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Sustainable Design and Life-cycle assessment of Connecting Rod for Material Optimization

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ABSTRACT

Sustainability in the development and manufacture of new products is a strategy that is widely accepted in principle, although not yet widely practiced. The integration of environmental requirements throughout the entire lifetime of a product needs a new way of thinking and new decision tools to be applied. This paper describes the concept of an approach to product development, based on paradigm for sustainable manufacturing. A case study of connecting rod is done for material optimization and reducing environmental impact in the entire cycle.

1. Introduction

There is now a well-recognized need for achieving overall sustainability in industrial activities, arising due to several established and emerging causes: diminishing non-renewable resources, stricter regulations related to environment and occupational safety/health, increasing consumer preference for environmentally-friendly products, etc. In particular, the manufacturing sector, which lies at the core of industrial economies, must be made sustainable in order to preserve the high standard of living achieved by industrialized societies and to enable developing societies to achieve the same standard of living sustainably. Further, the sustainability improvement effort must yield benefits at all elemental levels involved: environmental, economic, and societal. The most widely accepted general definition of sustainable development is provided by the United Nations' Brundtland Commission Our Common Future (1987): '*developmentthat meets the needs of the present without compromising the ability of future generations to meet their own needs*.' However, during practical implementation theresult of each sustainability enhancement exercise must be specific to that situation, while also attempting to maintain the holistic objective given by the above-mentioned definition. Hence, efforts to make manufacturing more sustainable must consider issues at all relevant levels – product, process, and system – and not just one or more of these in isolation.

At the product level there is a need to move beyond the traditional 3R concept promoting green technologies (*reduce, reuse, recycle*) to a more recent 6R concept forming the basis for sustainable manufacturing (*reduce, reuse, recover, redesign,remanufacture, recycle*), since this allows for transforming from an open-loop, singlelife-cycle paradigm to a theoretically closed-loop, multiple life-cycle paradigm Joshi et al. (2006). At the process level there is a need to achieve optimized technological improvements and process planning for reducing energy and resource consumptions, toxic wastes, occupational hazards, etc., and for improving product life by manipulating process-induced surface integrity Jawahir& Dillon (2007). At the system level there is a need to consider all aspects of the entire supply chain, taking into account all the major life-cycle stages pre-manufacturing, manufacturing, use and post-use over multiple life-cycles.

Considering the complexities involved in the above-mentioned focus areas for sustainable manufacturing, optimized solutions, and corresponding underlying models, are necessary. This paper describes modelling, analysis and sustainable assessment by taking the case of connecting rod. In this project existing connecting rod that is of forged steel is replaced by ductile iron and Aluminium. A 2D drawing is drafted from the calculations. A parameterized model of connecting rod is modelled using CATIA software. Analysis is carried out by using ANSYS software. Sustainable assessment is done using Solid Works- 2014. Finite element analysis and Sustainable assessment of connecting rod is done by considering three materials, viz.forged steel, ductile iron & aluminium. The best combination of parameters like Von misses stress and strain, deformation and factor of safety were done in ANSYS software and the parameters like carbon footprint, total energy consumption, water eutrophication, air acidification, electricity consumption, natural gas consumption and cost were done *in Solid works-2014.*

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2. Material and Methods

There is no simple way of how to develop sustainable products. According to the thermodynamic laws, total sustainable products are not possible to develop in general. However, there are many diûerent approaches and definitions of how to develop sustainable products. The main problem is still unsolved which is the fact that the world not sustainable by itself.

2.1 A sustainable product must be a successful product

A good sustainable product must give as much satisfaction as possible for the user. If not, it will be unsuccessful on the market and an economic failure. There are estimations, which tell us that nearly 90% of all technically good products will not be a success on the market for various reasons Patrick (1997). When releasing sustainable products on the market, it is reasonable to believe that the risk for failure is not less. It is also important to inform people as to what basis a certain product is considered to be sustainable or not and why they should buy it.

