" A CRITICAL ANALYSIS AND EVALUATION FOR SELECTION OF MATERIAL FOR INDUSTRIAL ROBOTS USING ANALYTICAL HIERARCHY PROCESS”

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Key words : Robotics, Material, Design, Analytical Hierarchy Process, Decision Making, Significance

Abstract:

Robotics is one of the emerging field in the engineering. It covers various areas such as industrial, agricultural, medical and automated vehicles. Industrial robots are more widely used in a variety of working environment from precision manufacturing to heavy industry in extreme conditions of operation. The industry require where adaptability, precision and reliability and material choice often determines how efficient a robot performs the job. Materials are the backbone of industrial robots which represent its durability, flexibility and performance. Generally, variety of materials used in robotics such as steel, aluminum, Titanium and carbon fiber consists with different characteristics like strength, density, elasticity and Thermal conductibility. The metallic properties and its significance is different in each metal. The material selection in robotics depends on the application and various factors like strength, density, MoE and Thermal Conductivity. Selection of robot right material is a big decision to ensure its performance and reliability otherwise serious failures arises. In many industrial engineering applications the final decision is based on the evaluation of a number of alternatives in terms of a number of criteria. This problem may become a very difficult one when the criteria are expressed in different units or the pertinent data are difficult to be quantified. The Analytic Hierarchy Process (AHP) is an effective approach in dealing with this kind of decision problems. This paper examines some of the practical and computational issues involved when the AHP method is used in industrial engineering application.

1. INTRODUCTION.

The Robots not entered into the manufacturing industry until the early of 1960. Robots involved in the manufacturing industry in 1960. The first programmable robot was invented by the George Devol and named as “Unimate”. It is initially implemented in General Motors industry in 1961 for moving the metal pieces from place to another. In between 1980 and 1990 many advancements came in robotics and involved in various other industries such as automotive, food processing and electronics etc.

The 21st century is remarkable for Industry 4.0 reached significant milestones in the development of Robotics. Recent landscape of robotics in manufacturing is more degree of automation and digitization. It is remarkable beginning of new era of robotics in manufacturing industry. Robots involved in manufacturing industry by storm, performs various tasks to enhance the productivity, quality and safety while reducing the errors. Over the years, robots perform various critical tasks with integration of innovative technologies such as artificial intelligence, machining learning, data science and Internet of Things. These technologies make the robotics as smarter, autonomous and more interconnected for manufacturing. 2

Robotics combines various engineering and technology disciplines. It plays a vital role in the manufacturing industry for enhancing the precision, safety and productivity. Robots perform the automation of repetitive, labor-intensive and harmful tasks by reducing the human intervention. It will contribute strategic roles, cost savings, increased production and flexibility in manufacturing. Robots can perform various tasks in manufacturing such as assembly, material handling, welding, cutting and machining to increase the productivity by reducing cycle times.

Metals are playing vital role in building robots. Robotic body made-up with variety of materials such as steel, aluminum and hard plastic depends on its application. The metallic properties and its significance is different in each metal. The mechanical engineers often face the critical situation in selection of metal among multiple properties. The Analytic Hierarchy process can solve such complexity in decision making for selection of material.

The remaining part of the paper is as follows. The Section 2 describe the related work focusing on The method of Analytical Hierarchy Process and material selection based on its properties. The overview spectrum of Materials and its properties mentioned in Section 3. Section 4 presents the methodology of Analytical Hierarchy Process for selection of material for industrial robot. Section 5 describes the experimental evaluation of material selection using the AHP mathematical derivations. Finally a discussion about future scope and inferences discussed in section 6.

2. LITERATURE REVIEW

A Systematic literature is a way of discovering, assessing and inferring knowledge and insights related to problem area. Over the years many researchers identified the role of material selection in robotics engineering and carried out the huge amount of work in the area of material selection. This concept of taxonomy can be useful in extending the core knowledge of material selection in robotic technology. The relevant literature falls into AHP Mathematical model for decision making, metallurgy and mechanical engineering.

Analytical Hierarchy Process and Analytical Network Process implemented for selection of suitable material for an Axle in Multiple Attribute Decision making(Atual Sharma et al., 2015). The raking method explores the selection of priority for manufacturing of an axle for motorcycle from various criteria.

