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Original scientific paper

Optimization of a Soccer Robot Components Using Engineering Generative Design Approach

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Abstract: The object of the present study is to design and develop the chassis parts of a soccer robot, including the main chassis and electronic assembly member using innovative design techniques. Generative design is an iterative process that leverages software algorithms to create and evaluate numerous design options based on defined parameters and constraints. In this study, Autodesk Fusion 360 software was utilized, incorporating inputs such as preserve and observe geometry, starting shape, load cases, and manufacturing methods. These techniques were influenced by factors including product capacity, cost, and material choices. It is particularly beneficial in additive or conventional manufacturing, enabling the creation of complex geometries with ease. This approach allows designers to explore new possibilities, reduce material waste, and enhance the overall manufacturing process. The study here aimed to minimize material usage, improve the robot's stability, weight reduction and innovation, thereby reducing production costs while maintaining structural integrity. Also, various engineering materials with previous methods and materials throughout this approach. The Innovative design process application method begins with the definition of the problem. After that 3D modelling was performed and appropriate materials were defined and selected. Accordingly, design optimization was achieved by applying generative design methods. At the end of the process, production was carried out using 3D printing technology to obtain prototypes that were produced, tested and evaluated. The optimal conditions were obtained up to 38 and %45 weight reduction leading to a revised and improved version of the robot. This research highlights the efficiency of processes in optimizing material utilization, improving product stability, and minimizing waste.

Keywords: autodesk fusion 360; additive manufacturing; computer aided design; generative design; optimization; weight reduction; 3D printing

1 INTRODUCTION

Generative design (GD) can have the potential to change the manufacturing environment which allows the creation of optimized complex shapes and internal structures [1, 2]. It can benefit companies from all sectors in terms of the production process. It is a design and research process [3]. Designers or engineers enter design goals, as well as parameters such as performance requirements, materials, manufacturing methods, and cost constraints, into the design software [4]. The software quickly generates design alternatives by exploring all possible permutations of a solution. It tests and learns what works and what does not work each time [5]. The method can be used in fields such as automotive, aviation, robotics, construction and architecture, and industrial machinery [6, 7]. With this method, some of the optimizations of the designs can be produced by traditional methods and some by additive manufacturing methods [6]. In a study conducted in 2021, a weight reduction of approximately 36% was achieved using the generative design method without compromising the structural function of the part [8]. In another remarkable study in 2021, the authors compared three different materials and modelled the mechanical part on the robot by examining and redesigning it using this method, showing that the weight was significantly reduced, by approximately 85-90 percent, allowing the robot part to be designed more economically [9]. The studies examined have inspired the emergence of this study. Therefore, it is important to carry the developing methods further by supporting them with scientific studies. Accordingly, the aim here is to redevelop and improve the Near East University (NEU) Islanders football robots by NEU. Teams make innovations in their robots every year to implement new developing technologies and provide the opportunity to test them in competitions. NEU Islanders football robots were participating in one of the world's most prestigious robot competition RoboCup and became the world champion in 2018, Canada [7, 10]. Consequently, new robots are improving and developing each year for these competitions. Industry 4.0 enhances this by enabling Computer Numerical Control (CNC) machines to utilize data for production processes. Additive manufacturing (AM) technology plays a crucial role [4, 11]. It is offering greater flexibility and precision in production, reducing the need for extensive prototyping, moulds, and processes [12]. The main objective of the study here is to modify a soccer robot using generative design methods and also to compare manufacturing techniques such as AM and CNC machining and different materials to evaluate an optimal range of parameters such as production cost, usability, and manufacturability to develop and reproduce robot components more effectively [13].

2 LITERATURE REVIEW

Generative design (GD), CAD, and Computer-Aided Manufacturing (CAM) are interconnected in modern design and manufacturing, with generative design aiding in the early-stage exploration of multiple design alternatives [11]. CAD software integrates generative design algorithms for visualization and refinement, while CAM transforms the finalized designs into machine instructions for manufacturing. This integration improves efficiency, optimizes designs for materials and performance, and ensures manufacturability [6, 14]. Designing complex products or special projects requires designers to explore multiple alternatives CAD can assist in the early design stages, helping designers explore possibilities. Fig. 1, illustrates CAD and GD relations [14].

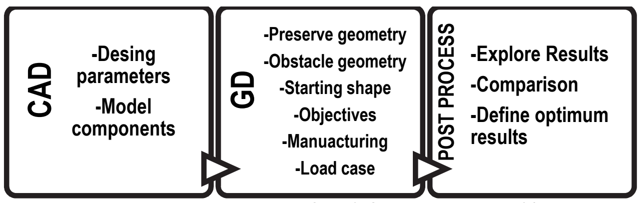

Figure 1 Relation between CAD & Generative design [14]