2.2 Sustainable development

The following areas are examples of important issue connected to sustainable development Welford (1996):

- *Ecology:* Ecology is study of integrating ecology and engineering, concerned with the design, monitoring, and construction of ecosystems. According to Mitsch (1996) "the design of sustainable ecosystems intends to integrate human society with its natural environment for the benefit of both".
- *Energy:* Sustainable energy is the form of energy obtained from non-exhaustible resources, such that the provision of this form of energy serves the needs of the present without compromising the ability of future generations to meet their needs.
- *Environment:* Environmental sustainability concerns the natural environment and how it endures and remains diverse and productive. Since natural resources are derived from the environment, the state of air, water, and the climate are of particular concern.
- *Transportation:* Transportation is a large contributor to greenhouse gas emissions. It is said that one-third of all gasses produced are due to transportation. Buehler &Pucher (2011) Some western countries are making transportation more sustainable in both long-term and short-term implementations Barbour & Deakin (2012).
- *Economics:* Due to rural poverty and overexploitation, environmental resources should be treated as important economic assets, called natural capital Barbier (2010). Sustainable development may involve improvements in the quality of life for many but may necessitate a decrease in resource consumption. According to John Baden (2008) "the improvement of environment quality depends on the market economy and the existence of legitimate and protected property rights."
- *Corporate:* Corporate sustainability is a business approach that creates long-term Consumer and employee value by creating a "green" strategy aimed through transparency and proper employee development toward the natural environment and taking into consideration every dimension of how a business operates in the social, cultural, and economic environment. It also formulates strategies to build a company that fosters longevity.
- *Architecture:* Sustainable architecture is architecture that seeks to minimize the negative environmental impact of buildings by efficiency and moderation in the use of materials, energy, and development space. Sustainable architecture uses a conscious approach to energy and ecological conservation in the design of the built environment.
- *Income:* At the present time, sustainable development as well as solidarity or Catholic social teaching can impact reduce the poverty. Because over many thousands of years the 'stronger' (economically or physically) used to defeat the weaker, nowadays, no matter what we call the reason for this decision – within Catholic social teaching, social solidarity, and sustainable development – the stronger helps the weaker. Sustainable development reduce poverty through economic (among other things, a balanced budget), environmental (living conditions) and also social (including equality of income) dimensions Adamiak&Walczak (2014).
- *Politics:* The political is defined as the domain of practices and meanings associated with basic issues of social power as they pertain to the organisation, authorisation, legitimation and regulation of a social life held in common. This definition is in accord with the view that political change is important for responding to economic, ecological and cultural challenges. It also means that the politics of economic change can be addressed.
- *Culture:* It is a fourth dimension which is added to sustainable manufacturing. It was not included in triple bottom line. It inaugurates a new perspective and points to the relation between culture and sustainable development through a dual approach: developing a solid cultural policy and advocating a cultural dimension in all public policies.

Another, rather new approach to meet the demand for measuring the sustainability of a product is to use the conception Triple Bottom Line (TBL). The TBL term was first coined by John Elkington and according to him: ''…the term triple bottom line is used as a framework for measuring and reporting corporate performance against economic, social and environmental parameters''. The TBL concept involves the traditional economic bottom line together with the society and the environment.

2.3. Sustainability issues at the product level

Due to the numerous energy and material input and output streams involved in a product's life, the necessity of considering the total product life-cycle in order to evaluate a product's sustainability score for comparison and selection between different alternative designs, or between different production scenarios, is well recognized. An extensive analysis of streamlined life-cycle analysis (SLCA) methods is presented in a pioneering textbook covering various methodologies, including matrix approaches using target plots, for five major product life-cycle stages: pre-manufacture, manufacture, product delivery, use, and recycling Graedel, &Graedel (1998). In more recent work the simplified total life-cycle of a product was assumed to consist of four key stages – pre-manufacturing, manufacturing, use and post-use – since product delivery was considered as only one among the several delivery activities Jaafar et al. (2007). To achieve multiple product life-cycles with the goal of near-perpetual product/material life, design and manufacturing practices for next generation products must consider these product life-cycle stages using a more innovative 6R approach, as described above.

2.4. Environmental impact with the LCA-method

Life Cycle Assessment (LCA) is a useful tool for understanding the impact of the environment. A product is evaluated step by step from cradle to grave, where cost, impact, expected lifetime, etc. can be evaluated in a quite easy way. A simple way to account for an environmentally friendly production is to give every product an environmental load. This can be done with, for example, the Environmental Load Unit (ELU) index/kg or unit. ELU is a sum of the environmental load for a product with respect to production, material, transports, etc. during the whole lifetime of a certain product. The ELU can be seen as a way to express how much it will cost to restore the environment as it used to be before a certain impact. However, note that there is no way that is 100% accurate when comparing diûerent production, breaking down or recycling methods. It is for example not easy to compare glass bottles or paper packs, e.g., milk, and to say what is the most environmentally friendly (or sustainable) material for milk transportation. The paper pack is used only once and then normally burnt. The glass bottle is used a number of times but needs extra energy for transportation (because of its quite high weight) and needs detergents and water for cleaning before every new filling.