The material selection in robotics based on specific application and material properties. The metallurgy plays vital role in robotic design engineering (Chithanya. B.V et al, 2001). The engineering design criteria and facts considered when selection a particular material for a certain design

Examine the practical and computational issue when AHP method the engineering applications. The final decision depends on the evaluation of used numbers alternatives and number of criteria. This problem may be very difficult due to numbers of alternatives and criteria (Evangelos Triantaphyllou et al, 1995) .

The collection of requirement from various stakeholders in adequate, timely is crucial than anything else in the requirement engineering in the software development life cycle(Healen Sharp et al.,1999).

The implementation of two Multi Criteria Decision Making methods such as FAHP and FTOPSIS for ideal solution and most convenient for robot selection in real time environment (Mahmood Shahrabi,2014).

The Analytical Hierarchy Process Decision Making Method for Selection of Robot of operation of Spot Welding (Rajani & Jawahar Babu, 2016). The selection of appropriate robot for Spot Welding based on various technical parameters.

The principles and Philosophy of Multi criteria decision making approach [AHP] invented various applications (Thomas L. Satty, 1990).

3. OVERVEIW SPECTRUM OF MATERIALS AND ITS PROPERTIES

Metal are playing vital role in building robotics applications. Robotic arm made-up with variety of materials such as steel, aluminum and hard plastic depends on its application. Industrial robots frequently used such material like cast iron and steel due to its strength and durability. Aluminum used in robots due to its lightweight property to operate on a machine(Chithanya B.V et.al., 2017). The other material titanium or carbon fiber composites used in specialized robots for space applications. The selection of material depends on various factors i.e intended use of application, ability to handle heavy load, operational environment with required precision and durability(Sahil Dilip Yadav et.al, 2021). .

Generally, the following materials will be used in the robotics design.

Steel : Steel material generally used in robotics due to its high strength, toughness and enough suitable for components work in harsh conditions in a repetitive task. It is remarkable characteristics such as temperature resistance, corrosion-resistance being hard easily and excellent machinability. Steel is durable and strong enough, often used in the structural components of robots. It is ideal for frames, gears, motor components and for end effectors.

Aluminum : Aluminum material used in industries due to its magnificent lightweight, weldability, heat resistance and corrosion resistance characteristics which are suitable lightweight robotics arms. It is weldable with heat resistant and can be coated with a protective oxide layer(anodized) to enhance its corrosion resistance. Aluminum is more expensive metal than steel. In Robotics applications Aluminum is used for frames (polished exteriors), customized enclosures, end-of-arm tooling, wheels and bearings.

Plastic : Plastic material is light weighting and Acetal has added for boasting the good dimensionality, stability with low friction. These properties in robotics required for repeat actions or for sliding. Hard plastic material used in the 3D printing for creating custom parts and prototypes of robotics arms. It is an inexpensive than other robotic materials, so generally used in frames, casings, housings etc.

Titanium: Specialized robots used for the specific purpose applications where weight is a critical factor. It includes fiber composites with high strength to weight ratio along with corrosion resistance. Soft, stretchy and electrically conductive hydrogels are used for creating the robotic skin and touch sensor.

Carbon Fiber : The Carbon fiber material is a chemical and mechanical process made of thin strands of the elements of carbon. It consisting of thin strong crystalline long chains of carbon atoms bonded together. The material with several advantages includes high strength and temperature tolerance, high tensile strength, high chemical resistance, light weight and low thermal expansion. Due to these reasons carbon fiber very popular in building airplanes, military, civil engineering, musical instruments, motorsports including with other competition sports.

The material selection in robotics is crucial and its depends on various factors, like Strength, Density, MOE and Thermal Conductivity. Generally robots made with steel, aluminum, titanium. and Carbon Fibre based on application. Each material has advantages and disadvantages, selecting of material a critical task in robot design.

The following properties are considered while choosing materials.

Strength : Strength is an ability of material to withstand a load or force, without failure. It is important factor in designing the industrial robots. Robots often need to be both strong and lightweight. Strength is an important property in structural applications, where materials must endure forces without breaking. Aluminum and carbon fiber have a good strength-to-weight ratio, while steel is high strength with heavier.

