structure in Ansys and the various iterations were carried out.

Various additive manufacturing processes have been studied from the literature. It has been seen how the amount of material used can be reduced by additive manufacturing. Furthermore, sustainability has been studied to utilize the various resources in a judicious manner. The carbon footprint and power consumption of the various processes have been calculated to select the best process. Even though many researchers worked for manufacturing practices for various automobile components, sustainability of manufacturing practices was not reported. The major focus of this work is to optimize the design of automobile components and calculate the sustainability of manufacturing through material reduction, energy consumption, CO_2 emissions, etc. This work also concentrated on comparison of present manufacturing processes with additive manufacturing.

The objective of the paper is to introduce a process for design and optimization that also considers additive manufacturing and sustainability. The project introduces this process by using an example of a four-wheel drive gearbox. Design of gearbox includes calculation of loads, material selection, and optimization. This work is focused on sustainability analysis to compare the carbon footprint of various manufacturing processes.

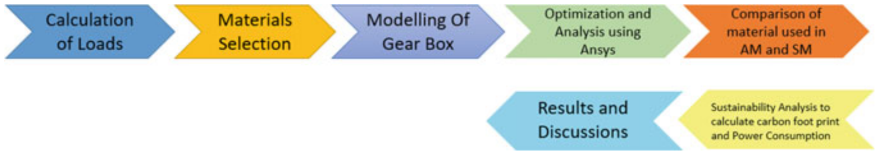


Fig. 1 Methodology of the project

2 Methodology

The methodology starts with the calculation of the loads acting on the different components of the gearbox. The materials then have been selected for the components. The design of the gearbox is then made using SOLIDWORKS. The components have then been analysed using Static Structural in ANSYS. The optimization process was hence completed by performing multiple iterations of the component designs such that the weight is minimum with an appreciable factor of safety (Fig. 1).

The material usage is then calculated in the case of additive and subtractive manufacturing and compared. The amount of material saved by the use of additive manufacturing is then calculated. Sustainability Analysis is further done. The carbon footprint and power consumption of various additive manufacturing processes is then calculated to select the most suitable process. A design process is hence proposed that also takes into account additive manufacturing and sustainability.

3 Design Specifications of Gears

The parameters considered to design a gear are given in the following Table 1.

Step 1: Calculation of Loads and Material Selection of Components

The total tractive force required for an ATV to climb an incline has been calculated. The gear ratio is calculated from that (Fig. 2).

Table 1 Optimized design parameters of gearbox

S. No	Parameter	Value
1	Tractive force	2292.46 N
2	Tractive torque	669.4 Nm
3	Gearbox ratio	9:1
4	Face width	

Gear Design

Total Tractive force= mg Sinθ + μmg Cosθ

= 230*9.81*Sin 60 + 0.3*9.81*Cos 60

= **2292.46** N

Total Tractive Torque= Total Tractive force* Radius

= 2292.46 * 0.292

= **669.4** Nm

Input Torque* Gearbox Ratio= 669.4 N

74 * R = 669.4 N

R=9:1

Face width Calculation, First stage

Z = 15

mn = 3 mm

mt = 3/ Cos 15

= 3.11 mm

d = z* mt

= 15 * 3.11

= 46.65 mm

V = pi*d*n / 60

= (3.14 * 46.65 * 3800) / (60 * 1000 * 0.9)

= 10.31 m/s

Ft = W/V

= 6714/10.31

= 651.21 N

Kv = (Sqrt (18+sqrt (200)/78)

= 1.26

$\sigma e = \sigma e' * k_L\, k_V\, k_S\, k_R\, k_T\, k_F\, k_N$

σb = σe/2 = 173.34 Mpa

J = 0.4 * 0.98 = 0.392

$\sigma b = (F_t / b\, M_n\, J) * K_V\, K_D * (0.93 K_m)$

b = 13 mm

Bearing Force, First Stage

V= π*d*N/ 60

= (3.14 * 15 * 3.11 * 20000) / (60 * 1000 * 3.9)

