Material Selection Methodology for a Go-kart Chassis using FEA and Weighted Decision Matrices

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Abstract: Performance enhancement in automobile parts is usually focussed on design optimization, but a periodic investigation into the material used can provide significant increments as well. This ideology is explored deeply in this paper as the material selection process of a go-kart chassis is demonstrated in the form of load calculations, property comparisons, and finite element analysis. The philosophy behind setting priorities in terms of mechanical properties and finite element analysis results is also discussed. The results are compared using a weighted decision matrix to ensure a balanced decision. This method of comparison can be divided into 3 steps where first, the properties are given weightage, followed by scoring and calculating a cumulative score for each material in correspondence with the criteria considered. These scores were then used to compare all the materials. The material selected based on the result improved the performance of the chassis in terms of safety and performance in a student competition.

Keywords: : AISI,Chassis, FEA, Go-kart, Material Selection

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1. Introduction

Generally, researchers share a consensus that AISI 1018 is the most suitable material for a go-kart chassis [3]. The few other papers look into aluminium grades like 6061-T6 [4]. Thus, largely, AISI 1018 is an industry standard[1]. This complacency of selecting the material on just the basis of mechanical properties leaves an unexplored area in the design methodology for a go-kart chassis [2]. However, it is important to ensure the decision is balanced appropriately between not just performance and cost efficiency, but also safety [28]. This is attempted in this paper.Comprehensive research into a material's properties and its behaviour under relevant loads is the foremost priority when developing a durable chassis. Prime examples can be found on the stress-strain curve itself, from the value of stress at which a material begins to yield (especially in ductile materials) to the value of its ultimate stress, at which it reaches its fracture point. An instance of axial deformation in any member in a spaceframe chassis would inevitably initiate deformations in adjacent members. This phenomenon depends on the value of axial stiffness, derived from the elastic modulus of the material and dimensions of the specific rod. Thus, it is important to know this threshold value for each member before we can aim to design a sufficiently safe and economic chassis.Materials are broadly classified based on these properties as brittle and ductile. Brittle materials demonstrate almost no deformation before they break, as can be observed in the case of glass. On the other hand, ductile materials can deform permanently after a certain limit. This limit proves useful in predicting how well a material will deform and hold shape to form components, as well as how the component would react to working stresses. Common engineering metals can also show disparity, as cast iron fractures easily under a sharp blow, but mild steel would only bend [6]. A lightweight chassis can promote dynamism in a go-kart with respect to its racing characteristics. Thus, it must be factored into design considerations.

In this paper, a methodology to understand and select the most suitable material to design and manufacture a go-kart chassis, based on fundamental research of such characteristics and Finite Element Analysis (FEA) of the chassis with the materials shortlisted based on considerations such as safety, cost, etc. Mechanical properties of the materials are defined and compared. A cumulative report is then prepared based on the comparison of the materials based on the mentioned criteria [29]. For FEA, a chassis of a kart with an estimated total mass of 170 kg with the driver was analysed. The chassis used in the paper was a space frame type chassis. The outer diameters of the hollow cross-section pipes were 31.75mm (for outer body members) and 25.4mm (for internal members and body mounts) with the thickness being 1.6mm. The minimum cross-section was kept 25.4mm to meet the need of safety with respect to modal analysis. SOLIDWORKS 19.0 was used to measure and design the structural members of the chassis and ANSYS 18.1 was used for its analysis.

