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CASE STUDY

Integrating sustainability and remanufacturing strategies by remanufacturing quality function deployment (RQFD)

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Abstract

The objective of this paper is to ensure remanufacturing by considering the possible design, material and process changes. A novel remanufacturing quality function deployment (RQFD) was developed to bring out the possible changes to the existing product. To accomplish the above objective, RQFD phase I (voice of customer to engineering metrics) and RQFD phase II (engineering metrics to components of case product) were developed. Based on the results, the improvements options in design, process and materials were identified. The sustainability performance for the original and modified design was identified to understand the environmental benefits achieved through the proposed method. The proposed method has been applied to brake caliper components. The practical applications of the research are expected to help the manufacturers of brake calipers to minimize negative impacts on the environment, energy conservation and natural resources and are safe for stakeholders and are economically sound.

Keywords Quality function deployment (QFD) · Remanufacturing quality function deployment (RQFD) · Sustainability · Life cycle analysis (LCA) · End of life (EoL) · 6R

Abbreviations

Al	Aluminum
$CaCO_3$	Calcium carbonate
CO	Carbon monoxide
CO_2	Carbon dioxide

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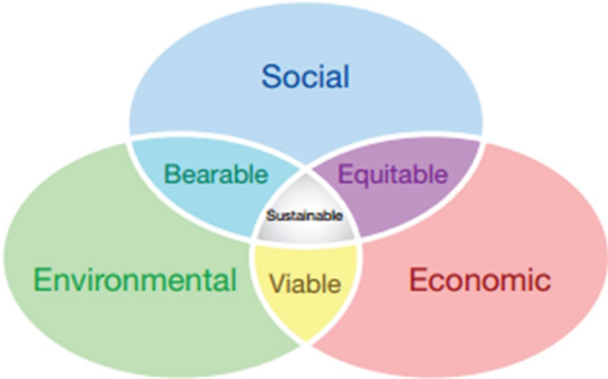
ECQFD	Environmentally conscious quality function deployment
EM	Engineering metrics
EoL	End of life
Fe	Iron
Fe_2O_3	Iron oxide
gm	Gram
GQFD	Green quality function deployment
HAP	Hazardous air pollutant
K_{1c}	Fracture toughness at 10^7 cycles
Kg	Kilogram
Kg/m^3	Kilogram per meter cube
LCA	Life cycle analysis
LCC	Life cycle cost
Mg	Magnesium
MJ	Mega-joules
NO_X	Nitrogen oxides
ºC	°C
OEMs	Original equipment manufacturers
$P0_4$	Phosphate
Pa	Pascal
Pa $m^{0.5}$	Pascal per meter square
PM	Particulate matter
ProdSI	Product Sustainability Index
QFD	Quality function deployment
RQFD	Remanufacturing quality function deployment
SCM	Supply chain management
Si	Silicon
SMEs	Small and medium enterprises
SO_2	Sulfur dioxide
SOX	Sulfur oxides
SSCM	Sustainable supply chain management
VOC	Voice of customer
VOCs	Volatile organic compounds
Zr	Zirconium
ρ	Density
σ_e	Fatigue strength

1 Introduction

Sustainable manufacturing is the creation of manufactured products through economically sound processes that minimize negative environmental impacts while conserving energy and natural resources (Sarkis 2001). Sustainable manufacturing also enhances employee, community and product safety (Kulatunga et al. 2015). Figure 1 shows the triple bottom line of sustainability.

Figure 2 shows integral elements of sustainable manufacturing. As described in Fig. 2, the integral elements of sustainable manufacturing combine product, process and system levels of the manufacturing to get a sustainable result. Sustainable manufacturing considers

Fig. 1 Triple bottom line of sustainability



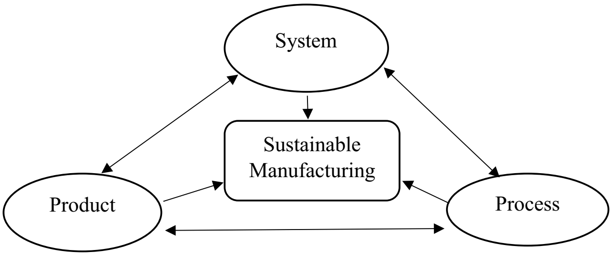


Fig. 2 Integral elements of sustainable manufacturing

entire life cycle of the product. The consideration of sustainable manufacturing helps the companies to achieve the waste reduction, improve competitive advantage, build a reputation and comply with environmental regulations. 6R is an innovative and creative tool through which triple bottom line of sustainability can be achieved, i.e., environmentally appropriate, socially acceptable and economic viable. Traditional 3R focuses on reducing, recycling and reusing of materials and energy resources, while 6R concept aims at ensuring the overall sustainability of the products after it EoL disposal (Ljungberg 2007). The concepts that are considered in 6R are: remanufacture, reuse, recover, recycle, redesign and reduce. Figure 3 demonstrates the closed-loop material flow that facilitates 6R approach.