= 1.25 m/s

F_T = W/V

= 4000 / 1.25

= 3200 N

$F_M = F_T \tan \varphi / \cos \beta$

= 3200 tan 20 / Cos 15

= 1205.79 N

$F_a = F_T \tan \beta$

= 3200 * tan 15

= 857.44 N

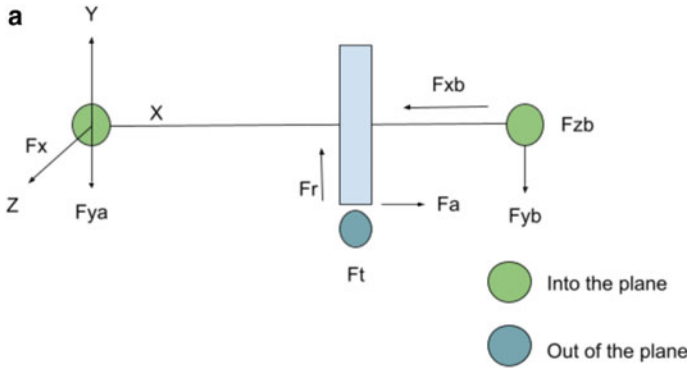


Fig. 2 **a** Design dimensions with calculations. **b** Design dimensions with calculations

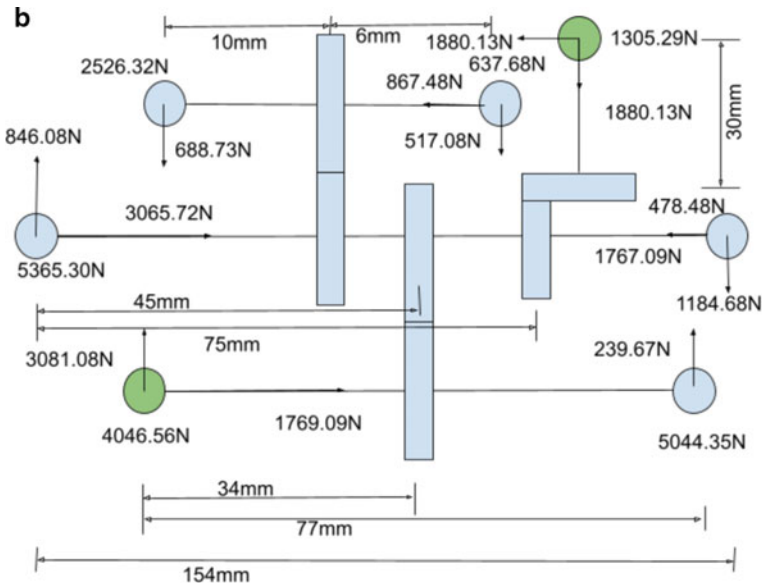


Fig. 2 (continued)