2.1 Generative Design in Literature

Generative design (GD) is an iterative process involving software that generates a specified number of outputs meeting given constraints [3, 15]. Designers or engineers input parameters, constraints, intended outputs, requirements, materials, and manufacturing methods into the generative design software [1, 6]. The Autodesk Fusion 360 software explores all the possibilities and permutations of a solution; thus, the software will design multiple solutions [16]. This will allow to create innovative structures that are perfectly optimized for use [14]. GD is an efficient way of getting optimized parts, it can provide to create lighter parts and help to consolidate and get more durable pieces. Also, it does not require a finished design. It allows to explore the design space of material possibilities from an existing file with only basic information and requirements and optimizes the strength and weight of the product [5, 11]. The cabin compartment in the Airbus A320 model was redesigned and manufactured using generative design techniques. The new part produced is half the weight of the original part and provides a fuel saving of 3,180 kg per part. This reduction can lead to a reduction in CO_2 emissions of 166 metric tons per aircraft per year. Also, the new design was originally designed for the metal additive manufacturing process [17, 18]. In addition, in a study conducted in the aircraft industry in 2021, it was aimed to emphasize environmental factors by conducting experiments to reduce the weight of the Aircraft Seat Structure part [19]. There are many important scientific studies on this subject in the literature. Some of them are the study published in Bayburt University Science Journal and the studies conducted by Nottingham Trent University; here, experimental studies were carried out in robot application using additive manufacturing technology with the design of Humanoid Robot Arm Part [9, 20]. In Technical University of Cluj-Napoca, Cluj-Napoca in Romania, gear optimization was performed using GD with AM technology in a study [21]. The optimization with generative design tools for race car crank bell lever design was conducted on an industrial case to investigate to what extent these tools are suitable for use in early design stages and what the main differences are between them [22].

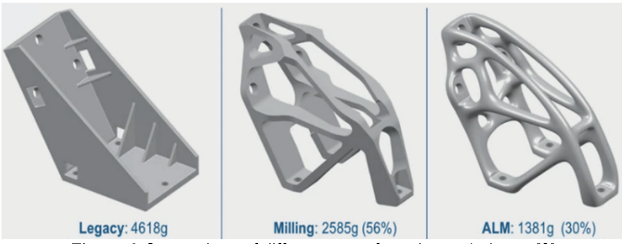

Figure 2 Comparison of different manufacturing techniques [8]

Fig. 2 is divided into three distinct shapes which illustrate different manufacturing processes. The first part is designed and represents conventional manufacturing methods, the second part shows cases production through CNC machining and the third part is for additive layer manufacturing (ALM). In the normal design of 4618 g, a %56 weight reduction was achieved by using the generative design method and the traditional production method.

In the third part, additive layer manufacturing was used as production with the generative design method and a total weight reduction of %86 percent was achieved [23].

2.2 Robocup Organization

The year 1997 was an important year for robotics and artificial intelligence (AI) to take a new form. In May of that year, IBM's Deep Blue, controlled by AI, defeated the world chess champion. On July 4, 1997, NASA's Mars Pathfinder mission successfully landed, deploying the first autonomous robotics system, Sojourner, on the surface of Mars. RoboCup took its first steps toward developing robotic soccer players capable of defeating a human World Cup champion team, alongside these achievements. The concept of robots playing soccer was initially introduced by Professor Alan Mackworth from the University of British Columbia, Canada, in a paper titled "On Seeing Robots," presented at VI-92 in 1992. Before the match, the robots are programmed with artificial intelligence and communicate with this software using a computer, camera, and Frequency modulation (FM) transmitter. The control system of the robots is shown in Fig. 3 [24].

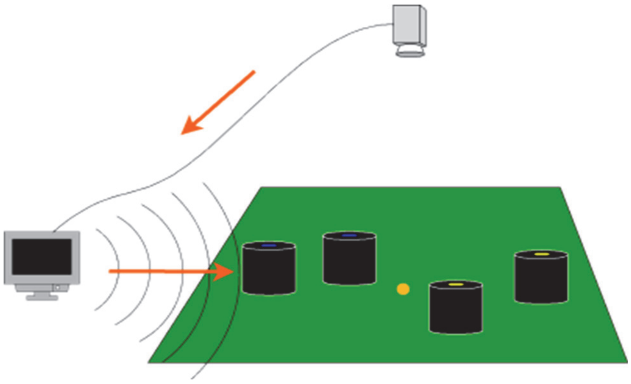
Figure 3 Robots communication system in field [24]

2.3 NEU Islanders

NEU Islanders are an interdisciplinary team consisting of Near East University students and experienced engineers. The team has been participating in RoboCup events since 2012 [10]. Every year, there are significant developments in the teams of autonomous football-playing robots. The NEU Islanders robot system consists of three main components: robot mechanical hardware, electronics and control software [7]. NEU Islanders competes in the Small Size League. The Small Size League, also known as the F180 League, is one of the earliest divisions in RoboCup Soccer [24].


Figure 4 During soccer robot competition at Canada [7]

It focuses on the challenges of intelligent cooperation and control among multiple robots/agents in a fast-paced environment, utilizing a hybrid centralized/distributed system. Each match involves two teams of six robots. The robots must comply with F180 rules, fitting within a 180 mm diameter and standing no taller than 15 cm.

They play soccer with an orange golf ball on a 9m by 6m green carpeted field. A standardized vision system, known as SSL-Vision, tracks all field objects using data from four overhead cameras mounted 4m above the field. The system is open-source and community-maintained. Off-field computers handle the coordination and control of the robots, with wireless communication via commercial radio transmitter/receiver units. Fig. 4, shows the view of players from our robot football team on the field [24].

3 EXPERIMENTAL SET-UP AND METHODOLOGY

Developing and analysing a product is usually used to experiment and change which process has an important feature on the emergence of the process and what these inputs are aimed at to achieve the desired output. Experiments can be planned to collect various combinations of elements. An effective method of experimental planning is to obtain meaningful data at the least possible cost and to achieve the required strong and lightweight structure; the materials to be selected and the production processes are important factors for optimum outputs. These inputs and outputs will be obtained on a platform, with the generative design method of the Autodesk Fusion 360 program, which provides the opportunity to design optimization and analysis [25]. In this work, the road map for improving product stability and robustness, minimizing material waste and reducing the cost of building an agile robot's parts such as the main chassis and electronic assembly member, is given in Fig. 5 [26, 27].