Manufacturing/remanufacturing processes like lean manufacturing and green manufacturing have less impact on the environment and generate eco-friendly products which can be processed for further use after products end of life and have an ease of disposal. It also helps to facilitate a closed-loop material flow (Fig. 3). These concepts help in the design phase of a new product and are considered during all the life cycle stages (raw material acquisition until disposal). Remanufacturing, redesign and reduce concepts can be used during manufacturing stage, while reuse, recycle and recover can be used after the end of life (post use) of any product (Keoleian and Menerey 1994). The rebuilding of a product/components to its primeval state is remanufacture. (Hatcher et al. 2011). Reusing a component/product with a little or no change is reuse. Recover is process of recapturing product/component from customers or processes (Harrold 2009). Recycle is extracting material from product/component by applying machining and chemical processes so that it can be used as raw material for another purpose. Redesign mainly focuses on allowing capabilities

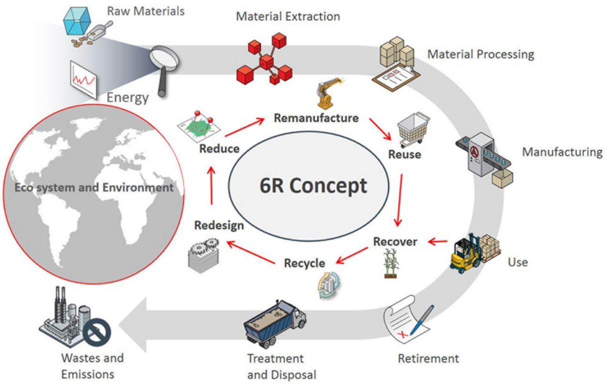


Fig. 3 Closed-loop material flow—6R approach

to remanufacturers by providing ease to the remanufacturing processes (Badurdeen et al. 2009). Reduce is minimizing new resources (resources to manufacture, transport, and dispose of products) (Eddy et al. 2013).

From the literature review, it is inferred that integration of sustainability and 6R has not been done in the manufacturing of mechanical components. Also, critical engineering concepts have not been considered to check the feasibility of the product after optimizing as in the case of alternators. In another research, only environmental aspect is considered for remanufacturability where there is a scope for including social and economic aspects for overall sustainability as in case of remanufacturing mobile phones. In order to address the above-mentioned need, this work aims to contribute to the literature of sustainability and remanufacturing by addressing the following two research questions.

- How to analyze the mechanical component for integrating the sustainability and remanufacturing?

In this research, Remanufacturing Quality Function Deployment is compiled using 6R tools to map the critical component of the brake caliper. In RQFD, the customer requirements/voice of the customer (VOC) are listed down which focuses on remanufacturability of the product and the solution to their needs are represented by engineering metrics which comprises the 6R's. At the product level, the focus is on sustainable consumption of raw materials and redesigning the case products for lightweight without affecting its functionality (reduce the material consumption and hence design change is performed on the critical component). Also, as there is no research done on brake caliper for making it more sustainable using the gaps mentioned above, it leaves a scope for further research in this field of study.

The paper is organized as follows. Section 2 surveys the literature on QFD, ECQFD, GQFD and sustainable manufacturing, analysis and orientations. Section 3 describes the solution methodology. Section 4 provides an overview of the automobile component manufacturing company that is the subject of the case study and applies the methodology developed in this study to analyze RQFD for brake caliper in order to identify critical component. Section 5 describes sustainability orientations performed on critical component of the brake caliper and suggests changes in design, material and process for better incorporation of sustainability in manufacturing brake caliper, followed by results and discussion in Sect. 6 and conclusions in Sect. 7.

2 Literature review

The following subsections minutiae the literature review conducted on the perception of sustainable manufacturing, life cycle analysis and quality function deployment.

2.1 Review on sustainable manufacturing

Due to the rapid increase of motorization around the world, there has been a sharp rise in carbon footprint associated with manufacturing automobiles which have led to a possibility of a negative irreversible impact on climate change (Solomon et al. 2009). Sustainable business development in manufacturing and service sectors hence become critical in nullifying the effect of global warming and carbon footprint in manufacturing an automotive component (Gunasekaran et al. 2012). Sustainable manufacturing should amalgamate economic, social and environmental aspect (Lozano and Rodrigo 2008) as the focus on pollution control alone is not sufficient to achieve sustainability (Mihelcic et al. 2003; Rajesh 2020a). To imbibe economic, social and environmental dimensions, it becomes necessary to consider sustainable concepts at product, process and system level of manufacturing (Jayal et al. 2010).