Density : Amount of mass per unit volume defines as density. The high density of a material, the more it will weight for a specific volume. It is material fundamental property represented as (ρ). The influence of density will be on the material selection in perspective of weight factor such as automotive, aerospace and packaging. Density determines the weight, which is fall under the physical property of metal. The high density material such as steel provides high strength than a lower density material. Ex. Aluminum is light weight structure where as steel with more density.

Elasticity: Elasticity of material is ability to return to its original shape and shape when a distorting force is removed. The Hooke's Law defines that the force applied to material is proportional to its deformation until the elastic limit not exceeds. Material elasticity represents as Young's Modulus is a ratio between stress and strain. The high elasticity materials motivate high stiffness. Considering this property in design for applications where stiffness is needed under load. Ex. Springs. Material with low Young's modules has low stiffness with high flexibility. It will deform and return to its original shape once load is removed. .

Thermal Conductivity: Thermal conductivity is a physical property that, measure of materials able to transfer the heat. It is represented as the amount heat transfer through a unit area of material in unit time under the unit temperature. The thermal conductivity depends on the atomic structure, density and temperature. Normally, high thermal conductivity metals atoms are tightly packed together and loosely bound electrons can easily transfer heat. The high thermal conductivity of a material can transfer the heat more faster than low thermal conductivity. Materials with high thermal conductivity such as copper and aluminum and material with low thermal conductivity such as glass and air. Etc.

Thermal conductivity property plays a vital role in designing heat transfer systems. Low thermal conductivity materials are used where heat needs to be insulated, such as building insulation and refrigerators. The property used in many application such as Heat transfer, thermal insulation, Thermal energy storage. In daily life this property used in cooking, Heating and cooling and refrigeration.

4. METHODOLOGY OF ANALYTICAL HIERARCHY PROCESS FOR MATERIAL SELECTION

The Selection of material in industrial robot is plays vital role, it depends on various material properties such as strength, density, MOE and Thermal Conductivity. Each material have advantages and disadvantages, selection of material a critical task robot design engineering.

In 1980, Saaty invented the multi-criteria decision making approach called "Analytic Hierarchy Process" and improved by Vargas in 2001. The method used by Anderson et al in Management science for decision making. It is flexible method for decision making for solving the complex multi criteria problems which both objective and subjective. The method finds solution for various issues in real time applications. The multi criteria decision making finds the solutions for problems with multiple criteria's and many alternatives (Thomas L Saaty, 1990).

4.1. Structure of AHP Method

The Analytic hierarchy process[AHP] is a well defined mathematical model decomposed into small and more detailed elements.

The Analytic hierarchy process divided into three levels

1.Goal 2. Criteria's 3 Alternatives

In this method, initially identify the various materials industrial robot from the stakeholder and the selection based on criteria's (ie Strength, Young module's (MOE), Density, Thermal Conductivity) are identified as per the industrial purpose in order to prioritize material against its properties. The feasible hierarchy made in analytical hierarchy process is pair wise comparison to each other.. The mechanical engineer will assign significance on the scale from 1 to 9 as per the defined table-1. The AHP is not only prioritizes materials but also give the knowledge much degree of importance than other. In this method 'n' no. of materials to be compared as n(n-1)/2 pair wise comparisons. During the implementation of AHP redundancy might take place, therefore consistency ratio must exists in order to know that justifiable prioritization has been achieved.

Table 1: Scale of relative importance (Saaty ,1990)

Weight	*Definition*	*Explanation*
1	Equal importance	Two activities in *equal* importance
3	Moderate importance	One activity *moderate* over another
5	Strong importance	One activity *strong* over another
7	Very strong importance	One activity *very strong* in practice over another
9	Extreme importance	One activity *Extreme* over another.
2,4,6,8	Intermediate values between two activities	When compromise is needed.
Reciprocals of above non Zero : If activity I has of above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with it		

The matrices framed on the base of pair wise comparison with respective criteria, the corresponding maximum left eigenvector is approximated by using the geometric means of the each row (Triantaphyllou and Mann, 1990). Initially the consistency index(CI) can derived with sum of columns in the judgment matrix and multiply the resulting vector by vector of priorities (i.e approximated eigenvector) calculated earlier. The result is approximation of the maximum eigenvalue denoted by λmax. Then, the consistency Index (CI) obtained by using the formula as $CI = (\lambda max-n) / (n-1)$. Finally consistency ratio (CR) calculated with formula $CR = CI / RCI$ where Random Consistency index (RCI) as per given table.2.