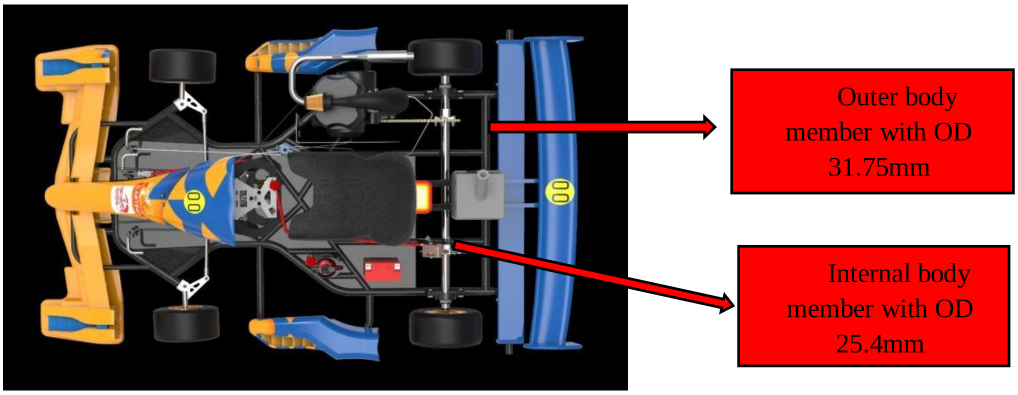


Fig.1: CAD Design and Render of an assembled Go-Kart.

2.Material Selection Methodology

Selection of material has to be made based on the complete evaluation of properties, safety, cost etc. and the affect these factors make on the final performance of the kart. A methodology is defined below mentioning the major considerations and calculations made for the overall comparison of materials.

2.1 Performance Requirements of the kart

The first characteristic that comes to mind when the word performance is used with respect to automobiles is acceleration. It is a well-known fact that for an applied force, the acceleration generated is inversely proportional to the mass of a body. Thus, the material used for the second heaviest component of the go-kart, the chassis, has a great potential to provide performance increments. As discussed earlier, it can also improve racing characteristics by boosting the dynamism of the go-kart. Weight reduction also translates to an improvement in fuel efficiency [27] which can be accomplished in multiple ways like using low density materials (eg. Steel) without compromising on stiffness and reliability, topology optimization of designed parts to maintain a sufficient factor of safety and replacing spot welded joints with other methods that promote weight reduction.

Secondly, the chassis must also act as an efficient impact attenuating device in a go kart, by keeping the stress generated to a minimum. This could be critical in the instance of a crash. Thus, the material selected must possess adequate properties to withstand such a scenario.

2.2 Economic effectiveness

When a material is being chosen for a particular component in a car, cost acts as a major factor in this decision. For student competitions, it is necessary to stay within the range of the budget allotted to a particular team and not overspend. The cost is usually divided into three sectors: the cost of raw materials, the manufacturing value added, and the cost of designing and validating the product. For this paper, selection of material for the chassis is the aim taking these 3 sectors into consideration. Composite Materials are inarguably more expensive than alloy steels and cast irons currently in use. Because the cost of lighter metals may be higher, decisions to use them must be justified by improved performance. Hence, one of the major barriers to the use of composite materials is their high cost, and since we want to select the best material based on all factors, materials like carbon fibre and other composites are avoided to maintain the balance between cost and performance.

2.3 Candidate Materials:

The initial screening of the materials was done based on performance requirements, economic factors, availability, manufacturability, etc., mentioned in Figure 2. [5]

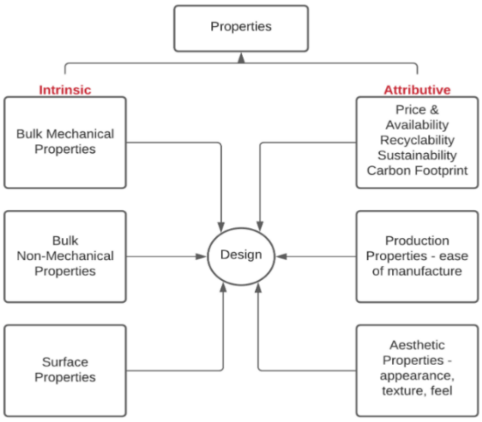


Figure 2. Factors for candidate material selection

The chosen materials are:

- Gray Cast Iron
- Aluminium 6063-T6
- AISI 4130 Steel, annealed at 865°C furnace cooled 11°C/hour to 680°C air cooled.
- AISI 1340 Steel, annealed at 800°C, furnace cooled 11°C/hour to 600°C, air cooled
- AISI 1030 Steel, annealed at 845°C
- AISI 1118 Steel, annealed at 790°C (1450°F)
- AISI 4320 Steel, annealed at 850°C (1560°F)
- AISI 1018 Steel, cold drawn