The human ingenuity has helped to develop an approach to sustain the environment for future generation, i.e., through sustainable methods of development (Brundtland 1985). Sustainable manufacturing relates to creating a product that is economically viable, socially acceptable and environmentally feasible (Glavic 2007). Sustainable manufacturing has modernized the existence of companies by integrating environmental requirements into every single phase of product development (Kaebernick 2003). Environmentally manufacturing practices like pollution prevention, reduce or recycle resource and product stewardship have laid a positive impact on manufacturing outcomes like decreasing manufacturing cost and improving product quality (Rusinko 2007).

Ijomah (2004) has defined remanufacturing as "*The process of returning a used product to at least OEM original performance specification from the customers' perspective and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent*". Some of the key benefits of remanufacturing are that it helps the manufacturer to sell the product at low cost while maintaining the product quality and enables manufacturers to maintain the brand name by preventing unauthorized remanufacturing of its product done by recollecting products at its EoL from customers and hence maintaining standards of their customer services. This process also helps to reduce financial penalty regarding environmental regulatory purpose. Remanufacturing acts a powerful tool to analyze product design by getting the failure mode information, thus helping design engineers to make an advanced design (Ijomah and Winifred 2010; Zhang et al. 2019).

2.2 Review on life cycle analysis

Life cycle analysis (LCA) is a methodological framework to evaluate the environmental impact of any product across its life cycle, which is also known as 'cradle to grave' analysis. Applications of LCA are largely untapped as they have the tremendous scope of implementation across all industries. LCA has helped multinational companies in material choices, technology choices, benchmarking and infrastructure choices. LCA has also been used by SME's and start-ups to reduce overheads and operating costs. Also, LCA is a powerful tool in shaping governmental policies (Rebitzer et al. 2004).

Environmental-conscious requirements are stressed in all stages of product development process by using LCA and EoL (Kaebernick et al. 2003). A study further adds value toward sustainability during new product manufacturing by introducing remanufacturing to decrease EoL environmental impact (Sutherland et al. 2008). Assessment of product sustainability analysis using a case study of automotive organization ascertains the benefit and need to find the environmental impact of a product during its development (Vinodh and Jayakrishna 2013).

Life cycle sustainability analysis study on remanufacturing of alternators for decision making for the design of product and plant, considering the optimal location remanufacturing is dependent on two factors (i) where the used alternators are sourced and (ii) where the remanufactured alternators are going to be used (Schau et al. 2012). Further, a study has been performed to show that electrical and electronics products are suitable for remanufacturing which provides case studies of Chinese e-waste recyclers that suggests the electrical and electronic products are not highly suited to the remanufacturing process (Hatcher et al. 2013). The factors that affect decisions concerning pre-processing inspection have given a relationship between pre-processing inspection and the subsequent remanufacturing process time for returned cores (used products) (Ridley et al. 2015). An integrated model encompassing the approaches such as environmentally conscious quality function deployment (ECQFD), life cycle assessment (LCA) and sustainability analysis has been studied to give an eco-friendly option and remanufacturing feasibility of that component was inspected. Also, the environmental impact of the component was examined for better analysis (Vinodh and Jayakrishna 2014; Puglieri 2020). A detail examination reveals the need of coordinating product and supply chain design decision for a sustainable supply chain by including the 6R concept in closed-loop supply chain giving a sustainable supply chain (Metta and Badurdeen 2013; Mathivathanan et al. 2019).

Total life cycle sustainability analysis of the additively manufactured product was done which laid emphasis on additive manufacturing over conventional manufacturing for sustainability by giving results result on economy sub-index, environment sub-index, and society sub-index resulting for better sustainability of product (Hapuwatte et al. 2016). Product Sustainability Index (ProdSI) is a metrics-based framework to evaluate the total life cycle sustainability of manufactured product which provided a comprehensive assessment of the overall product sustainability by incorporating the triple bottom line, the total product life cycle and the 6R approach (Shuaib et al. 2014). Furthermore, an in-depth investigation has revealed the necessity to identify the design issues that hinder and aid the remanufacturing of mobile phones by implementing a European Union objective open-access component database where original equipment manufacturer (OEM) component data and updated component performance information were found, improving the quality and identification of components and hence aid component recovery (Long et al. 2016).