Table 2: Random Consistency Index (Defined by Satty,2000)

Matrix Size(n)	Random Consistency Index
1	0
2	0
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45

If $CR <=$ acceptable (i.e. 0.10) indicates good level of consistency for decision making otherwise inconsistency of judgments. In case of inconsistency then the process to be reviewed and improved. The acceptable consistency represents more reliability in decision making.

The weights of importance of the criteria's are also determined by using pair wise comparisons. If the problem has M alternatives (i.e Materials) and N criteria(i.e Properties), then the decision maker is required to construct N judgment matrices (each criteria) of order M*M and one judgment matrix of order N*N (for N criteria) . Finally, the decision problem final priorities denoted as A^{i}_{AHP} .

$$A^{i}_{AHP} = \sum_{j=1}^{N} a_{ij} w_j, \text{ for } i = 1, 2 \ldots M \quad \text{----} \quad (1)$$

4.2. Algorithm

1. Define the problem and the main objectives to make the decision.
2. Build the hierarchical structure as Figure 3, the root node as the goal of the problem, Middle level represents criteria's and lower level indicates alternatives. The entire structure overviews the criteria and the alternatives.
3. Build a set of pair wise comparison matrices based on criteria. The each element in an upper level is used to compare the elements in the level immediately below with respect to it. For each comparison matrix, calculate to find the Eigen value, consistency index CI, consistency ratio CR, and normalized values for each criteria / alternative.
4. Use the priorities obtained from pair wise matrix in global matrix. The scale for rating characteristics should be established and described in a precise way. Do this every element. Then for each element in the level below add its weighted values and obtain its overall or global priority. Continue this process of weighting and adding until the final priorities of the alternatives in the bottom most is obtained. The final value is used to make a decision about the objective.

4.3. Mathematical derivatives

Step 1:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1,n} \\ a_{21} & a_{22} & \cdots & a_{2,n} \\ a_{31} & a_{32} & \cdots & a_{3,n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{n,n} \end{bmatrix} a_{i,j} = 1, for\ i = j, a_{i,j} = \frac{1}{a_{j,i}} for a_{i,j} \neq 0$$

Step 2: Find the n^{th} root of product of each row.

Step 3: Derivation of Priority (pk). The numbers are normalized (each row n^{th} -root value) by dividing them with their sum.

$$Normalized\ Matrix ----$$

$$P = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ p_n \end{bmatrix} \quad A = \frac{(AXP)}{P} = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \cdot \\ \cdot \\ \lambda_n \end{bmatrix}$$

$$\lambda_{\max} = \frac{\lambda_1 + \lambda_2 + \lambda_3 + ... + \lambda_n}{n}$$

$$\textit{Consistency Index } C_I = \frac{\lambda_{\max} - n}{(n-1)}$$

$$\textit{Consistency Ratio} = \frac{C_I}{R_I} \quad R_I \textit{ is Random Index.}$$

Step 4: AHP formula for decision making:

$$A^i_{AHP} = \sum_{j=1}^{N} a_{ij} w_j, \text{ for } i = 1, 2 \ \ldots M \quad ---- \quad (1)$$

5. EXPERIMENTAL EVALUATION OF THE PROBLEM

The objective of the study is the Material Selection and prioritization using Analytical Hierarchy Process with respect to the property (i.e. Strength, Density, MoE and Thermal Conductivity). The entire problem represented diagrammatically as follows.