The transportation to diûerent customers and the environmental influence from the cleaning process must then be weighted and estimated. The emissions from burning or recycling of the paper must be compared with, e.g., the discharge from the detergents. Today we have a certain way of weighing the emission factors aûecting the environment, but tomorrow it can be changed, because of increased knowledge of certain risks of a special emission. The LCA methodology is probably the most widespread technique for evaluating environmental impacts associated with material products Bovea& Vidal (2004). There are typically six important steps involved in an LCA evaluation Hui et al. (2004):

- Extract from material.
- Manufacturing with, e.g., ennobling and refinement.
- Packaging stage.
- Transportation of, e.g., material and the ready product.
- Product user stage.
- Product disposal stage.

These steps can then be divided into smaller steps in order to get a more precise view of the life cycle, like: Extract of material, Design, Market research and Product Development, Process planning, Purchase of materials, Production and Assembly, Product Control, Treatment of waste, emissions and noise, Packaging and storage, Marketing, Selling or Leasing, Delivery, Use, Service and Maintenance, Renovation/Upgrading, Reuse/Recycling and Final utilisation. Some important methods for evaluating environmental impacts together with the LCA method are: Eco-Indicator_99 Goedkoop&Spriensma (2001), Environmental Priority System (EPS) Steen (1999. The evaluation makes it easier to compare different materials, manufacturing methods, service intensity, etc. side by side, which is of vital importance when developing sustainable products Krozer& Vis (1998).

2.5. Guidelines for sustainable development

In order to develop more sustainable products, some important points are to be noticed

i. Reduce the materials and the use of energy for a product including services during its lifetime.
ii. Reduce emissions, dispersion and creation of toxics during its lifetime.
iii. Increase the amount of recyclable materials.
iv. Maximise the sustainable use of renewable resources.
v. Minimise the service intensity for products and services.
vi. Extend the useful life for a product.
vii. Assess and minimise the environmental impact over the product lifetime.
viii. Having a ''Functional economy'' is a way to substitute products with services.
ix. Use ''Reverse logistics'' which means that all eûorts are used in order to reuse products and materials.
x. Increase the eûciency of a product in the usage phase.

2.6 Material Selection

Material selection is a fundamental part of design, it offers many opportunities for reducing environmental impacts. In the sustainable design context, materials present the designer with some of the most difficult problems. The life of a product begins with the acquisition of materials. For designers, the choice of materials is crucial. The material used has a major impact on the environmental performance of a product, influencing its energy efficiency in manufacture and use, how easily it can be recycled, or whether it represents a hazard when eventually disposed of. Consideration of materials should begin at the earliest stage of the design process, with selection made in the context of how the product will be used, whether recycling is possible, and what performance characteristics are demanded. There is considerable confusion about whether some materials are inherently less damaging to the environment than others. Some may consume more energy or non-renewable materials in their production, but perhaps have a longer life span. Some are easier to recycle, while others are believed to degrade easily and harmlessly. When disposed of by incineration, some materials are valuable because their energy content can be reclaimed, but there may be concerns about the substances released into the atmosphere during the incineration process. No one type of material can claim overall environmental superiority. Material selection has to be considered, therefore, as part of the total manufacturing and design process, taking into account the entire life cycle of the product. There are main criteria's that environment-conscious designer should consider to 'design for material conservation':

- *Design multifunctional products*: Products which have multiple uses are by natureeco-efficient, in that the same amount of material achieves a higher level of functionality. There are essentially two types of multiple functionality:
  1. *Parallel functions,* in which the same product may simultaneously serve severaldifferent purposes.
  2. *Sequential functions*, in which a product is retired from its primary use and thenapplied to a secondary use.
  3. *Specify recycled materials*: An important aspect of sustainable development is theconservation of non-renewable resources. Recently, many designers have begun to encourage the use of more 'environmentally conscious' materials.
  4. *Specify renewable materials*: Instead of recycling non-renewable materials, analternative approach to sustainable development is substitution of renewable materials. For example, materials developed through agriculture are renewable.
  5. *Use remanufactured components*: Product manufactured with refurbishedcomponents can potentially have the same level of quality as ones manufactured with brand new components.
  6. *Design for product longevity*: From a consumer point of view, longer-lived productsare generally more desirable because of convenience and cost savings. Apart from the life extension for the product as a whole, another way to achieve longevity is to extend the life of product components.