2.4 Mechanical Properties:

Comparison of materials based on their mechanical properties constitutes an important aspect in the material selection process. Properties like density, tensile strengths, modulus of elasticity, reduction of area and machinability are the major properties that affect the manufacturability and performance of the chassis based on safety and weight reduction. Density of the material signifies the weight that the chassis would carry after manufacturing. The material with the least density will form the lightest chassis, and vice versa. Yield strength symbolizes the minimum stress at which the deformation of a material becomes plastic. It can also be represented as the maximum stress bearable (on the stress-strain curve) before it starts diverging from the stress-strain proportionality, owing to the linearity of elastic deformation. All the values of stresses below this can withstand the elastic deformation associated with the material. Once the stress values exceeds this yield strength, the deformation caused is permanent. Certain plastics show linear elastic deformation leading to material fracture on reaching the maximum strength.

Hence, it can be understood that a material with higher value of yield strength can resist greater values of working stresses produced. Ultimate tensile strength is the maximum tensile load a material can withstand prior to fracture. It describes the material's resistance to fail or fracture under tensile loads. Bulk modulus is a numerical constant that describes the elastic properties of a solid or fluid when it is subjected to pressure on all sides. When pressure is applied to a material, its volume decreases, but it returns to its original volume when the pressure is removed. It describes a substance's resistance to a change in volume when acted upon by compressive forces on all sides. It is calculated by finding the appliedpressure per unit relative deformation. Hence, higher the valueof Bulk's modulus, lower the deformation occurring on impact. Poisson's ratio is the ratio of the lateral shrinkage strain to the tensile strain. However, since all candidate materials have close to equivalent values, it is not used as a benchmark comparison. Reduction in area at break is the maximum decrease in cross-sectional area at the fracture expressed as a percentage of the original cross-sectional area. Percentage reduction in area is used to measure the ductility, which is a material's ability to withstand large plastic strains under stress before fracture. Reduction is calculated in % by$\left(\frac{A_0 - A_{Break}}{A_0} x\ 100\right)$. Thus, higher the % reduction in area of a material, greater the ability to withstand tensile forces. The best material according to this consideration will be determined based on the cumulative result of all these properties. [5]

2.5 Finite Element Analysis (FEA)

Finite element analysis (FEA) is used as a computer aided method for understanding the behaviour of the chassis when subjected to physical force in the real world. Finite element analysis determines whether the chassis will break, wear out, or perform as intended. Here the chassis is divided into small sizes, known as element and collective elements on the model form a mesh. The software solves the conditions for individual elements and shows a collective result. The computer solves by the computational method provided.

The chassis was modelled in SOLIDWORKS 2019 as shown in Figure 3. Analysis of the designed chassis was obtained using ANSYS 18.1. For selection of material, only front static structural analysis was carried out as impact from the front is one of the most common phenomena under natural conditions, forming a base for all safety considerations for the kart, and subsequently would provide sufficient information about the behaviour of the material when a load acts on it [26]. On ANSYS, the chassis is input with the maximum possible load computed via hand calculations, and solved by providing the necessary boundary conditions for the front impact analysis which include fixed supports, displacements, and the load applied on the chassis as shown in Figure 5. Because the stress distributed value produced from the analysis must always be within the range of the yield stress value of the material chosen, the optimal FOS for such structures should be more than 1. Higher the value of FOS, better will be its stress distribution, reducing the risk of failure. Thus material with the highest FOS would be given the best rank after comparison.

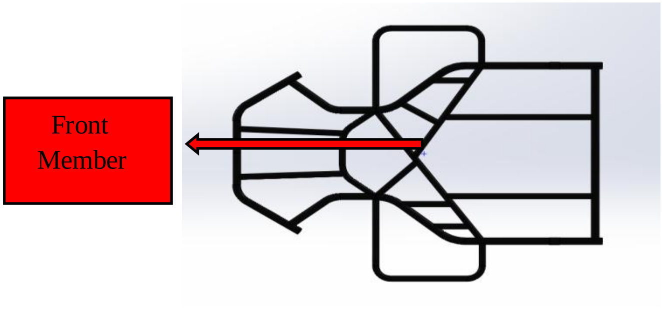


Figure 3. Geometric Model of Chassis

2.5.1 Force Calculation:

G-Force Method of Static Structural Testing [7]:

During front impact, a 5G force is believed to function on the kart. It is measured as:

G-Force (G) = M x g Impact force = 5G

= 5 x M x g

= 5 x 170 x 10

= 8,500 N

The same can be verified by the Work-Energy Theorem.