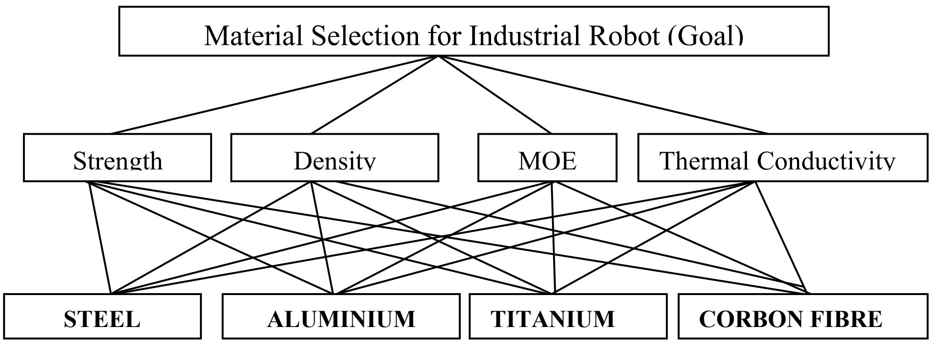

Figure. 1 : Hierarchical decomposition of Criteria's & Alternatives

In the material selection problem four metals taken into consideration as alternatives. Every metal have chosen four properties with less or more significance. The Analytic Hierarchy Process is multi criteria Decision making method can find out the material with optimum properties in material selection. The Analytical Hierarchy Process can form the following five decisions matrices with pair wise compression from table. 3 to 7 with respect to certain criteria and calculated priority vector represented in the bar graphs from figure 2 to 6.

Table 3: Weights of alternatives pair wise comparison in perspective of Strength.

STRENGTH (Criteria)	Steel	Aluminium	Titanium	Carbon Fibre	Priority Vector

Steel	1	5	7	9	0.654
Aluminium	1/5	1	3	5	0.204
Titanium	1/7	1/3	1	3	0.096
Carbon Fibre	1/9	1/5	1/3	1	0.046
Total Priority					1.000
λmax. = 4.170,		**CI** = 0.057,		**CR** = 0.063	

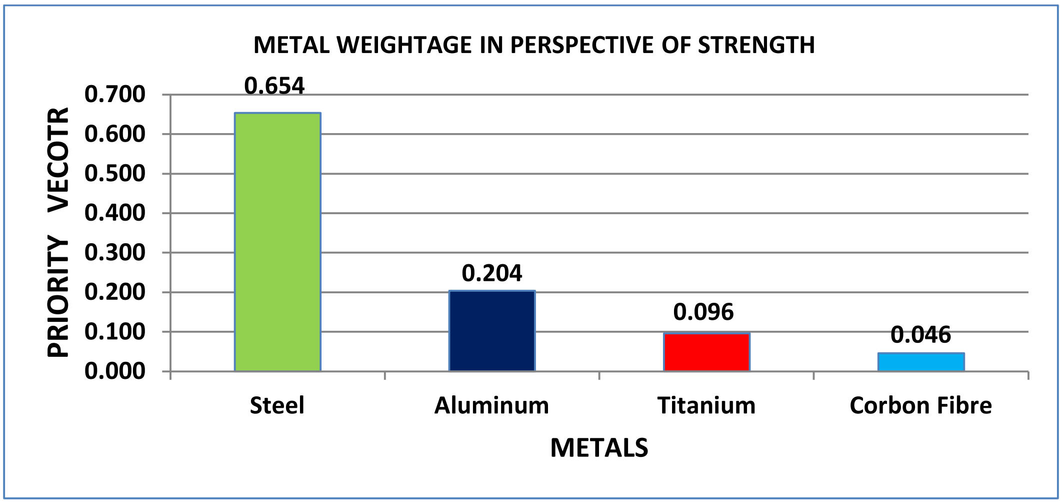

Figure 2 : Weights of Metals in perspective of Strength

Table **4:** Weights of alternatives pair wise comparison in perspective of Density.

DENSITY (Criteria)	Steel	Aluminium	Titanium	Carbon Fibre	Priority Vector
Steel	1	3	7	9	0.607
Aluminium	1/3	1	3	5	0.245
Titanium	1/7	1/3	1	3	0.101
Carbon Fibre	1/9	1/5	1/3	1	0.048
Total Priority					1.000
λmax. = 4.087,		**CI** = 0.029,		**CR** = 0.032	