Gear 1

(TE (z- axis)) Fyb * 76 – Fx *16 – Fa * 23.33 = 0

Fyb = 517.06 N

(FE (y- axis)) Fya- Fr + Fyb = 0

Fya = 688.73 N

(TE (y- axis)) Ft * 16 = Fzb * 76

Fzb = 673.68 N

(FE (z- axis)) Fza – Ft + Fzb = 0

Fza = 2526.32 N

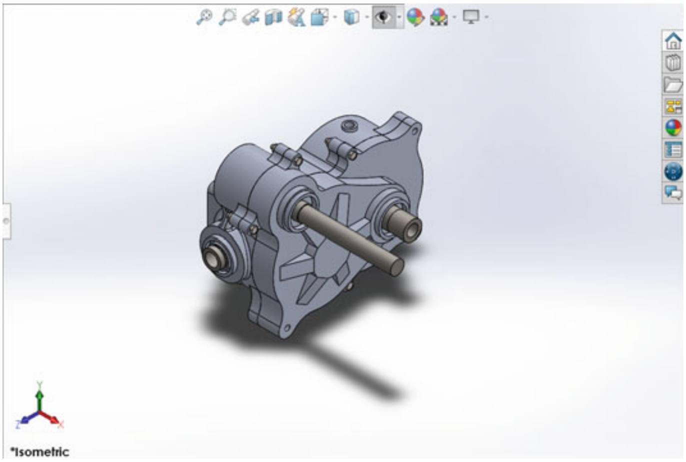


Fig. 3 Design of the gearbox

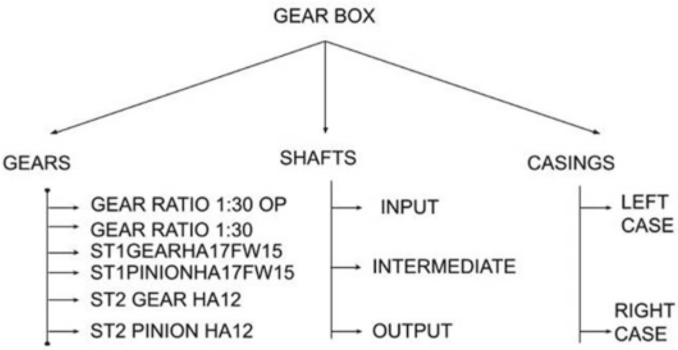


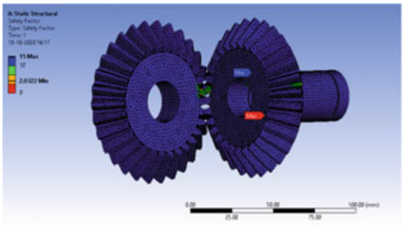
Fig. 4 Components included in a gearbox

4 Design of Gearbox

A gearbox has been designed in SOLIDWORKS considering the various design parameters studied in various research papers (Figs. 3 and 4).

5 Structural Analysis and Optimization of the Components

Structural analysis has been done on the components. The loads calculated have been applied. The simulation has been done using Ansys 2020 R2. Weight has been reduced while keeping an appreciable safety factor (Fig. 5).



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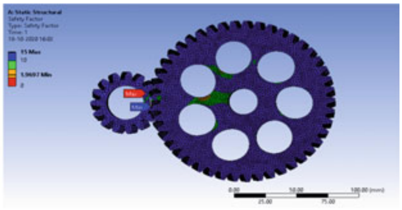

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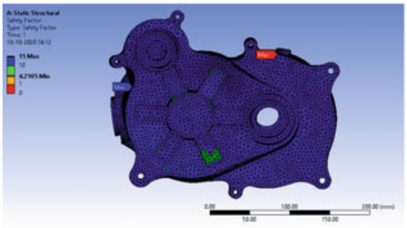

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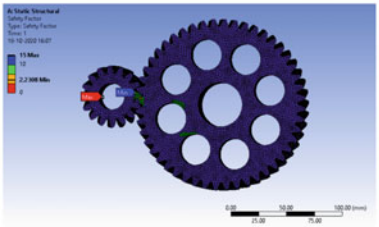

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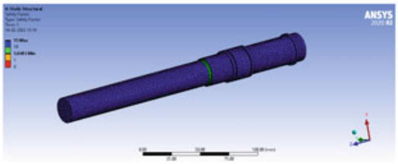

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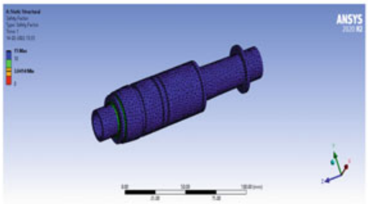

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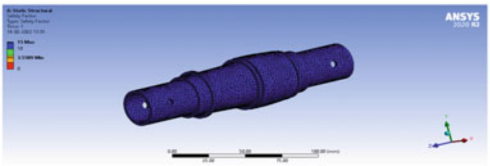

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Fig. 5 Analysis and optimization of the component

6 Application of Additive Manufacturing Techniques

The material that has been saved by using additive manufacturing has been calculated. Both mass and volume of the material saved have been shown in Table 2 along with the percentage difference. These values have been calculated using SOLIDWORKS software. The weight and volume of the material used in both manufacturing processes, i.e., subtractive and additive manufacturing processes have been calculated and compared.

The following images illustrate the designs in both the cases, i.e., additive and subtractive manufacturing (Fig. 6).

7 Materials Selected

Gears—AISI 4340

Reason—Ease of machining, High Yield Strength of 710 MPa which is 16000 psi more than that of AISI 4130 (Fig. 7).

Casing—Aluminium 6061 T6.

Reason—High strength to weight ratio, Easy to machine.

8 Sustainability Analysis

SOLIDWORKS Sustainability has been used to analyse and compare the carbon footprint and energy usage in different additive manufacturing processes. The data has further been used to decide the most suitable process for the components. Carbon footprint has been given preference over energy consumption here.

8.1 Input Parameters Values for Manufacturing of Gearbox

For sustainability in SOLIDWORKS, prior one needs to consider a few parameters such as what type of material we are going to use for our product, what is the location of manufacturing, where the product will be used, and how many years it is built to last. For this the following table shows the parameters considered for this project (Table 3).