Consider impact velocity on the kart to be 20m/s with an impact time of 0.2s during the front and rear impact.

Calculations:

Work Done = Kinetic Energy

$= 1/2\ mv^2 = 1/2 \times 170 \times 20^2 = 34{,}000N$

Also, Work Done = Force x Displacement

34000 = Force x (velocity x time)

34000 = Force x (20 x 0.2)

Force = 8,500N

This calculated force was now input on the front member of the chassis for the finite element analysis for further investigation of the materials based on the factor of safety and deformation.

2.5.2 Element (Meshing)

Meshing is the process of breaking down an object's continuous geometric space into thousands or more shapes in order to properly define the physical shape of the object. The more detailed the mesh, the longer the processing time and the higher the accuracy of the 3D CAD model, allowing for high precision simulations. The size of the mesh was kept to be 5mm to comply with the hardware of the system and the type of mesh used was tetrahedral as seen in Figure 4.

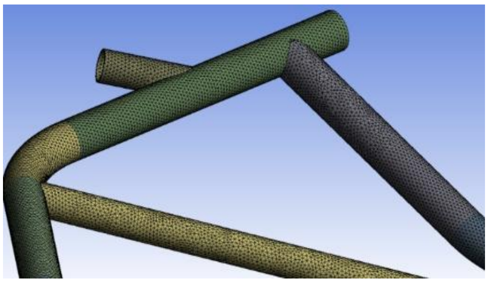


Figure 4. Chassis member after meshing

2.5.3 Boundary conditions

The boundary conditions include the constraint points, displacement points and the member on which the force is applied as shown in Figure 5. For front structural analysis, the chassis is constraint about the rear bearing points, while the stub-axle mounting points acts as displacement points. The force is applied on the frontmost member of the chassis for this analysis.

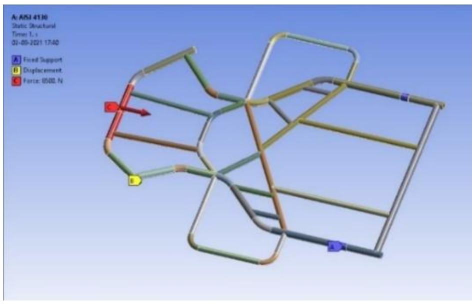


Figure 5. Boundary conditions applied for analysis

2.5.4 Solutions for Finite Element Analysis

The analysis for all the candidate materials was conducted on ANSYS 18.1 to obtain the FOS and deformation undergone by the designed chassis when a load acts on it in front static impact. The consequent results for each material can be observed in Figures 6-21.

i) GRAY CAST IRON:

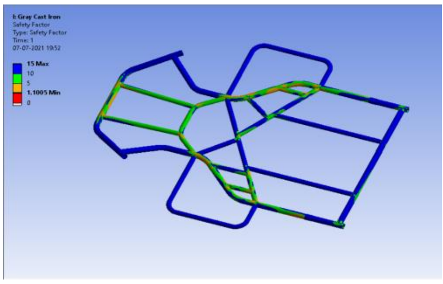


Figure 6. Gray Cast Iron FOS

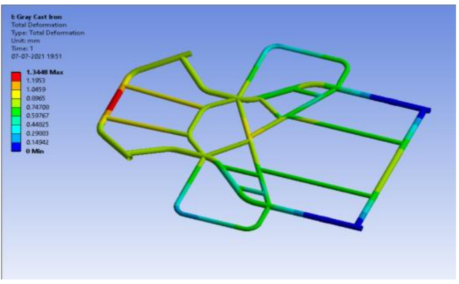
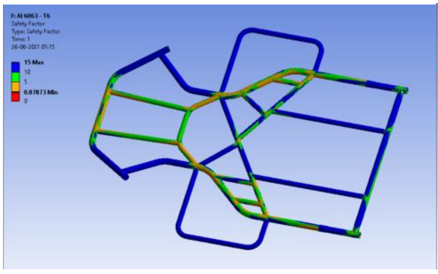