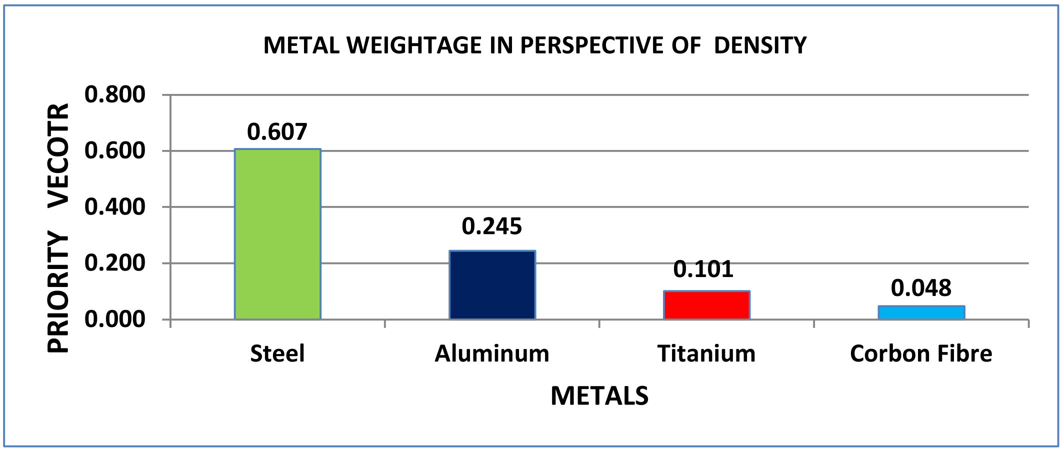

Figure 3 : Weights of Metals in perspective of Density

Table 5: Weights of alternatives pair wise comparison in perspective of Elasticity(MOE).

Elasticity(MOE) (Criteria)	Steel	Aluminium	Titanium	Carbon Fibre	Priority Vector
Steel	1	5	7	9	0.654

Aluminium	1/5	1	3	5	0.204
Titanium	1/7	1/3	1	3	0.096
Carbon Fibre	1/9	1/5	1/3	1	0.046
Total Priority					1.000
λmax. = 4.170,		**CI** = 0.057,		**CR** = 0.063	

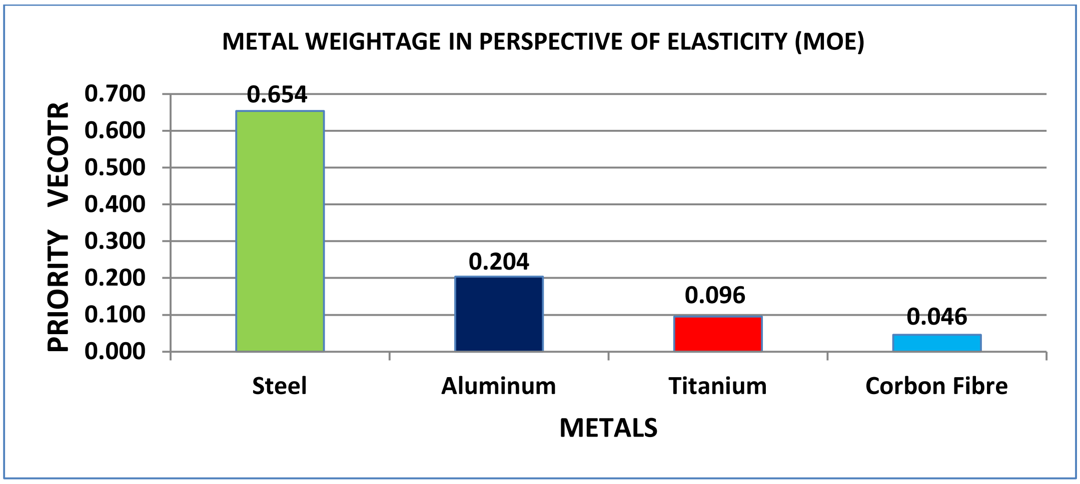

Figure 4 : Weights of Metals in perspective of Elasticity

Table 6: Weights of alternatives pair wise comparison in perspective of Thermal Conductivity.