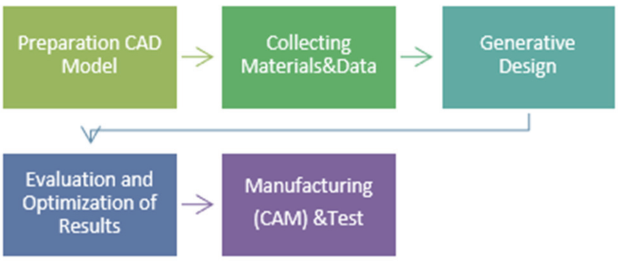

Figure 5 The road map for improving product [26, 27]

Production methods before performing the generative design process can be analysed according to four different ways. The program shapes the optimum design according to these production processes namely, Unrestricted, Additive, Milling, Casting [26, 27].

3.1 Development of CAD Model

A robot must fit inside a cylinder that is 0.18 meters wide and 0.15 meters high at any point in time. Additionally, the top of the robot must adhere to the standard pattern size and surface constraints. In the earlier version, the robot had a speed of approximately 3.5 meters per second and a weight of about 2.46 kg (excluding cover and battery).

Fig. 6 belongs to electronic assembly member that is earlier version. The comparative evaluation criteria include costs, lead time, rigidity, material usability, and weight..

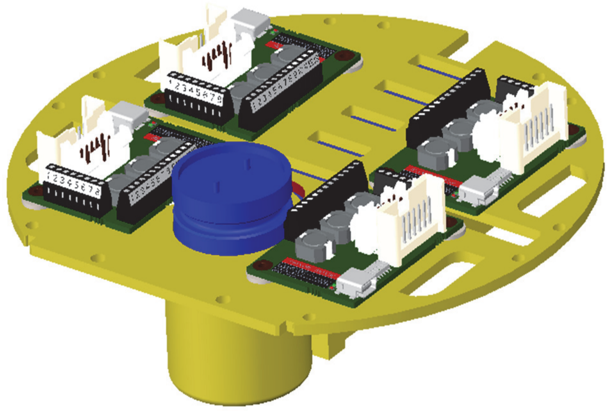

Figure 6 Earlier version of electronic assembly member

Tab. 1, shows in detail the material properties of four different polymer materials Polylactic Acid (PLA+), Acrylonitrile Butadiene Styrene (ABS), Polyethylene terephthalate glycol (PETG) and acrylonitrile styrene acrylate (ASA), for the part to be redesigned with the generative design method.

Table 1 Materials properties of electronic assembly member [28]

Material	Yield Strength / MPa	Flexural Strength / MPa	Tensile Strength / MPa	Flexural Modulus / MPa	Elongation at Break / %	Density / g/cm^3
ABS	66	66	43	2348	22	1.04
PLA+	74	75	63	2108	12	1.25
ASA	35	35	50	4300	30	1
PETG	58.1	68	52.2	1800	225	1.23

This analysis is used to compare parts produced using the traditional design method without utilizing generative design. The comparison encompasses production cost, component weight, and production time. Also, the materials of the previous version of the part are compared with the earlier design. In this study, the comparisons of the new design made according to generative design are also shown in the results section [28].

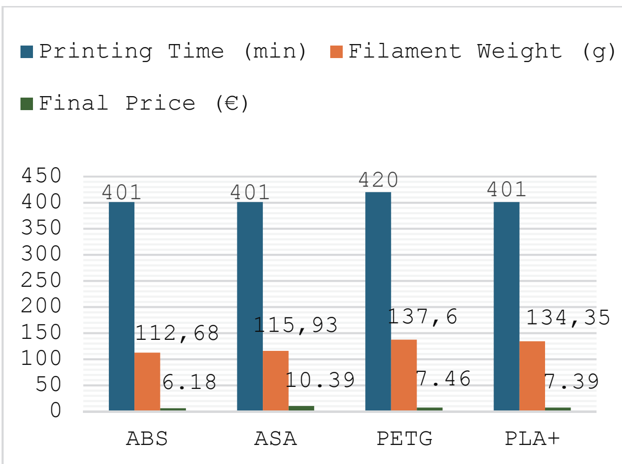

Figure 7 Comparison of price, weight, and printing time

Fig. 7 compares the workpieces produced with different materials and in different combinations according to the earlier design in terms of time, weight, and production costs, and the results show the production cost and production time of each part.

The metal housing for the earlier robot's main body needs improvement. It was produced using the 3-axis CNC method from an alloy steel material with a previous design of 344 g. The goal is to utilize generative design to develop a lighter version without compromising durability. This will involve re-manufacturing it using advanced technology and comparing it with production methods to achieve the desired outcome.