A total life cycle-based approach describes sustainable SCM (SSCM) to extend beyond the 3R's of reduce, reuse and recycle to 6R's that include recover, redesign and remanufacture by offering offers a definition of SSCM incorporating product life cycle-based thinking, the 6R methodology, and the closed-loop system's approach (Badurdeen et al. 2009). A case study describes sustainable design-oriented product modularity combined with 6R concept by proposing an effective methodology of sustainable design-oriented product modularity to integrate sustainable factors such as environment, economy, and society into product design process through the product representation with respect to module clustering criteria by integrating 6R concept into module clustering criteria such as function, manufacturability, and end-of-life options to achieve objective of sustainable design (Yan and Feng 2014).

2.3 Review on quality function deployment

Akao developed a concept called quality function deployment (QFD) which provided a method to ensure quality at each stage of the product development process (Kogure et al. 1983). QFD acts as a tool to bridge the gap between customer needs and engineering requirements. This tool enables any company to make market-led technology-driven decisions (Thurston et al. 1993). The benefit of QFD is in creating synergies and/or contradictions between the correlation of user expectations (the "What's) and the engineering metrics (the "How's") for a new product development (Marsot and Jacques 2005). Some researchers have carried out different studies by streamlining the engineering metrics of the QFD on any one broad concept. Green QFD concept has been developed by integrating QFD with a life cycle approach to product development (Cristofari et al. 1996). Since then there has been a considerable development in GQFD. A new methodology integrates LCA and life cycle cost (LCC) into QFD, which is termed as GQFD-II (Zang 1999). Further, a methodology has been proposed for integrating Life Cycle Impact Assessment into the greenhouse with the use of AHP (analytical hierarchy process) for selecting the best product concept (Mehta and Wang 2001). Another variation of QFD investigates the use of environmental-conscious design using QFD for the environment (QFDE) (Masui et al. 2003). Using ECQFD, LCA and sustainability analysis, an integrated model had been developed and tested on an automotive assembly manufacturing process (Vinodh et al. 2014). Although the extensive study is done with the use of QFD in product development, no study features the use of remanufacturing in QFD. This paper proposes a new framework in order to attain sustainability in product development by using RQFD wherein the correlation of customer needs is done with the 6R's as the engineering metrics of RQFD.

2.4 Gaps identified from the literature

The context of this research is based on the application of sustainability tools on single-piston floating type brake caliper. Braking effect in disk brake calipers is caused due to the movement of brakes pads against the rotor surfaces by the hydraulic piston actuators. The working is based on the force that driver applies on the brake pedal, which forces the brake fluid through the piston and hence causes the brake pads to clamp against the rotor (Puhn 1985). While there is extensive research done on the casting of brake caliper (Houria et al. 2015 and Maijer et al. 2004), few investigations have reported the use of 6R tools along with sustainability analysis while manufacturing which considers the environmental impact. 6R methodology (reduce, reuse, recover, redesign, remanufacture, recycle) involves achieving total sustainability through all the life cycle stages (Jawahir et al. 2016; Rajesh and Rajendran 2020).

A system level sustainability analysis is done to find the impact of individual components of brake caliper on the environment throughout its life cycle during the design stage itself. This, along with the LCA analysis of the critical component, helps in determining the key parameters to be used in process change of manufacturing the critical component. The data obtained from sustainability analysis are also used in material change analysis of the critical component where the aim is to choose suitable material on the basis of sustainability characteristics required without compromising on its functional capability.

The aim of this paper is to present a conceptual framework model using the three orientations of sustainability which is a design change, process change and material change of the respective product. The motivation of this work comes from the vivacity and vehemence in researching in subjects which aim to optimize manufacturing in order to make the final product sustainable throughout its life cycle. It is the need of the hour to have a lesser impact on the environment, social viability and economic feasibility in its function during all the product life cycle stages. So, it becomes very important to consider a study which helps amalgamate mechanical engineering concepts with 6R to make brake caliper more sustainable.

3 Methodology

The methodology adopted in this study is shown in Fig. 4. Literature review was conducted on sustainable manufacturing, 6R approach, remanufacturing, life cycle analysis, sustainable manufacturing, quality function deployment (QFD), environmentally conscious quality function deployment (ECQFD). Based on the literature review, research gaps in the present literature are identified upon which a framework based on integrating sustainability and 6R approach is employed on a component identified, i.e., brake caliper. A detailed discussion is carried out with the experienced engineers pertaining to RQFD, and the averages of the appropriate customer weight are taken as final values in RQFD tables through which critical engineering parameters have been established. Thereafter critical components are identified by performing RQFD-II analysis. Overall sustainability analysis of each critical component is performed which indicates the most critical component. This component which has the greatest environmental impact is subjected to three types of orientations, viz.

i. Orientation 1—design change
ii. Orientation 2—material change
iii. Orientation 3—process change

A modified component is developed by making necessary changes in the original component. These two are compared on the lines of sustainability, and corresponding results obtained are discussed.