2.6.1. Minimum Use of Material

For all designers, one of the first rules should be to minimize the quantity of any material chosen wherever possible. The benefits of this, can be seen at the product's life, from the conservation of resources, through the reduction of energy and pollution in manufacture and use, to the minimization of the problems of disposal. Minimizing materials demands careful attention to production processes as well as to the design itself. A reduction in the amount of material used is desirable because of cost savings, in addition to the environment benefits of saving resources.

In addition, weight reduction is a key objective. Using less material obviously saves direct costs as well as minimising the environmental burden. Reducing materials usage should go beyond simply minimising a particular design. For some products, weight reduction brings significant benefits during later stages of a product's life. This is especially true of itemssuch as packaging, where lower weight cuts transports costs and can ease handling. In this case, designers should be consider some crucial points:

- Ensure that the choice of materials is appropriate to the expected life of the product.
- Use renewable materials from a sustainable source where this is appropriate.
- Use recycled materials if possible.
- Avoid or minimise materials containing toxic chemicals.
- Minimise materials use both by the choice of design approach and through detailed design.

2.6.2. Using recycled materials

Designers and manufacturers should be increasingly aware of the possibility of using recycled materials. In general, materials that have come from a recycled source are more environment-friendly than those from virgin sources. Not only does recycling reduce the waste, it is often far more energy efficient. There is an important point that, depending on processing methods and final use, recycled materials may sometimes be less environment-friendly than they seem, but any recycled material should be investigated as a possible resource.

Materials which are difficult to recycle may have other benefits, such as greater energy efficiency. The replacement in the automobile industry of easily recyclable steel and iron by hard-to-recycle plastics helped improve fuel consumption because of the savings that could be achieved in the weight of the car.However, the inclusion of higher quantities of plastic made it more difficult for scrap merchants to retrieve the metal parts, thus increasing their costs and diminishing the value the metal recycling process. Efforts now being made to develop plastic components which are easy to dismantle and separate, and which be recycled themselves, may reduce this problem.

2.6.3. Biodegradable Materials

Biodegradable materials are another possible resource which demands careful consideration. Natural substances such as wood and cotton are inherently biodegradable, and may therefore be preferable in many applications to plastics, which will not biodegrade. The development of biodegradable plastics may be useful for items which have to be disposed of after limited use. They might also be used for products which are regarded by consumers as disposable, especially for those which end up in the sewage system, although a better alternative might be to encourage reusable product instead.

3. Result and Discussion

The objective of the present work is to analyse and sustainable assessment of connecting rod made of ductile Iron forged steel and aluminium. In this project the material (forged steel) of connecting rod replaced with ductile iron and aluminium. Connecting rod was created in CATIA. Model is imported in ANSYS 14.0 for analysis and in Solid Works-2014 for sustainable assessment. After analysis done in ANSYS a comparison is made between existing steel, ductile iron and aluminium connecting rod in terms of factor of safety, deformation, stresses, carbon footprint, total energy consumption, water eutrophication, air acidification, electricity consumption, natural gas consumption and cost.

3.1 Material Properties

The material properties of the different materials that are used for analysing are listed below

Table-1 properties of Materials

Material Selected	Forged Steel	Ductile Iron	Aluminium alloy 2024
Density Kg/m^3	8050	7.2	2767.990
Young's Modulus, E, GPa	221	170	73.1
Poisson's Ratio	0.3	0.275	0.33
Yield Strength, MPa	625	379	324
Ultimate Strength, MPa	827	552	469

3.2 *Finite Element Analysis of connecting Rod for material optimization using ANSYS 14.0.*

In order to make the connecting rod's confirmation with the Software's help, the Finite Element Method is used; Finite Element Method is a Numerical procedure that can be used to obtain solutions to a large class of engineering problems involving stress Analysis, Heat Transfer, & Fluid Flow etc. ANSYS is a comprehensive general purpose FEA computer program that may be used to solve a variety of problems. The basic steps involved in any Finite Element Analysis consist of the following phases: - Pre-processing Phase, Solution Phase & Post processing's Phase.

In the first stage, the users create the model to be analysed or import it, & define the Elements type, Real Constants, Material Properties. The model is discretized in to Finite Element that is, subdivide the problem in to Nodes & Elements. Assume a shape function to represent the physical behaviour of an element, which is continuous function, is assumed to represent the solution of an element. Develop equation for an element & assemble the elements to present the entire problem & construct the Global Stiffness Matrix.

In the second stage, the initial conditions and boundary conditions are imposed, & loads are implemented & solve a set of linear or nonlinear algebraic equations simultaneously to obtain nodal results, such as displacement value at different nodes.