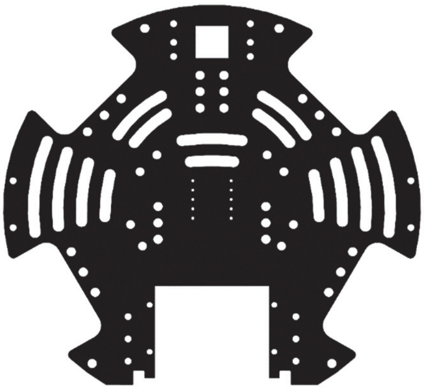

Figure 8 The earlier version of robot main chassis soccer robot

The earlier version of robot main chassis shown in Fig. 8, was made from an alloy steel. The selection of materials plays a crucial role in production planning and prototyping. It is imperative to thoroughly evaluate the distinctive properties of each material and guarantee their compatibility with the appropriate production method. Failure to do so could result in costly setbacks. Fig.8 belongs to the earlier version. The new version materials selection for main chassis includes Aluminium 6061-T651, Aluminium 5083-H111, Aluminium Si10Mg, Titanium-6AL-4V (3.7164/3.7165), and Stainless Steel 316L. The materials specified in Tab. 2 were planned to be compared with CNC, 3D printing, and their manufacturability and other factors are compared. Also, Tab. 2, lists the materials to be analysed and optimized of main chassis [29].

Table 2 Materials properties of main chassis [29]

Material	Yield Strength / MPa	Modulus of Elasticity / GPa	Tensile Strength / MPa	Elongation at Break / %	Density / g/cm^3
Al6061 T651	276	270	310	17	2.70
Al 5083 H111	115	70	270	16	2.66
Al Si10Mg	300	7.9	450	5	2.68
Ti Ti-6AL-4V	1100	114	1170	10	4.43
SS 316L	205	193	515	60	8.00

3.2 Model Preparation to Generative Design Process

At the beginning of the generative design process, the fusion 360 generative design process is started on the prepared CAD file as indicated in Fig. 9. These processes follow each other in order. If all inputs are not correct then the generative design result will not be as desired and correct results cannot be obtained. The path followed for the two workpieces is indicated in detail in Fig. 9.
The robots weight approximately 2.5 kg. Therefore, during the match, the robots apply forces of certain intensities to each other according to their collision speeds.

Using the equations below, the average collision force of the robots against each other during the match was specified as 5, 15, and 25 Newtons (N) respectively. The force distribution acting on the parts was determined during the generative design load case inputs, and the results were concluded according to the study.

$$\text{a) } F_{\text{avg}} = \left(\frac{0.5 \cdot m \cdot v^2}{d}\right) = \text{kg}\,\frac{\text{m}}{\text{s}^2} \qquad \text{(N)} \tag{1}$$

$$\text{b) } F_{\text{avg}} = \left(\frac{m \cdot v}{t}\right) = = \text{kg}\,\frac{\text{m}}{\text{s}^2} \qquad \text{(N)} \tag{2}$$

The formula for impact force is expressed in terms of the body's velocity (speed) in m/s on impact (v), its mass (m) in kg, collision distance (d) in meter, and the (t) is time in sec.

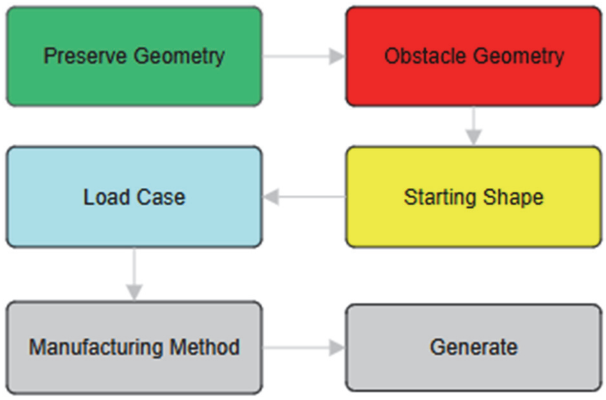

Figure 9 Flow chart sample preparation [30]

Figs. 9 and 10 represent generative design preparations process for two distinct parts. Before the generative design process begins, essential inputs must be entered. The observed geometry, shown in red, indicates the boundaries beyond which the design should not extend. The green areas denote the geometry that must be preserved, while the yellow areas represent the initial shape where the process will be applied. Generative design techniques were then used on these specified areas. In the fourth stage, the forces acting on the component are identified. Once these four stages are fully and accurately defined, the production methods are chosen and the optimisation process begins.

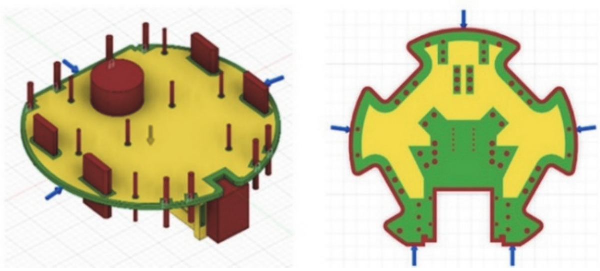

Figure 10 Sample preparation for generative design

4 RESULTS AND DISCUSSION

The Generative Design results of an Electronic Assembly Member are shown in Figs. 11, 12 and 13, the outputs of four different materials and three different load conditions are compared, then, recommended design iterations are determined. Numbers 1,2,3,4 in the figures represent ABS, PLA+, ASA, PETG materials, respectively. Generative design generates outcomes based on constraints defined by the study type, using random values for the specified variables within their defined ranges. As a result, twelve different outputs were obtained.