4 Case study

The study was carried out in an automobile braking system manufacturing organization located in Tamil Nadu, India (hereafter designated as ABC). ABC is the manufacturer of calipers, actuation, drum brakes, valves, disk brakes and many other automotive products. The organization is certified with TS 16,949, ISO 14,001, OSHAS 18,001, EN 16,001 standards and many other excellence awards. The case component considered here is single-cylinder floating-type caliper. ABC aspires to attain greater sustainability in their product design and manufacturing practices of brake caliper to the best of their abilities. ABC was eager in developing a sustainable product in liaison with their customers, and they also wanted to do the design change over using the existing system without major changes. Considering their request, it was decided to modify their QFD approach as RQFD for making their product remanufacturable after their EoL disposal by imbibing the orientations of sustainability. This study helps such manufacturers to attain their aspirations for sustainability.

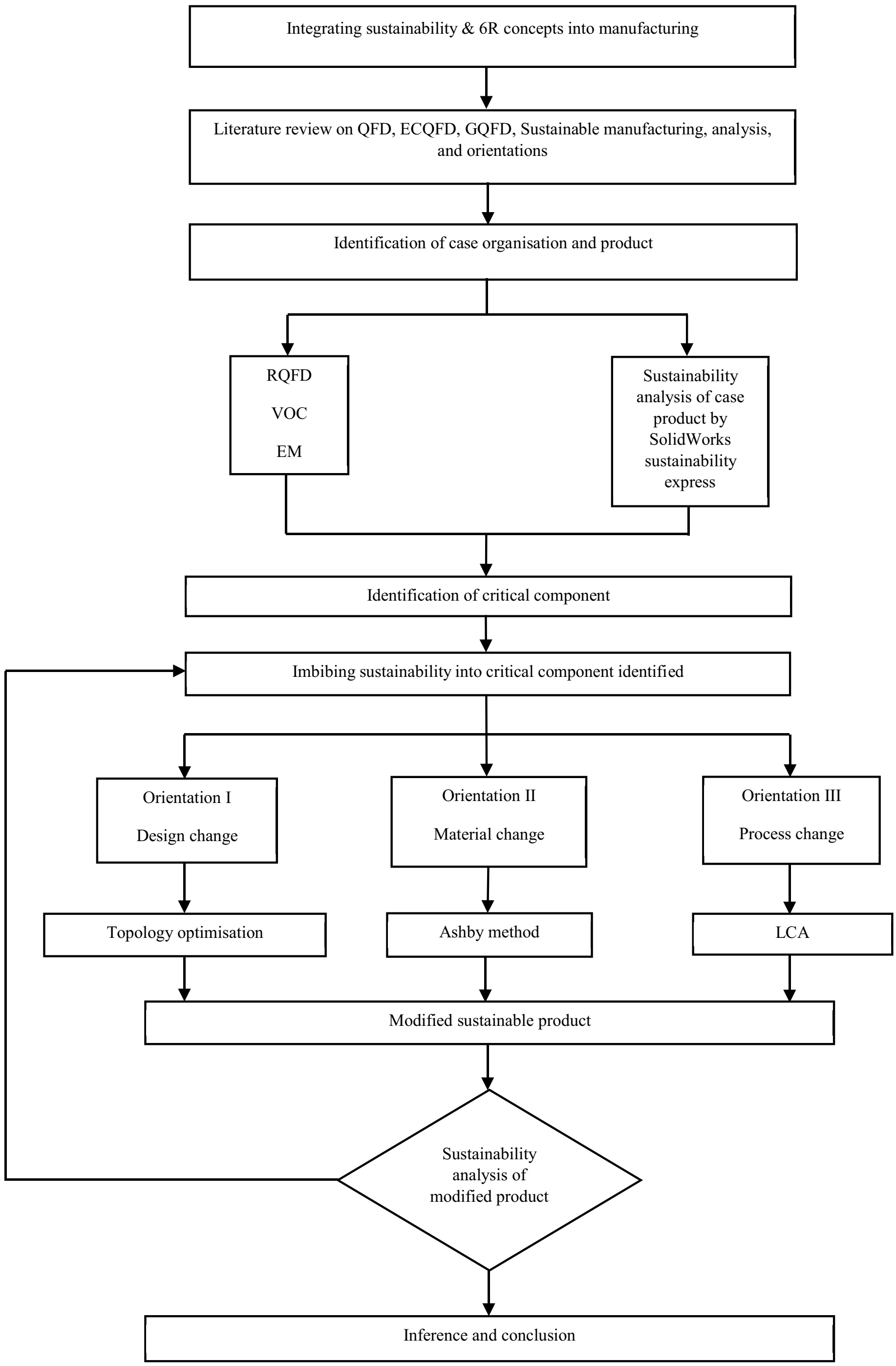


Fig. 4 Methodology adopted in this study

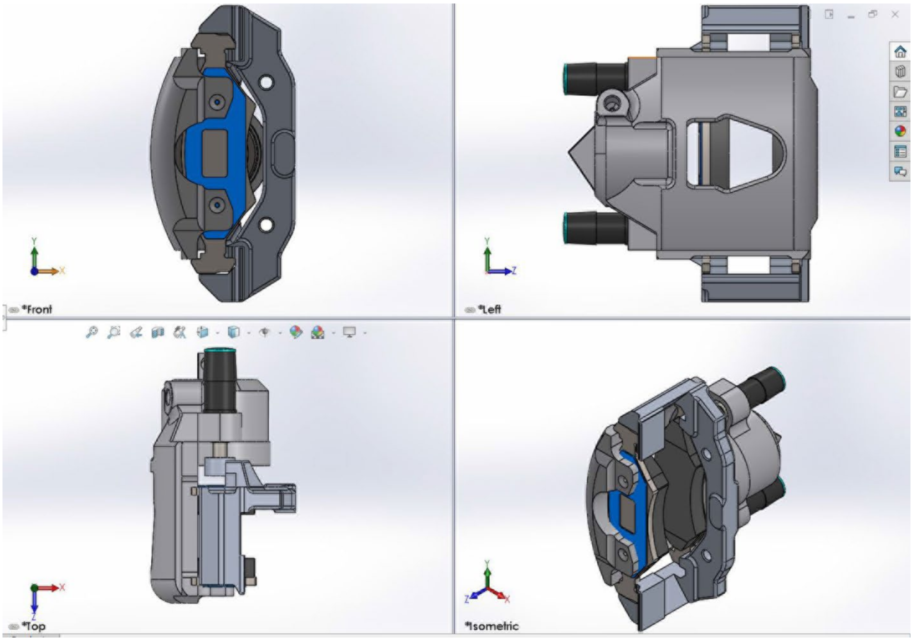


Fig. 5 Design of brake caliper

Table 1 Bill of materials of brake caliper

Components	Quantity	Material
Caliper frame	1	Al 356.0-T6
Caliper bracket	1	7075-O (SS)
Brake pads	2	Asbestos, alloy steel
Piston	1	AISI 1010 steel, hot rolled bar
Slider pins	2	ASTM A36 steel
Dust bellows	2	Rubber

4.1 Design of brake caliper