The last stage, post processing, allows the user to view the results obtained from the analysis. At this point you may be interested in values of principal stress, von-mises stress etc. ANSYS will offer you the possibility of understanding the behaviour of the model analysed in reality. Animation can also be used

For the three-dimensional model of the connecting rod based on the dimensions established in the CATIA V5R18 software, made by DASSAULT System is used. Figure1 represents the three-dimensional model of the connecting rod .The loading conditions are assumed to be static. Analysis done with pressure load applied at the piston end and restrained at the crank end or other load applied at the crank and Figure 2 represents the loads and boundary conditions of connecting rod.

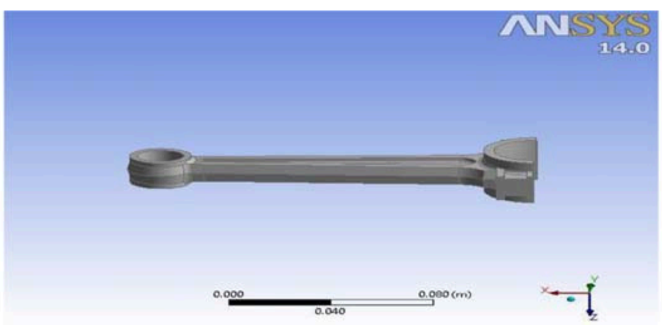

Figure 1: Model of connecting rod

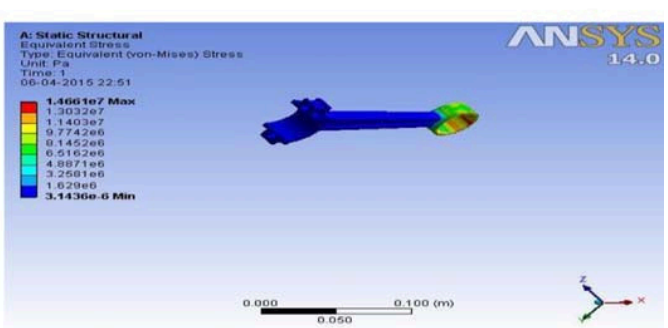

Figure 2: Loads and boundary conditions of connecting rod

After performing the analysis, the results are obtained as stress field and total deformations. For the different materials, the equivalent stress fields are calculated with the von Misses theory is shown in Figure 3, Figure 5, Figure 7 and Figure 4, Figure 6, Figure 8 representing the total deformation using forged steel, ductile iron and aluminium alloy - 2024.