Figure 7. Gray Cast Iron Deformation

ii) ALUMINIUM 6063-T6:



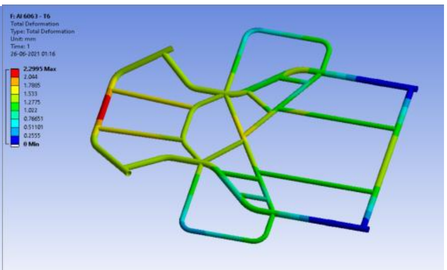
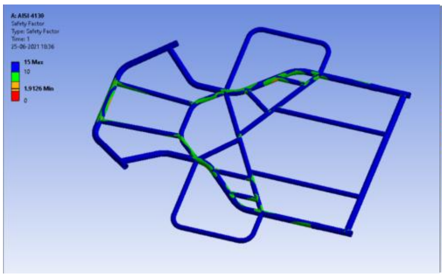


Figure 8. Al 6063-T6 FOS

Figure 9. Al 6063-T6 Deformation

iii) AISI 4130 STEEL:



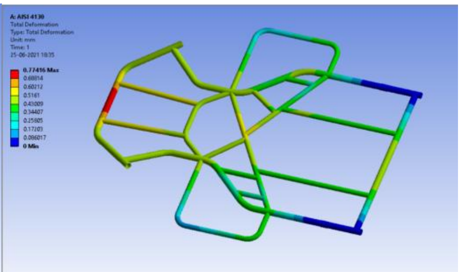
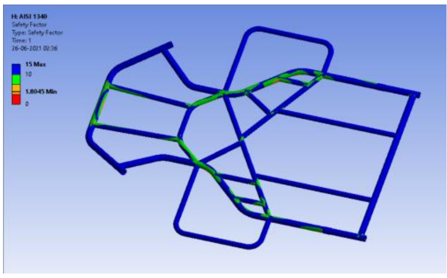


Figure 10. AISI 4130 FOS

Figure 11. AISI 4130 Deformation

iv) AISI 1340 STEEL:



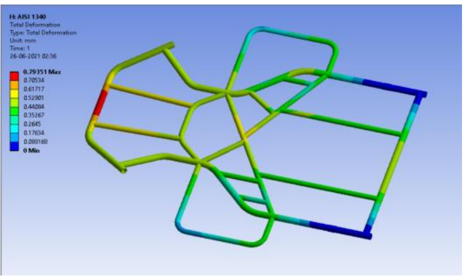
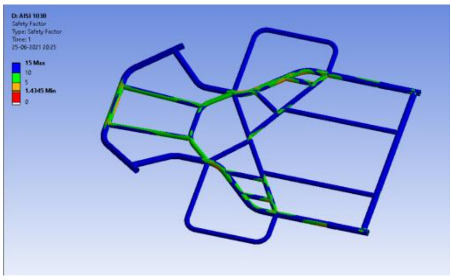


Figure 12. AISI 1340 FOS

Figure 13. AISI 1340 Deformation

v) AISI 1030 STEEL:



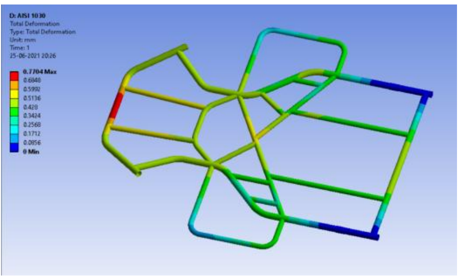
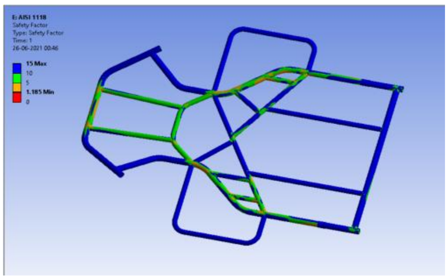


Figure 14. AISI 1030 FOS

Figure 15. AISI 1030 Deformation

vi) AISI 1118 STEEL:



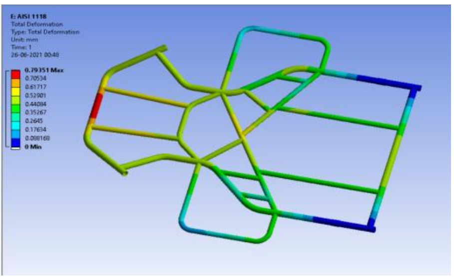


Figure 16. AISI 1118 FOS

Figure 17. AISI 1118 Deformation

vii) AISI 4320 STEEL:

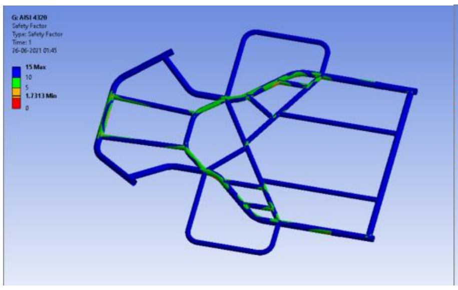


Figure 18. AISI 4320 FOS

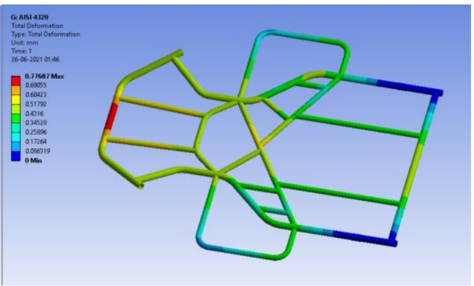


Figure 19. AISI 4320 Deformation

viii) AISI 1018 STEEL:

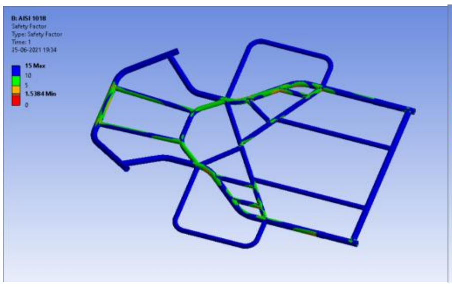


Figure 20. AISI 1018 FOS

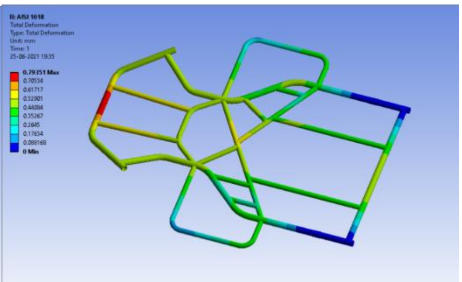


Figure 21. AISI 1018 Deformation

3.Results and Discussions

Weighted Decision Matrix: The weighted decision method of screening materials was adopted. This is a three-step process. [8][9]

- Since all properties do not carry the same importance, they were sorted into a priority order and each result listed above was given a "weightage" in the form of a decimal ranging from 0 to 1. The weightages add up to 1. This is demonstrated below in Figure 22.
- Next, the materials were assigned a score for each property, with the most desirable material based on a specific characteristic being 1 for that property, and the least desirable being 8. This is shown in Tables 2 and 4
- The ranks are multiplied with the corresponding weightages. The sums of these scores for each material are then compared, as in Table 5 and the material with the lowest number is deemed the most suitable for our purpose.

Step1:

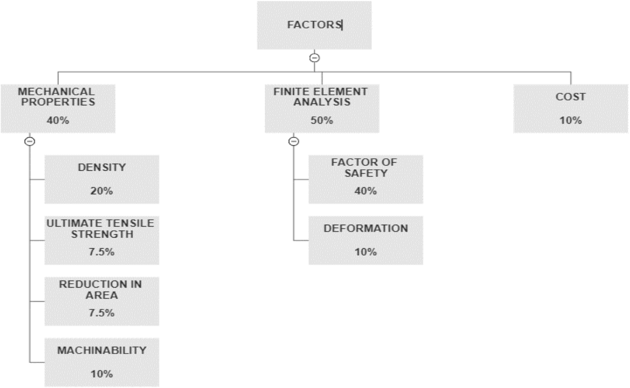


Figure 22. Flowchart showing weightage distribution

Since the chassis primarily serves the function of a load bearing structure, the finite element analysis results are prioritized. The factor of safety for a ductile material is given as: $\frac{TENSILE\ STRENGTH\ ,YIELD}{MAXIMUM\ \ WORKING\ STRESS}$