The single-cylinder floating-type caliper is made of aluminum A356.0-T6 manufactured using permanent mold aluminum die casting process. Figure 5 shows design of the single-cylinder floating-type brake caliper used as case product. SolidWorks 2016 was used for design purposes.

Table 1 lists the major components of brake caliper along with their material and quantity.

Table 2 RQFD-A

VOC	Engineering metrics (EM) how						
	Customer weights	Recover	Reuse	Recycle	Reduce	Redesign	Remanufacture
Biodegradability	2	2	3	5	2	2	0
Toxicity of materials	3	2	0	2	5	5	5
Functional effectiveness	5	3	3	2	0	5	5
Efficiency	5	5	2	0	5	3	5
Modularity	5	3	2	2	5	5	3
Resale value	3	3	5	5	2	2	2
Ease of disassembly	3	3	2	2	5	5	3
Reliability	5	5	5	0	0	3	5
Operational safety	3	3	3	0	3	5	3
Ergonomic	2	0	0	0	2	5	3
Ease of disposal	2	5	0	5	0	3	2
Raw score		127	96	67	103	151	139
Relative weight		0.186	0.140	0.098	0.150	0.221	0.203

4.2 Remanufacturing quality function deployment-I (RQFD-I)

The quality function diagram for remanufacturability (RQFD) (Table 2) is made considering the 6R in the engineering metrics. Voice of customers (VOC) which represents various concerns of the customer for brake caliper with respect to the factors like environment, economic and social implications of the used brake caliper. Appropriate customer weights are assigned to them. The rating between VOC objects and EM objects is indicated by means numbers which demonstrate factors called "relational strength". The weighting of VOC objects 5, 3 and 2 indicates a strong, medium and certain association.