Table 2 Material usage comparison between additive and subtractive manufacturing process

	Subtractive		Additive					
	Volume (cm^3)	Mass (g)	Volume (cm^3)	Mass (g)	Volume difference	Mass difference	Vol %	Mass %
Gears								
First stage								
Driving gear	35,637.4417	279.7539	17,590.9083	138.0886	18,046.5334	141.6653	50.63925057	50.63925829
Driven gear	252,640.5713	1983.2285	97,271.1427	763.5785	155,369.4286	1219.65	61.49820981	61.4982086
Second stage								
Driving gear	73,844.6047	579.6801	47,624.5802	373.853	26,220.0245	205.8271	35.50702804	35.50701499
Driven gear	571,565.1532	4486.7865	228,809.8723	1796.1575	342,755.2809	2690.629	59.96784076	59.96784113
Bevel stage								
Driving gear	128,816.188	1011.207	66,340.984	520.777	62,475.204	490.43	48.49949759	48.49946648
Driven gear	573,862.753	4504.823	97,731.483	767.192	476,131.27	3737.631	82.96953714	82.96954176
Shafts								
Input shaft	166,715.21	1308.71	109,707.79	861.21	57,007.42	447.5	34.19449251	34.19397728
Intermediate shaft	93,902.2	737.13	42,062.32	330.19	51,839.88	406.94	55.2062465	55.20600166
Output shaft	248,311.48	1949.25	119,828.23	940.65	128,483.25	1008.6	51.74277484	51.74297807
Casing	10,828,374.44	29,236.61	1,102,183.52	2975.9	9,726,190.92	26,260.71	89.82133906	89.82132333
				With Al	11,044,519.21	36,609.5824		
				Without Al	1,318,328.291	10,348.8724		

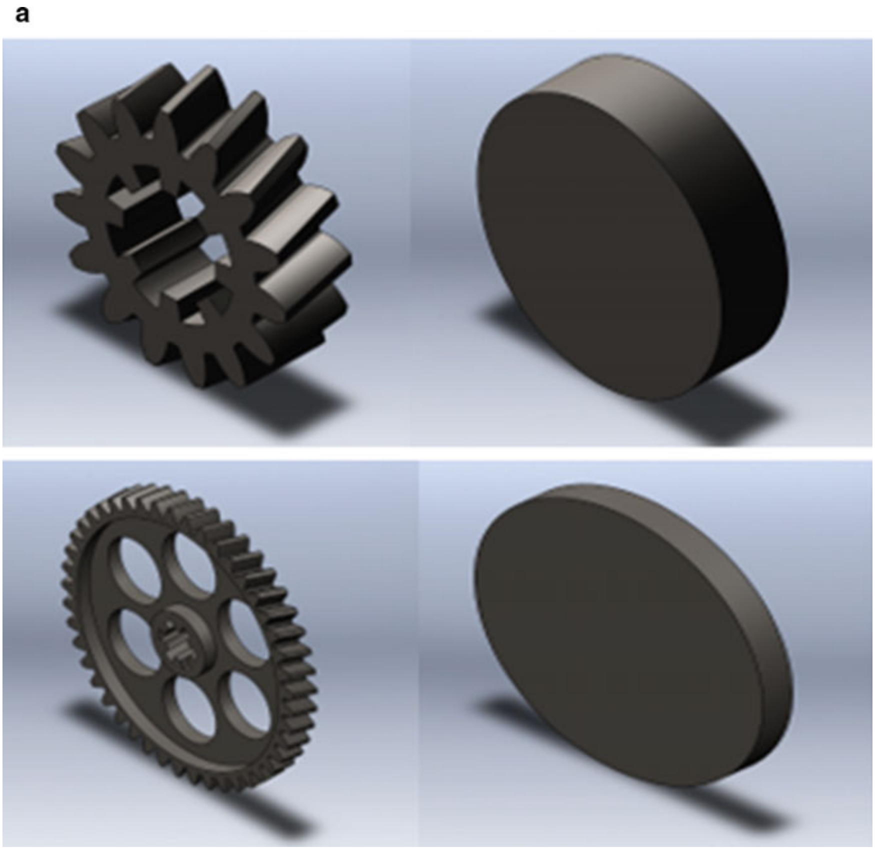

Fig. 6 **a** Material usage comparison of first stage gears. **b** Material usage comparison of second stage gears. **c** Material usage comparison of bevel gears. **d** Material usage comparison of casing. **e** Material usage comparison of shafts

8.2 Carbon Footprint

While burning the fossil fuels gases such as carbon dioxide and many others add up into the atmosphere resulting in an increase in the earth's temperature. Global warming potential is the impact factor used for the carbon footprint value of the earth. Global warming also causes problems like species extinction, evaporation of water bodies, severe weather conditions, etc. Tables 4, 5, 6, and 7 show carbon footprint values for different components such as gears, shafts, and casings of the gearbox which are calculated in SOLIDWORKS for different manufacturing processes like extrusion, die casting, sand casting, and machined sand casting.