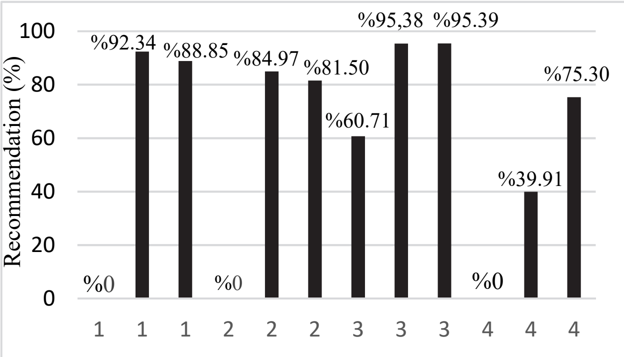

Figure 11 Recommendation of applied 5 N load generative design results

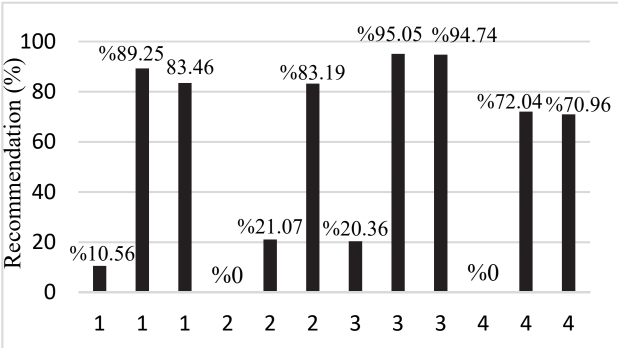

Figure 12 Recommendation of applied 15 N load generative design results

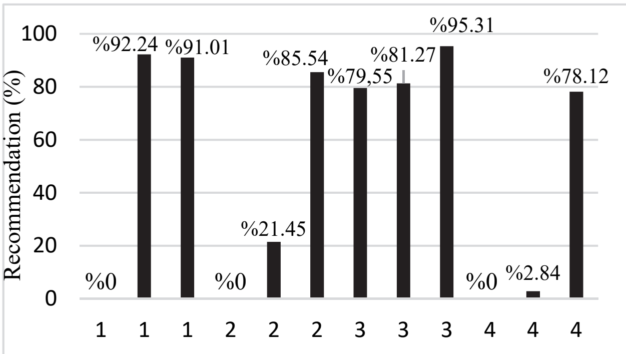

Figure 13 Recommendation of applied 25 N load generative design results

5, 15, and 25 Newtons (N) were applied force for a fixed geometry and the recomended outcomes were max weight reduction settings in the test run.

The Generative Design outcomes for the analyzed primary chassis component of the robot are presented in Fig. 14. Moreover, some abbreviations are listed. These are: Stainless Steel (SS), Titanium (TI), and Aluminium (Al).

25 Newtons force applied condition was analysed for the main chassis. As a result, the most suitable design was chosen after a thorough assessment of various iterations to ensure alignment with production and model requirements.

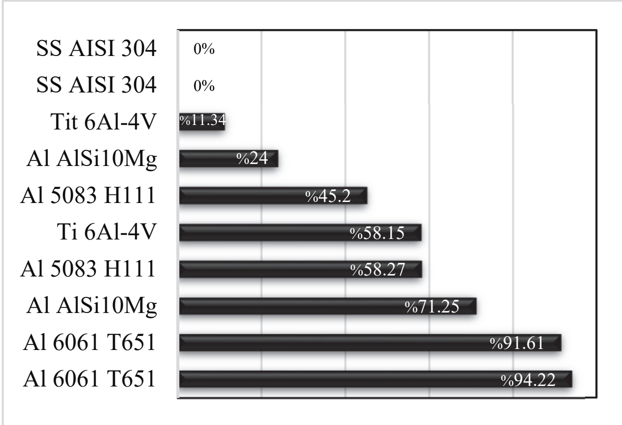

Figure 14 Generative design recommendation of main chassis

4.1 Generative Design Iterations

In this section, Generative Design iterations were calculated and finalized according to various mechanical factors such as load conditions, boundary conditions and material properties. The electronic assembly element was renewed and replaced. Then the main chassis where the motor and kick mechanism systems that make up the chassis were mounted in the second Generative Design example of the robot. Fig. 15 shows the generative design model output of the Fusion 360 program where these processes were performed and belong to the Electronic Assembly Member. Various studies in the literature demonstrate the potential of generative design in engineering processes. For example, Çokatar et al. (2022) stated that the robot arm part was reduced in weight and increased in performance by using 20 times less material on the part with the generative design method [31]. Similarly, Zaimis et al. (2021) reported that the weight of the landing gear part of an unmanned aerial vehicle produced in a 3-axis CNC was reduced by up to 36% by optimizing complex geometries using generative design in the aviation industry.

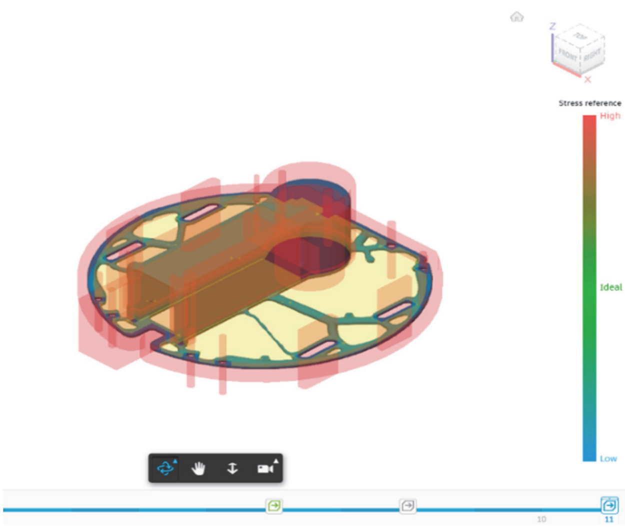

Figure 15 Generative design operation of electronic assembly member

4.1.1 Optimum Design Selection

In this section, the Generative Design outputs were examined and the most suitable model for the desired appearance and use of the robot was selected as a result of the comparisons made. All design outputs and the most suitable model are shown in Fig. 16.