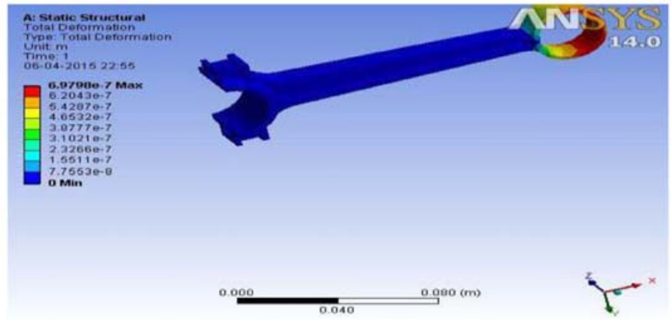

Figure 3: Von-misses stress of connecting rod for Forged Steel

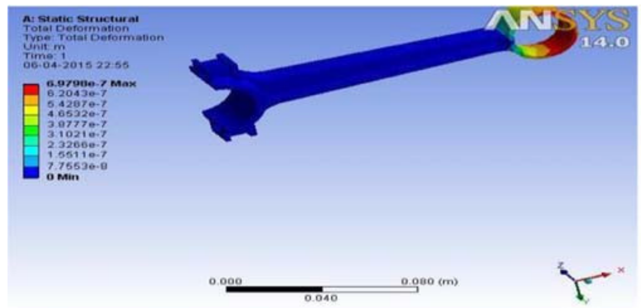

Figure 4: Total Deformation of connecting rod Forged Steel

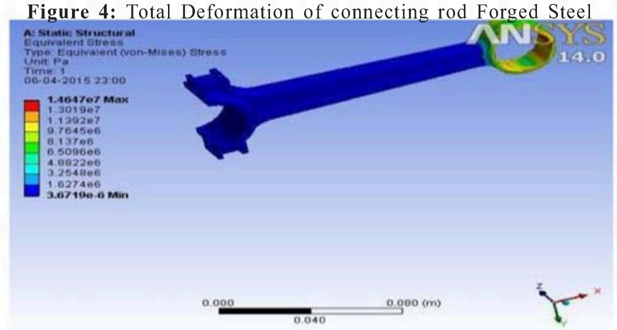

Figure 5: Von-misses stress of connecting rod ductile iron

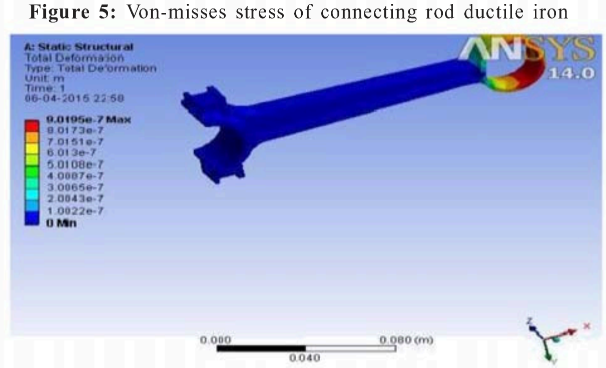

Figure 6: Total Deformation of connecting rodductile iron

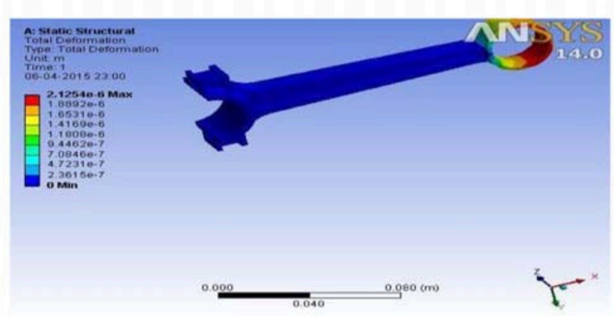

Figure 7: Von-misses stress of connecting rod of Aluminium alloy 2024

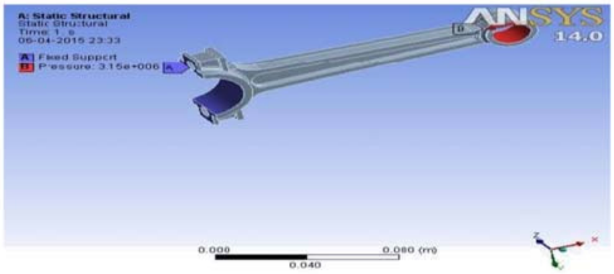

Figure 8: Total Deformation of connecting rod of Aluminium alloy 2024

3.3 Sustainable Analysis of connecting Rod for material optimization

Sustainable design is fast becoming a matter of global corporate citizenship. It means making decisions to ensure future environmental stability. Sustainable analysis is carried out in Solid Works-2014. Solid works sustainable assessment provides a screening level analysis of life cycle assessment (LCA). It is necessary as it tell us about product's entire life, which encompasses raw material extraction, material production, manufacturing, product use, end-of-life disposal, and all of the transportation that occurs between these stages. In Solid works its duration of use was kept for 10 years with10 years built to last. It was manufactured in Asia region and its region of use was kept North America and mode of transportation was chosen sea and distance of 1000 km kept for all the four materials i.e. forged steel, ductile iron, ductile iron (SN) and aluminium alloy 2024.

3.3.1 Environmental Impact Factors

Acid rain, water pollution, global warming, dying animals, plants, and fish. The list goes on. Accurately gauging our impact on the environment has only really come into focus in the past couple of decades. Sustainable design looks at how your product's development, from cradle to grave, will affect four crucial environmental factors: air acidification; carbon footprint; total energy consumed; and water eutrophication. Measuring these impacts will help you better design for the environment. Different environmental factors that was taken into consideration is enumerated below