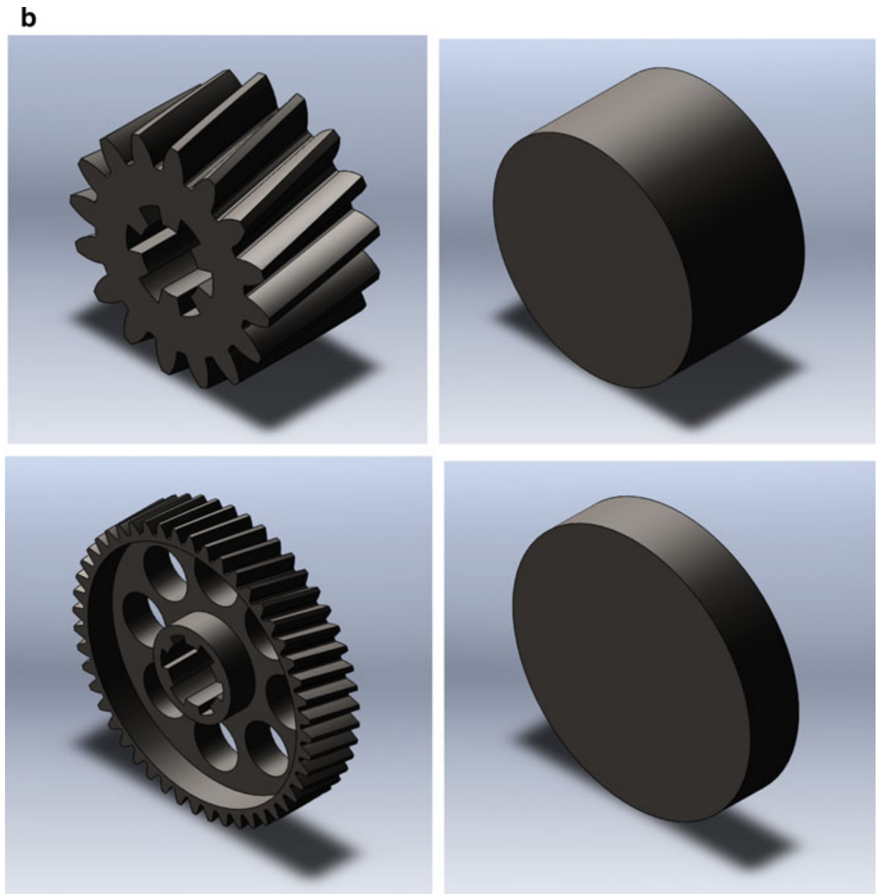

Fig. 6 (continued)

8.3 Energy Consumption Values for Manufacturing of Gearbox

Non-renewable energy resource consumption is calculated in megajoules (MJ). As a result of this consumption of electricity and fuels during the product manufacturing some or the other people on earth would be suffering due to their dependence on these energy resources. The average calorific value of energy demand of the non-renewable resources is expressed as total energy consumed. Tables 8, 9, 10, and 11 show energy consumption values for different components such as gears, shafts, and casings of the gearbox which is calculated in SOLIDWORKS for different manufacturing processes like extrusion, die casting, sand casting, and machined sand casting.

The results mentioned in the tables show us that the carbon footprint values for gears in the extrusion process is less when compared to die casting, sand casting, c