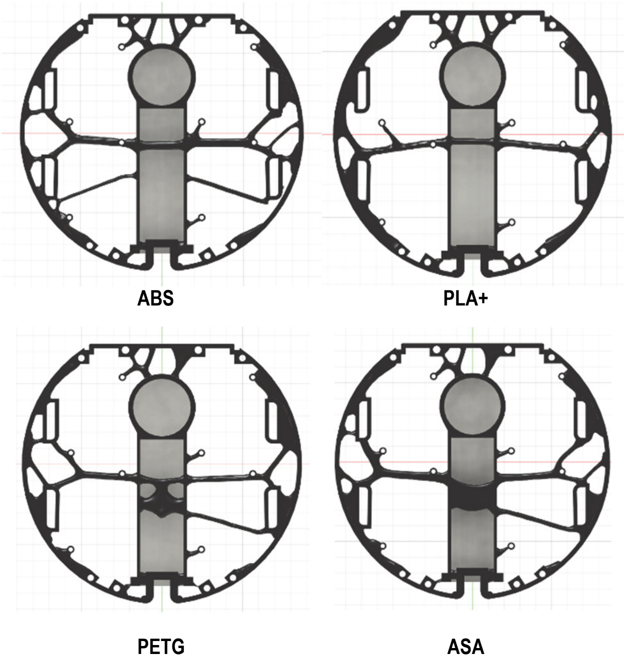

Figure 16 Generative design result exploration

Four different materials were analysed for the part in the middle layer of the robot. As a result of generative design, the most suitable design for the robot was ASA with a %95 recommendation, as seen in Fig. 13. A single prototype was fabricated utilizing ABS, ASA, and PLA+ materials, and its production was subjected to thorough examination. By examining the difference between ABS, PLA and ASA the production and analysis of the part was completed using the most suitable material with the Fused Deposition Modelling method (FDM). Figs. 16 and 17, provide a visual comparison between the earlier version and the newly generated version of the part.

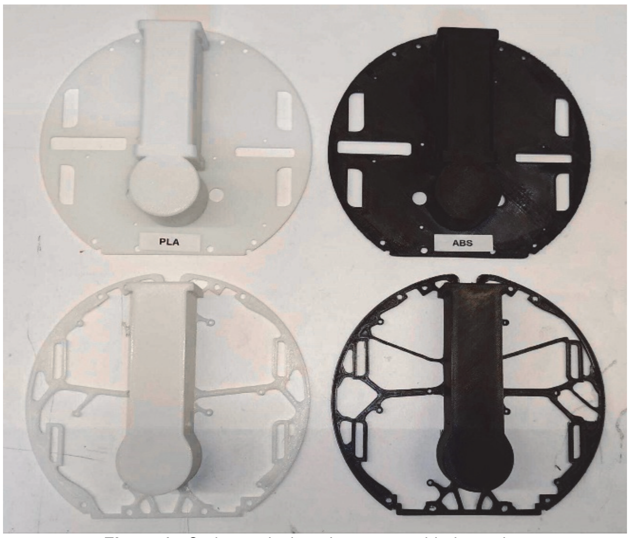

Figure 17 Optimum designed part assembled on robot

As a result of generative design, ASA with a %95 rate was obtained. Initially, ASA material was tested by applying optimum printing parameters and methods.

In the initial trial, the chosen material was deemed optimal for generative design. However, a production issue arose in the form of under-extrusion, resulting in inadequate material usage. Under-extrusion is a common challenge in 3D printing, characterized by insufficient filament extrusion, leading to compromised print quality and the presence of gaps between layers. The quality issue is clearly illustrated with the arrows in Fig. 18.

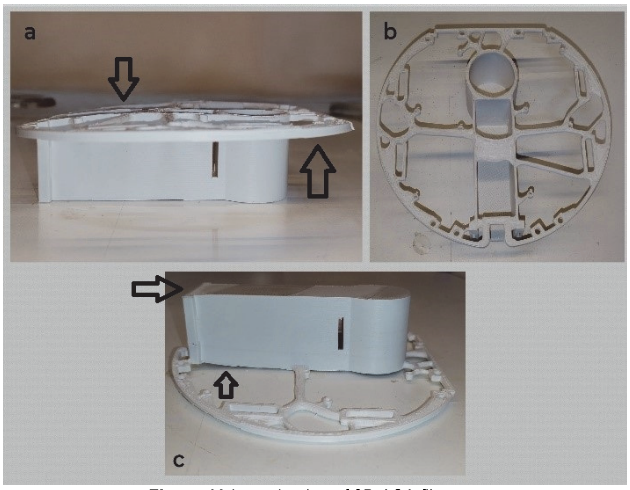

Figure 18 Investigation of 3D ASA filament

In the first printing attempts, a closed environment was created to maintain the stability of the environment. However, the resulting product was not completely satisfactory. The printing speed and temperature were adjusted according to the material properties and the default nozzle active cooling was on when using the 3D printing parameters. The first experiment exhibited problems such as poor surface quality, under extrusion and extruding enough plastic or insufficient material. In the desired model to be achieved, the nozzle active cooling was tried to be turned off and the printing orientation was changed. Hence, the printed test piece succeeded and the desired model was obtained. This was achieved by changing the printing direction as shown in Fig. 19, and a final product was produced successfully.