- *Carbon Footprint* – Carbon dioxide and other gasses resulting from burning fossil fuels accumulate in the atmosphere, which in turn increases the earth's average temperature. Also known as Global Warming Potential (GWP), carbon footprint is measured in units of carbon dioxide equivalent (CO2e). Scientists, politicians, and others blame global warming for problems like loss of glaciers, extinction of species, and more extreme weather, among others. Figure 9 representing carbon foot print for forged steel, ductile iron, ductile iron (SN) and aluminium alloy 2024 respectively.
- *Total Energy Consumed* –This is a measure of the non-renewable energy sourcesassociated with the part's lifecycle in units of mega joules (MJ). This impact includes not only the electricity or fuels used during the product's lifecycle, but also the upstream energy required to obtain and process these fuels, and the embodied energy of materials that would be released if burned. Total energy consumed represents the net calorific value of primary energy demand from non-renewable resources (e.g. petroleum, natural gas, etc.). Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are also factors. Figure 10 representing total energy consumed for forged steel, ductile iron, ductile iron (SN) and aluminium alloy 2024 respectively.
- *Water Eutrophication* - Eutrophication occurs when an overabundance of nutrientsare added to a water ecosystem. Nitrogen and phosphorous from wastewater and agricultural fertilizers cause an overabundance of algae to bloom, which then depletes the water of oxygen and results in the death of both plant and animal life. This impact is typically measured in either kg phosphate equivalent (PO4) or kg nitrogen (N) equivalent. Figure 11 representing water eutrophication for forged steel, ductile iron, ductile iron (SN) and aluminium alloy 2024 respectively.
- *Air Acidification* –Burning fuels creates sulfur dioxide, nitrous oxides, and otheracidic air emissions. This causes an increase in the acidity of rainwater, which in turn acidifies lakes and soil. These acids can make the land and water toxic for plants and aquatic life. Acid rain can also slowly dissolve man-made building materials such as concrete. This impact is typically measured in units of kg sulfur dioxide equivalent (SO2). Figure 12 representing air acidification for forged steel, ductile iron, ductile iron (SN) and aluminium alloy 2024 respectively.

Figure 9: Carbon foot Print for four materials

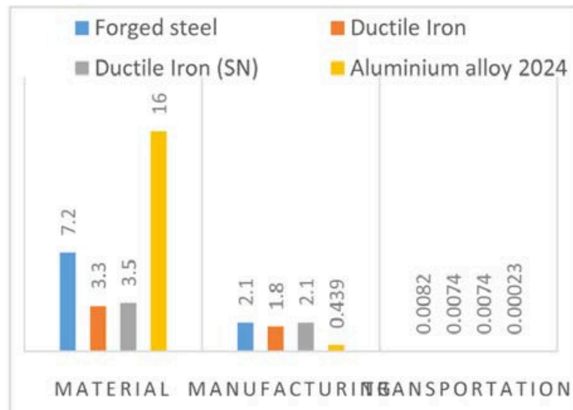

Figure 10: Total energy Consumed for four materials

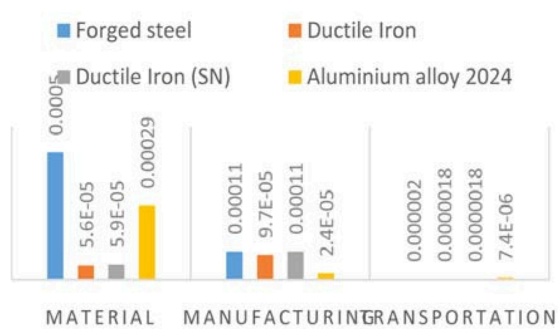

Figure 11: Water Eutrophication for four materials

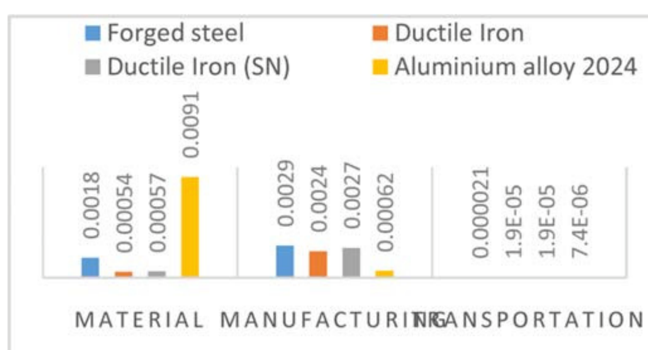

Figure 12: Air Acidification for four materials

3.3.2 Economic Impact Factors

- *Electric energy consumption:* It is the form of energy consumption thatuses electric energy. Electric energy consumption is the actual energy demand made on existing electricity supply. Consumption of electric energy is measured in watt-hours. Electric and electronic devices consume electric energy to generate desired output (i.e. light, heat, motion, etc.). During operation, some part of the energy is consumed in unintended output, such as waste heat. Figure 13 representing electricity consumption for forged steel, ductile iron, ductile iron (SN) and aluminium alloy 2024 respectively.
- *Scrap rate:* Scrap consists of recyclable materialsleft over from productmanufacturing and consumption. Unlike waste, scrap has monetary value, especially recovered metals, and non-metallic materials are also recovered for recycling. So scrap rate is the percentage of failed assemblies or material that cannot be repaired or restored, and is therefore condemned and discarded. Figure 14 representing scrap rate for forged steel, ductile iron, ductile iron (SN) and aluminium alloy 2024 respectively.
- *Natural gas consumption-* It is the rate at which natural gas consumed inmanufacturing any product. It is measured in BTU/ LBS.As natural gas is a fossil fuel so its consumption will have an impact on cost as wells as on environment so it is one of the important economic factor. Figure 15 representing natural gas consumption for forged steel, ductile iron, ductile iron (SN) and aluminium alloy 2024 respectively.
- *Material Financial Impact -* This is the financial impact associated with thematerial only. The mass of the model is multiplied by the financial impact unit (units of currency/units of mass) to calculate the financial impact (in units of currency). Figure 16 representing material financial impact for forged steel, ductile iron, ductile iron (SN) and aluminium alloy 2024 respectively. Here currency is taken as US dollar.