Since the tensile yield strength is used to determine the factor of safety, its weightage has been clubbed with the factor of safety weightage. It is given the highest weightage (40%) as it describes the ability of the structure to sustain loads and prevent component failure. Similarly, the deformation in the design for a particular material changes with the value of its modulus of elasticity. Thus, its weightage has been clubbed with the weightage assigned to deformation. The chassis is one of the heaviest parts of a go-kart, and thus even a small percentage of weight reduction can result in a significant performance increment. Density, which relates to the weight of the final product, is thus given the highest priority amongst the mechanical properties. An excess amount of funds invested in the manufacture of chassis can hinder the possible development of another subsystem in the go-kart. Thus, cost of the materials per kilogram is factored into the decision, and allotted the next highest weightage. Tensile ultimate strength and reduction in area relate to the material's behaviour under loads that could end in fracture. Hence they are given equal weightage after cost. Since the material is bought in the form of hollow pipes, machining involves only cutting, bending and profiling. The equipment to carry these processes out is easily available. Thus it is assigned the least weightage.

3.1 Based on Mechanical Properties and Cost:

Table 1. Mechanical Properties and Cost of Materials [10]-[25]

Material	Density (g/cc)	Tensile Strength, Ultimate (MPa)	Tensile Strength, Yield (MPa)	Modulus of Elasticity (GPa)	Poisson's Ratio	Reduction of Area	Machinability	Cost / kg (in $)
Gray Cast Iron [10][11]	7.20	310	265	118	0.294	-	48.8 %	0.6-0.7
Aluminium 6063-T6 [12][13]	2.70	241	214	68.9	0.33	30 %	50 %	3.28 – 4.16
AISI 4130 Steel [14][15]	7.85	560	460	205	0.29	59.6 %	70 %	0.625 – 1.25
AISI 1340 Steel [16][17]	7.87	703	434	200	0.29	57.3 %	50 %	0.55 - 0.65
AISI 1030 Steel [18][19]	7.87	460	345	206	0.29	58 %	70 %	0.50 – 0.80
AISI 1118 Steel [20][21]	7.85	450	285	200	0.29	67 %	85%	0.50 – 0.56
AISI 4320 Steel [22][23]	7.85	580	425	205	0.29	58 %	60%	0.5-1
AISI 1018 Steel [24][25]	7.87	440	370	200	0.29	40 %	70 %	0.65 – 0.89

Step 2:

As mentioned above, the most desirable material based on a specific characteristic is ranked 1 for that property, and the least desirable is ranked 8. If multiple materials are equivalent for a certain property, they're assigned the same rank. The next best material is then ranked after counting these as 1 each. For example, if three materials are ranked third, the next best material would be ranked sixth as shown in Table 2.

Table 2. Scores of materials based on Mechanical Properties

Material	Density Rank x Weightage	Tensile Strength, Ultimate Rank x Weightage	Reduction of Area Rank x Weightage	Machinability Rank x Weightage	Cost x Weightage
Weightage	20 %	7.5 %	7.5 %	5 %	10 %
Gray Cast Iron	2 x 0.20 = 0.40	7 x 0.075 = 0.525	8 x 0.075 = 0.60	8 x 0.05 = 0.40	3 x 0.1 = 0.3