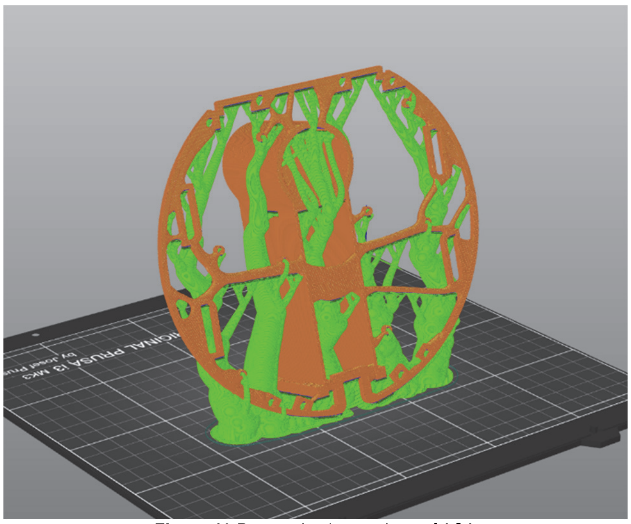

Figure 19 Pre-production settings of ASA

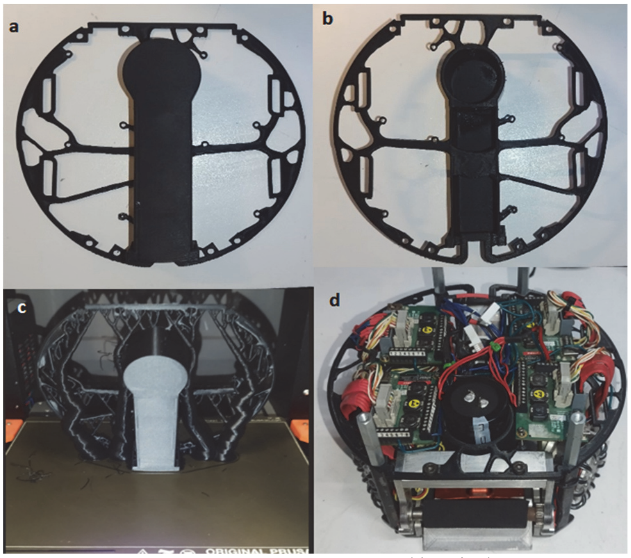

Figure 20 Final production and analysis of 3D ASA filament

Fig. 20 shows printing orientation of ASA filament and surface quality is better than the first orientation which was *x* direction. Good surface quality was achieved with this orientation but the printing time increased to 8 and a half hour and used more material to printing orientation and support settings. In addition, manufacturing cost increased by this setup.

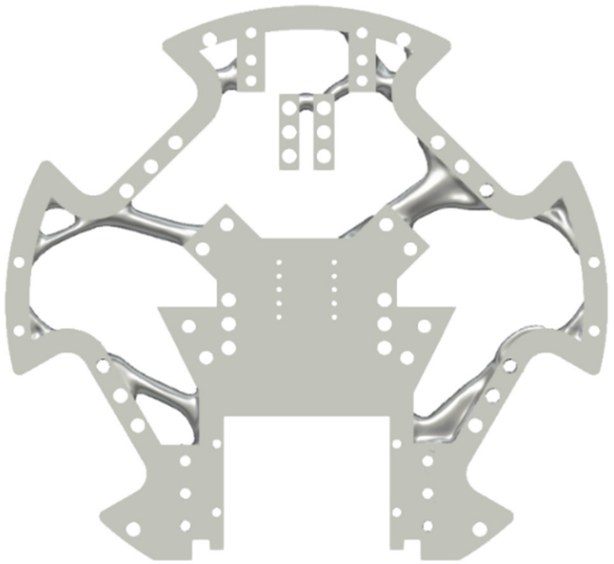

Figure 21 Investigation of main chassis

The metal part (as shown in Fig. 21) was re-modified and designed with the generative design module. Aluminium 6061 T651 alloy showed the highest performance with a recommendation percentage of 94.22% when manufactured using 3-axis milling and 91.62% under unrestricted manufacturing both with similar masses of around 0.092 kg. Aluminium AlSi10Mg alloy has a 71.26% recommendation in unrestricted manufacturing with a mass of 0.0909 kg, but its performance drops significantly to 24.03% when produced through additive manufacturing. Aluminium 5083 H111 has a 58.28% recommendation in unrestricted manufacturing with a mass of 0.09148 kg, and a slightly lower recommendation of 45.25% when using 3-axis milling. Titanium 6Al-4V alloy performed well under unrestricted manufacturing, with a 58.15% recommendation and a mass of 0.1534 kg, but its performance drops drastically to 11.34% in additive manufacturing, where its mass increased to 0.1579 kg.

Stainless Steel AISI 304 performed the worst, with a 0% recommendation in both 3-axis milling and unrestricted manufacturing, accompanied by the highest mass of 0.27317 kg. This indicates that Aluminium 6061 T651 alloy was the best-performing material among various manufacturing methods, while Stainless Steel AISI 304 was not recommended for the processes studied.

4.2 Evaluation of Manufacturing and Post processes

In Tab. 3, manufacturing cost table of the parts according to the materials of the football robot produced using FDM printing technology is given and calculations include printing cost parameters such as labour time, material cost, electricity, etc. Also, ASA material was used to understand calculation table.