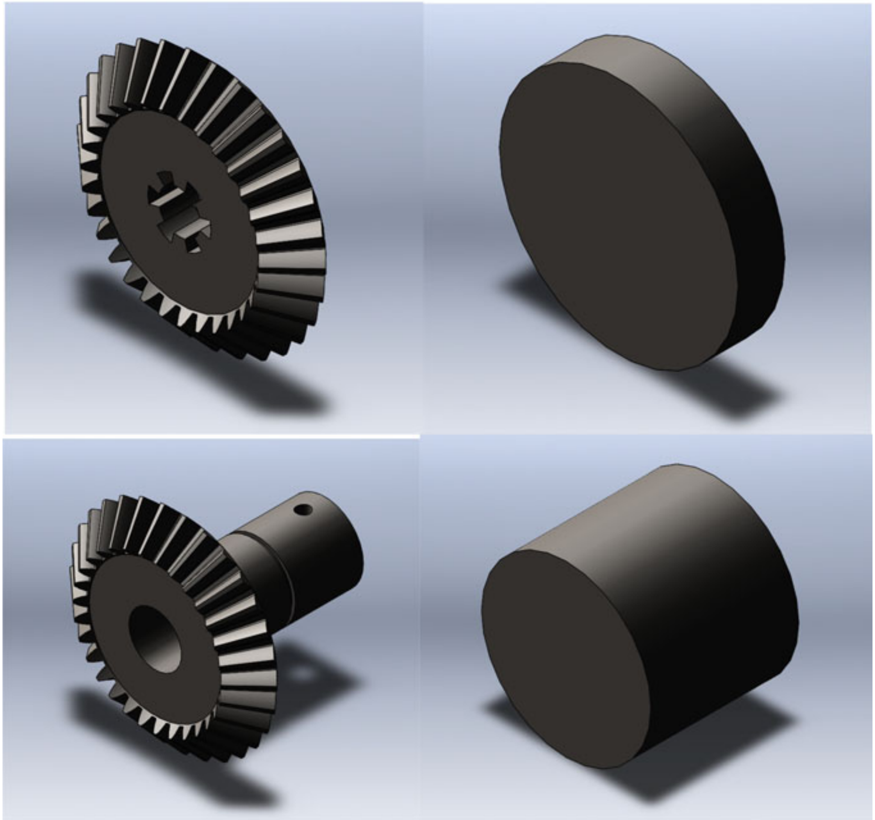

Fig. 6 (continued)

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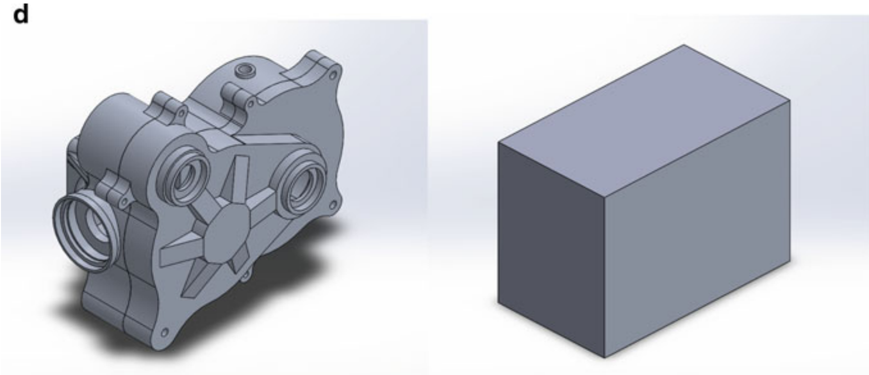

Fig. 6 (continued)

Fig. 6 (continued)

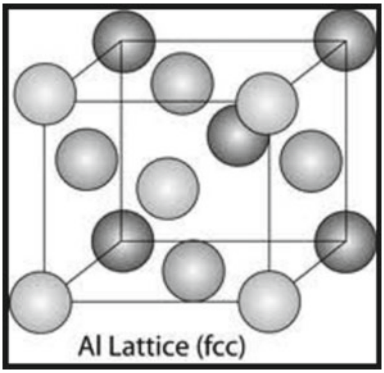

Fig. 7 Lattice structure of Aluminium 6061 T6

Table 3 Input parameters for sustainability analysis

Material class	Aluminium alloys
Material name	AISI 4340 for gears and shafts and for casing 6061-T6(SS)
Built to last	2 years
Region of manufacturing	Asia
Region of use	Asia
Manufacturing processes	Extrusion, die casting, machined sand casting, and sand casting

Table 4 Carbon footprint comparison of all gears in different manufacturing processes

	Extrusion	Die casting	Sand casting	Machined sand casting
Gear1	0.19	2.7	2.7	3.2
Gear2	0.141	2	2	2.4
Gear3	0.198	2.8	2.8	3.3
Gear4	0.032	0.453	0.453	0.536
Gear5	0.446	6.3	6.3	7.4
Gear6	0.089	1.3	1.3	1.5
	All the values are in Kg CO_2			