4. Conclusions

The introduction of environmental requirements for the product development process at all stages of a product's life leads to a new paradigm of sustainability, which is reflected in a new way of thinking, new application tools and methodologies in every single step of product development. Environmental requirements must be considered as equal partners to the traditional requirements of cost and quality. A number of tools and methodologies are already available, and some others are still being developed.

An industrial case study of connecting rod shows that the stress induced using ANSYS is less than the material allowable limit of stress. So the model presented here is well for safe design under given loading conditions. Hence ductile iron can be used as a material for manufacturing connecting rod. After comparing all the parameters i.e. carbon footprint, total energy consumption, water eutrophication, air acidification, electricity consumption, natural gas consumption and cost from the above graphs we conclude that ductile iron can be used as an substitute for wrought or cast steel components for manufacturing connecting rod. It is also clear from above graphical data that is obtained from solid works that ductile iron is more sustainable than forged steel and aluminium and also material financial impact is also low in ductile iron as compared to other materials.

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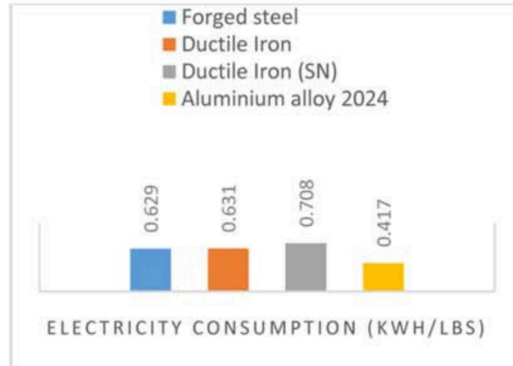

Figure 13: Electricity Consumption for four materials

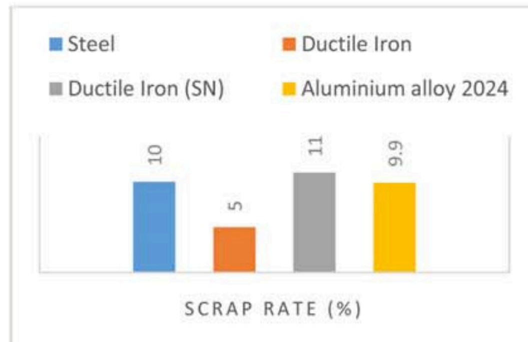

Figure 14: Scrap Rate for four materials

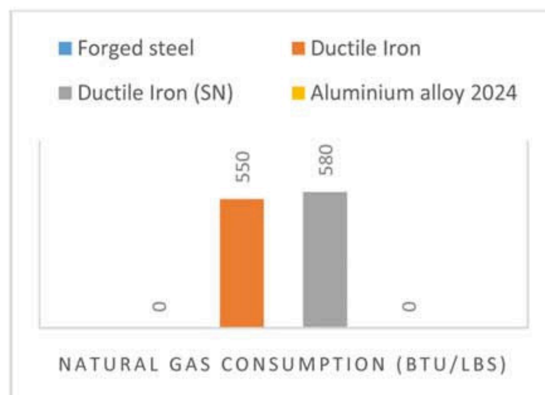

Figure 15: Natural Gas Consumption for four materials

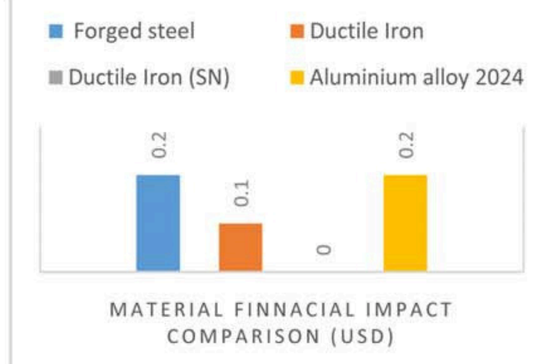

Figure 16: Material financial impact comparison for four materials

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