Table 3 Manufacturing cost calculation sample [31]

Time / min	Material	Filament Weight / gr	Cost / €
509	ASA	98.42	€10.39
Electricity Price (1 kW/h)			
Active	€0.21		
Printer Consumption			
Prusa MK3S	0.12	kW	
Filament			
Material	**Kilogram**	**Gram**	
ASA	€29.99	€0.04	
Printer Depriciation			
Printer	Active Price	Depriciation	
Prusa MK3S	€999.00	25000	Hours
		€0.00	Dep/min
Labor Cost			
Minumun Wage	€1050.00	160	hrs/mon
		€5.92	Hours

Table 4 Generative design outputs of electronic member assembly

Material	Printing Time / min	Filament Weight / g	Final Cost / €
ABS	329	69.9	€5.03
ASA	509	98.42	€9.89
PETG	319	85.25	€5.83
PLA+	346	93.6	€6.11

Tab. 4 includes a comparison of the production and labour costs for four different materials used in the electronic assembly member part. It shows cost calculations for the generative design outputs of the electronic assembly. Analysing the data for the filament types ABS, ASA, PETG, and PLA+ significant differences and trends emerge regarding printing time, printing quality, filament weight, and final price. Tab. 5 shows detailed comparative analysis of materials. The new version data set generally reflects faster printing times, particularly for ABS and PETG, while ASA's printing time increases significantly. All filaments in Tab. 4 used less filament compared to Tab, 3. In Tab. 3, with ABS and PETG showing the largest reduction, the final costs were lower across the second data set, with reductions for all filaments. This could reflect improved material usage or cost efficiency. The results obtained here have shown that this method is useful and that the product can be obtained very quickly, not only in terms of the weight of the product, but also without the need for material waste, unnecessary costs, molding as in other methods. Moreover, these benefits and carbon environmental effects should not be ignored.

Table 5 Comparative analysis of electronic member assembly

Material	Printing Time / min	Filament Weight / g	Final Cost / €
ABS	18% reduction (from 401 min to 329 min).	38% reduction (from 112.68 g to 69.9 g).	18.6% reduction (from €6.18 to €5.03).
ASA	27% increase (from 401 min to 509 min).	15% reduction (from 115.93 g to 98.42 g).	4.8% reduction (from €10.39 to €9.89).
PETG	24% reduction (from 420 min to 319 min).	38% reduction (from 137.6g to 85.25g).	21.9% reduction (from €7.46 to €5.83).
PLA+	13.7% reduction (from 401 min to 346 min).	30% reduction (from 134.35g to 93.6g).	17.3% reduction (from €7.39 to €6.11).

5 CONCLUSIONS

This study clearly demonstrates the advantages offered by generative design methods in the development of robotic systems. There are various studies in the literature that reveal the potential of generative design in engineering processes. Some of these, Çokatar et al. (2022) stated that the robot arm part was reduced in weight and increased in performance by using 20 times less material on the part with the generative design method. Similarly, Zaimis et al. (2021) reported that the weight of the landing gear part of an unmanned aerial vehicle produced in a 3-axis CNC was reduced by up to 36% by optimizing complex geometries using generative design in the aviation industry. This study differs from other studies in that the current research goes beyond material optimization in robotic systems and addresses issues such as environmental sustainability and carbon footprint reduction. In the study, the first of the re-optimized parts, the electronic assembly element, was used to compare the cost, production and mechanical properties of 4 different polymer materials and optimize the designs. As a result of the optimizations, the highest savings rate in terms of both filament weight and production cost were achieved in ABS and PETG materials, with a decrease of 38% and an average of 20%, respectively. ASA material, although more recommended in terms of mechanical properties (95%), caused the production time to be extended due to the problems experienced in printing. However, despite this, although there is a decrease in material weight and cost compared to the first version, it is more expensive than other materials. PLA+ material generally provided a successful balance in filament saving and cost optimization. The results confirm the benefits of this method. In addition, this study is more comprehensive than other studies, with the possibility of producing both polymer materials and metal materials with traditional methods using a 3D printer. It was investigated and the design and production cost comparisons of the GD method were made. For these reasons, the importance of this study increases. In the study, the material savings ranging from 39.8 to 43% and the weight reduction of 45% obtained in the robotic body design, offer impressive results like similar studies in the literature. In particular, the superior performance of the Aluminium 6061 T651 alloy was highlighted in another influential study. Walia et al. (2021) compared Aluminium alloy, carbon fibre, and polymer PA 12 materials in the robotics industry, stating that optimizing it with generative design achieved a weight reduction of between 85% and 90%. As a result, generative design technology is a powerful tool in the development of robotic systems. Furthermore, this study highlights the importance of innovative methods in robotic design processes that are compatible with sustainability goals. In comparison to similar studies in the literature, this research highlights the diverse contributions of generative design methods by considering not only technical outcomes but also environmental impacts. In this context, the study provides three main contributions to the literature in the field of robotic product design and development:

- Performance and cost optimization: The impact of the use of lightweight materials on the performance of the robots was quantitatively evaluated.
- Material performance analysis: Different material types and manufacturing methods are compared to create a comprehensive dataset to guide future designs.
- Emphasis on sustainability: The application of innovative approaches, material waste, and approaches aimed at reducing carbon footprint have encouraged the environmentally friendly design of robotic systems.

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