Table 5 Carbon footprint comparison of all shafts in different manufacturing processes

	Extrusion	Die casting	Sand casting	Machined sand casting
Shaft1	0.228	3.2	3.2	3.8
Shaft2	0.096	1.4	1.4	1.6
Shaft3	0.244	3.4	3.4	4.1
	All the values are in Kg CO_2			

Table 6 Carbon footprint comparison of all casings in different manufacturing processes

	Extrusion	Die casting	Sand casting	Machined sand casting
Casing1	1.5	2.4	1.4	1.7
Casing2	1.9	3.1	1.8	2.2
	All the values are in Kg CO_2			

Table 7 Average carbon footprint values of gears, shafts, and casings

	Extrusion	Die casting	Sand casting	Machined sand casting
Gears	0.18267	2.592167	2.592167	3.056
Shafts	0.18933	2.6667	2.6667	3.1667
Casings	1.7	2.75	1.6	1.95
	All the values are in Kg CO_2			

Table 8 Energy consumption comparison of all gears in different manufacturing processes

	Extrusion	die Casting	Sand casting	Machined sand casting
Gear1	16	24	15	18
Gear2	1.7	21	21	25
Gear3	2.3	30	30	35
Gear4	0.38	4.8	4.8	5.7
Gear5	5.3	67	67	79
Gear6	1.1	13	13	16
	All the values are in MJ			

Table 9 Energy consumption comparison of all shafts in different manufacturing processes

	Extrusion	Die casting	Sand casting	Machined sand casting
Shaft1	2.7	34	34	40
Shaft2	1.1	14	14	17
Shaft3	2.9	37	37	43
	All the values are in MJ			

Table 10 Energy consumption comparison of all casings in different manufacturing processes

	Extrusion	die casting	Sand casting	Machined sand casting
Casing1	16	24	15	18
Casing2	21	31	19	23
	All the values are in MJ			

Table 11 Average energy consumption values of gears, shafts, and casings

	Extrusion	Die casting	Sand casting	Machined sand casting
Gears	4.4633	26.633	25.133	29.7833
Shafts	2.233	28.333	28.333	33.333
Casings	18.5	27.5	17	20.5
	All the values are in MJ			

and machined sand casting and hence extrusion is the best additive manufacturing process for manufacturing of gears. In a similar fashion for shafts, extrusion is the best and for the casing, sand casting is the most suitable additive manufacturing process.

9 Results and Discussions

The design of the component has been completed using SOLIDWORKS. It has been analysed using Ansys and further optimized. An appreciable safety factor has been kept for all the components. The components' material usage has then been compared between both additive manufacturing and subtractive manufacturing scenarios. In this case, approximately 56.51% of the material has been saved in the case of additive manufacturing.

Further analysis is done to find out which additive manufacturing process can be used in order to have the least carbon footprint. SOLIDWORKS Sustainability has been used for this purpose. In the case of gears and shafts that are made of steel, extrusion comes out to have the least carbon footprint of 0.18267 $KgCO_2$ and 0.18933 $KgCO_2$, respectively. Sand Casting comes out to have the least carbon footprint of 1.6 $KgCO_2$ in the case of the casings that are made of aluminium.

The energy consumption has also been analysed. In this case, the results obtained are different. Gears and casings have the least energy consumption of 4.4633MJ and 2.233 MJ, respectively, in the case of the sand casting process. Manufacturing of shafts takes the least energy consumption of 17MJ when done through the extrusion process.

10 Conclusion

An optimized design of the gearbox has been completed using SOLIDWORKS and Ansys. The weight of the components has been minimized while maintaining an appreciable safety factor. Further, the material used has been compared between additive and subtractive manufacturing. It has been found that additive manufacturing results in the saving of approximately 56.51% of the material. It is hence better in this aspect. The sustainability analysis has further been done where the carbon footprint and energy consumption in various additive manufacturing processes have been compared to find the optimum process for manufacturing. The carbon footprint is the total amount of greenhouse gases generated in the processes. The power consumption talks about the total amount of electricity consumed during the process. The optimum process would then be decided by checking the values of these factors. If carbon footprint is to be given priority, then the process with the least carbon footprint would be preferred. If power consumption is to be given priority, then the process with the least power consumption would be preferred.

A new design process has hence been proposed which would also take into account the amount of material used along with the sustainability. The process will take into account important sustainability factors such as carbon footprint and power consumption.

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