Aluminium 6063-T6	1 x 0.20 = 0.20	8 x 0.075 = 0.60	7 x 0.075 = 0.525	6 x 0.05 = 0.30	8 x 0.1 = 0.8
AISI 4130 Steel	3 x 0.20 = 0.60	3 x 0.075 = 0.225	2 x 0.075 = 0.150	2 x 0.05 = 0.10	7 x 0.1 = 0.7
AISI 1340 Steel	6 x 0.20 = 1.20	1 x 0.075 = 0.075	5 x 0.075 = 0.375	6 x 0.05 = 0.30	2 x 0.1 = 0.2
AISI 1030 Steel	6 x 0.20 = 1.20	4 x 0.075 = 0.30	3 x 0.075 = 0.225	2 x 0.05 = 0.10	3 x 0.1 = 0.3
AISI 1118 Steel	3 x 0.20 = 0.60	5 x 0.075 = 0.375	1 x 0.075 = 0.075	1 x 0.05 = 0.05	1 x 0.1 = 0.1
AISI 4320 Steel	3 x 0.20 = 0.60	2 x 0.075 = 0.150	3 x 0.075 = 0.225	5 x 0.05 = 0.25	5 x 0.1 = 0.5
AISI 1018 Steel	6 x 0.20 = 1.20	6 x 0.075 = 0.450	6 x 0.075 = 0.450	2 x 0.05 = 0.10	6 x 0.1 = 0.6

Step3:

These ranks are multiplied with the corresponding weightage to give scores. Since Rank 1 indicates the most suitable material for any given property, the lowest score indicates the most suitable property for our purpose.

3.2 Based on FEA

The results obtained in Table 3 are deduced from section 2.5.4 shown from Figures 6-21.

Table 3. Summary of Static Structural Analysis (Front)

Material	Max Deformation	Factor of Safety (FOS)
Gray Cast Iron	1.3448	1.1005
Aluminium 6063-T6	2.2995	0.87873
AISI 4130 Steel	0.77416	1.9126
AISI 1340 Steel	0.79351	1.8045
AISI 1030 Steel	0.7704	1.4345
AISI 1118 Steel	0.79351	1.185
AISI 4320 Steel	0.77687	1.7313
AISI 1018 Steel	0.79351	1.5384

Similarly, the results obtained for FOS and deformations for respective materials through FEA as summarized in Table 3, are also given ranks, and consequent scores are calculated in accordance with the weightage allotted for both as shown in Table 4.

Table 4. Scores of materials based on FEA

Material	Max Deformation Rank x Weightage	Factor of Safety (FOS) Rank x Weightage
WEIGHTAGE	10 %	40 %
Gray Cast Iron	7 x 0.1 = 0.7	7 x 0.4 = 2.8
Aluminium 6063-T6	8 x 0.1 = 0.8	8 x 0.4 = 3.2
AISI 4130 Steel	3 x 0.1 = 0.30	1 x 0.4 = 0.4
AISI 1340 Steel	1 x 0.1 = 0.10	2 x 0.4 = 0.8
AISI 1030 Steel	1 x 0.1 = 0.10	5 x 0.4 = 2.0
AISI 1118 Steel	5 x 0.1 = 0.5	6 x 0.4 = 2.4

AISI 4320 Steel	4 x 0.1 = 0.4	3 x 0.4 = 1.2
AISI 1018 Steel	5 x 0.1 = 0.5	4 x 0.4 = 1.6

3.3 Cumulative Result

Once the scores based on mechanical properties [Table 2] and FEA [Table 4] are obtained, a cumulative score is calculated to determine the final result. The material with the lowest overall score will be deemed feasible for the required application.

Table 5. Cumulative Result based on the methodology

Material	Cumulative Scores
Gray Cast Iron	5.725
Aluminium 6063-T6	6.425
AISI 4130 Steel	2.475
AISI 1340 Steel	3.050
AISI 1030 Steel	4.225
AISI 1118 Steel	4.10
AISI 4320 Steel	3.325
AISI 1018 Steel	4.90

4.Conclusion

The material selection for the chassis of a go-kart was carried out by comparing different material properties in section 3.1 and finite element analysis as shown in section 3.2 specific to the design in a weighted decision matrix mentioned in section 3. Along with a complete understanding of available materials and their properties, this ensured that the material chosen struck a balance between our prioritised properties. Hence, AISI 4130 is deemed most appropriate for our purpose with the lowest score of 2.475 based on the result shown in Table 5 in section 3.3. In conclusion, the performance, reliability and cost-efficiency of the kart were enhanced by the use of AISI 4130 as the material of the chassis,utilised in a national level go-kart designing competition.

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