The raw score is calculated by multiplying the total sum by the respective customer weight and relational strength of each EM objects and relative weight is the average of the raw score for each object. Customer weights of each VOC were multiplied with relation strength of each engineering metrics, and the summation of the product was taken to calculate the raw score of each column. To calculate the relative weight, each raw score is divided by the total sum of the raw score. These values of raw score help in decision making by the product development team (Rajesh 2020b). The relational strength and customer weights are determined by an expert committee which comprises of all the technical department of the company where the study is carried out. A detailed discussion is carried out with the experienced engineers who give their opinion on the RQFD, and the averages of the given weight are taken as final values in RQFD tables. RQFD table gives the critical engineering parameter. Table 2 (RQFD-I table) shows ratings assigned between VOC objects and EM objects.

The investigation of RQFD-I table indicates that relative weight of redesigning is maximum followed by remanufacture, and that of recycling is minimum.

Table 3 RQFD-B

Engineering Metrics	Components characteristics						
	Phase I relative weight	Brake pads	Caliper bracket	Piston	Caliper frame	Slider pin	Dust boots
Recover	0.186	3	3	3	5	0	0
Reuse	0.140	5	5	0	5	0	3
Recycle	0.098	5	5	0	3	3	0
Reduce	0.150	0	3	0	2	0	0
Redesign	0.221	0	0	0	2	0	0
Remanufacture	0.203	5	5	0	3	0	0
Raw score		2.763	3.213	0.558	3.275	0.294	0.42
Relative weight		0.263	0.306	0.053	0.312	0.028	0.04

4.3 Remanufacturing quality function deployment-II (RQFD-II)

RQFD-II purely involves the employment of EM objects to all the components of the brake caliper. The comparative significance is obtained in a similar manner of phase I. The relative weight values obtained from RQFD-I are used as input in RQFD-II (Table 3) to shows the relationship between the engineering metrics based on 6R and all the components of brake calipers. As revealed in the RQFD-II table, it is found that caliper frame in the most critical component and caliper bracket and brake pads are the next important critical components, respectively. Table 3 shows the relationship between engineering metrics and components of brake caliper.

4.4 Sustainability analysis of brake calipers

4.4.1 Carbon footprint (CFP)

The carbon footprint of each component over their life cycle stages is tabulated in Table 4, and graph is plotted using these values to show which component has major emissions of CO_2 at different life cycle stages. From Fig. 6, it can be inferred that caliper frame has major emissions at material and manufacturing stage, while it has moderate emissions in transportation and end of life stage. Table 4 lists carbon footprint (CF) of brake caliper.

Table 4 Carbon footprint (CF) of brake caliper

Component	Material	Manufacturing	Transportation	End of life
Slider pins	0.085	0.011	1.30E-03	0.032
Piston	0.762	0.113	0.014	0.344
Caliper bracket	4.8	0.163	0.011	0.06
Brake pads	1.1	0.363	0.017	0.418
Caliper frame	7.2	1.5	0.023	0.126

Unit: Kg CO_2e

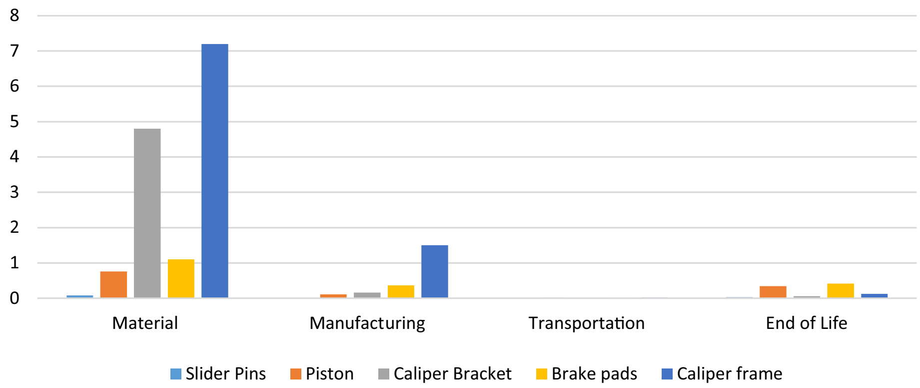


Fig. 6 Emission of CO_2 at each life cycle stages of the brake caliper

Table 5 Total energy consumption (TEC) of brake caliper

Component	Material	Manufacturing	Transportation	End of life
Slider pins	1.1	0.124	1.60E-02	0.356
Piston	10	1.3	0.171	3.8
Caliper bracket	59	1.6	0.134	0.075
Brake pads	13	3.6	0.208	4.6
Caliper frame	84	15	0.281	0.156