Thermal Conductivity (Criteria)	Steel	Aluminium	Titanium	Carbon Fibre	Priority Vector
Steel	1	3	5	9	0.571
Aluminium	1/3	1	3	7	0.272
Titanium	1/5	1/3	1	3	0.112
Carbon Fibre	1/9	1/7	1/3	1	0.045
Total Priority					1.000
λmax. = 4.087,		**CI** = 0.029,		**CR** = 0.032	

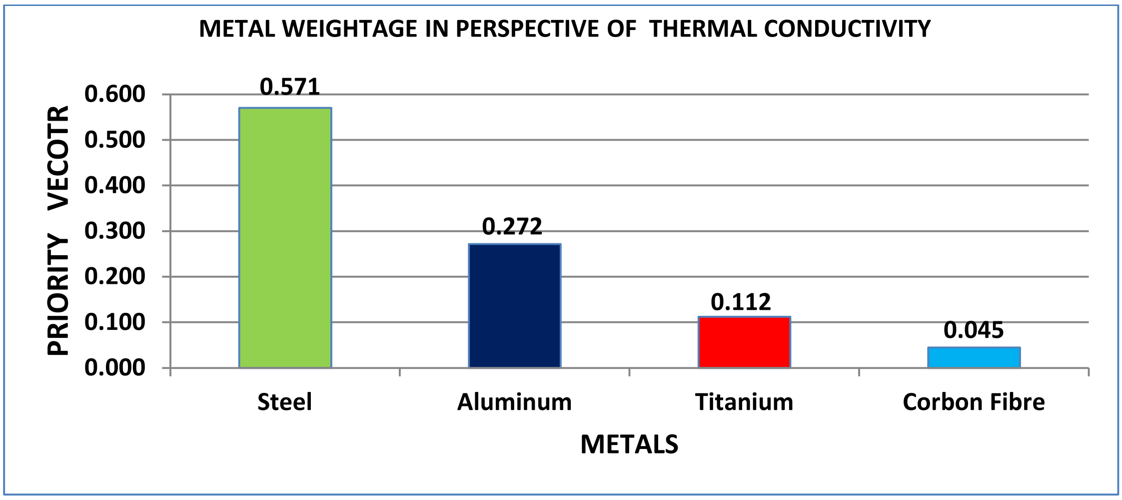

Figure 5 : Weights of Metals in perspective of Thermal Conductivity

The final step mentioned with judgment matrix table.7 based on the criteria importance of material Properties i.e Strength, Density, Elasticity and Thermal Conductivity.. The resultant Material priority vector represented with bar graph in the figure. 6.

Table 7 : Criteria importance of the Material of Industrial Robot

CRITERIA IMPORTANCE	Strength	Density	Elasticity	Thermal Conductivity	Priority Vector
Strength	1	3	7	9	0.596
Density	1/3	1	3	7	0.262
Elasticity	1/7	1/3	1	3	0.099
Thermal Conductivity	1/9	1/7	1/3	1	0.043
Total Priority					1.000
λmax. = 4.099,		**CI** = 0.033,		**CR** = 0.037	

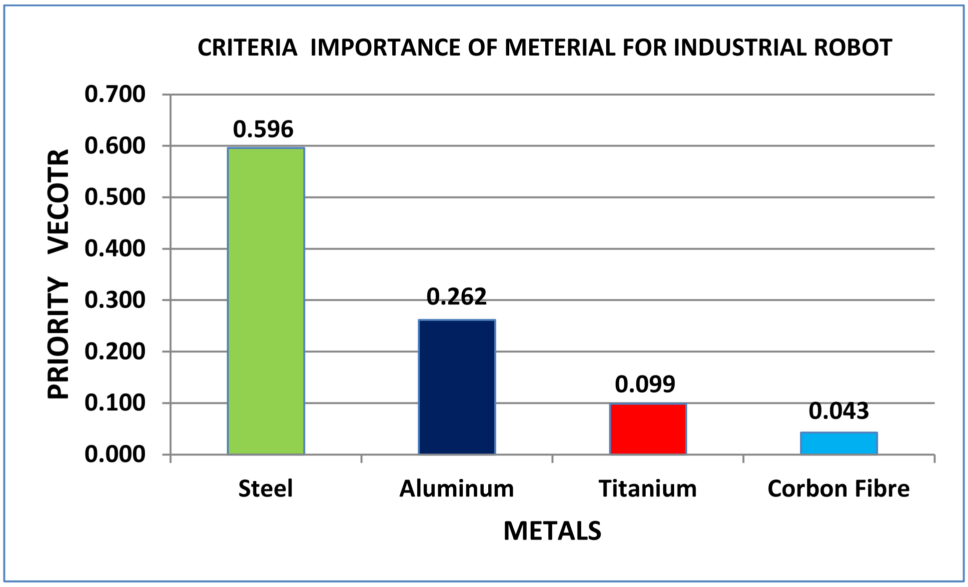

Figure 6 : Priority vector of the Material Properties

The previous priority vectors (i.e. Material and its Properties) are used to form the entries in final decision matrix table. 8 for the Selection of Specific Material for industrial Robot (i.e. calculated according to the formula (1) as follows. The results shown in the bar graph in figure. 7.

Table 8 : Decision matrix with Material and its property significance

METALS	Strength	Density	Elasticity	Thermal Conductivity	Priority Vector
Steel	0.390	0.159	0.065	0.025	0.638
Aluminium	0.122	0.064	0.020	0.012	0.218
Titanium	0.057	0.026	0.009	0.005	0.098
Corbon Fiber	0.027	0.013	0.005	0.002	0.046
Total Priority					1.000

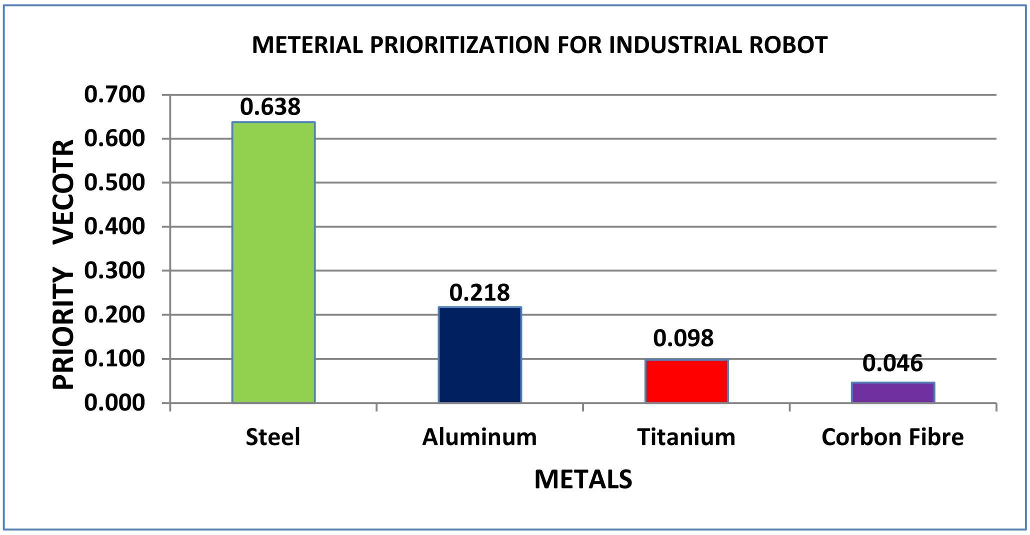

Figure 7 : Material Prioritization based on its properties.

Consequently the selection of material based on significance of properties which can ordered in table. 9 as the following.

Table 9 : Selection of Material based on its prioritization

METALS	Metal significance based on properties	Selection of Material on Priority Order
Steel	0.638	1
Aluminium	0.218	2
Titanium	0.098	3
Corbon Fiber	0.046	4

The resultant will be used for material selection for industrial robotic design and manufacturing process.

6. CONCLUSION AND FUTURE SCOPE

The material selection is the main objective of the Robotics design engineering. The Analytical Hierarchy process is effective decision making method for material selection and prioritization for industrial robot. There are many inherent complexities in material selection of industrial robot. With the numerical example. the authors suggests that when some alternatives to be very close to other and sensitive. The decision maker needs to very cautious. There is a need of extensive research in area of Multi Criteria Decision Making methods which is useful for Scientific and Engineering applications.

ACKNOWLEDGEMENT

We sincerely acknowledge to all the faculty of the Department of Computer Science & Engineering and Department of Mechanical Engineering, Mahaveer Institute of Science and Technology, Hyderabad for their support, guidance, and cooperation during the period of study.

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