Unit: MJ

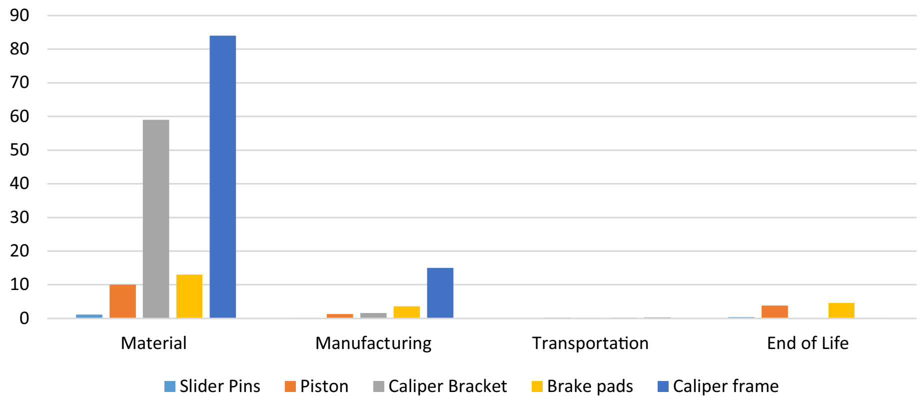


Fig. 7 Energy consumed at each life cycle stages of the brake caliper

4.4.2 Total energy consumption (TEC)

The total energy consumed by each component over their life cycle stages is tabulated in Table 5 and graph is plotted using these values to show which component has a large

Table 6 Air acidification (AA) of brake caliper

Component	Material	Manufacturing	Transportation	End of life
Slider pins	2.40E-04	1.10E-04	4.00E-05	1.70E-04
Piston	2.20E-03	1.20E-03	4.30E-04	1.80E-03
Caliper bracket	0.035	2.30E-03	3.40E-04	6.10E-05
Brake pads	3.30E-03	5.10E-03	5.30E-04	2.20E-03
Caliper frame	0.036	0.021	7.1E-04	1.3E-04

Unit: Kg of SO_2e

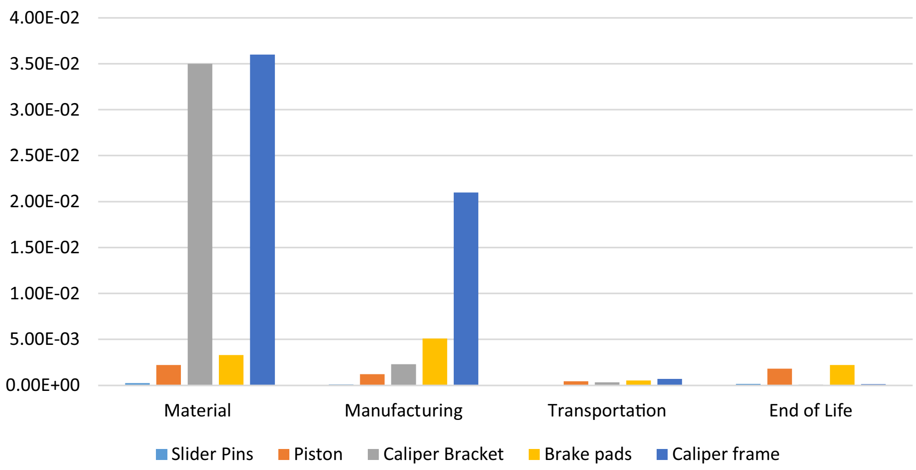


Fig. 8 Emission of SO_2 at each life cycle stages of the brake caliper

consumption of energy at different life cycle stages. From Fig. 7, it can be inferred that caliper frame consumes more energy during material and manufacturing stage as compared to other components. Table 5 lists total energy consumption (TEC) for different components of brake caliper at each stage of the life cycle.

4.4.3 Air acidification

The air acidification of each component over their life cycle stages is tabulated in Table 6 and graph is plotted using these values to show which component has major emissions of $S0_2$ at different life cycle stages. From Fig. 8 it can be inferred that Caliper frame has major emissions at material, manufacturing and transportation stage as compared to other components. Table 6 lists air acidification (AA) values for different components of brake caliper at each stage of life cycle.

4.4.4 Water eutrophication

The water eutrophication of each component over their life cycle stages is tabulated in Table 7 and graph is plotted using these values to show which component has major

Table 7 Water eutrophication (WE) of brake caliper

Component	Material	Manufacturing	Transportation	End of life
Slider pins	9.70E-05	5.30E-06	3.80E-06	2.20E-05
Piston	2.00E-04	5.70E-05	4.10E-05	2.40E-04
Caliper bracket	1.10E-03	8.90E-05	3.50E-05	1.20E-05
Brake pads	9.20E-04	2.00E-04	5.00E-05	2.90E-04

Unit: Kg of PO_4e

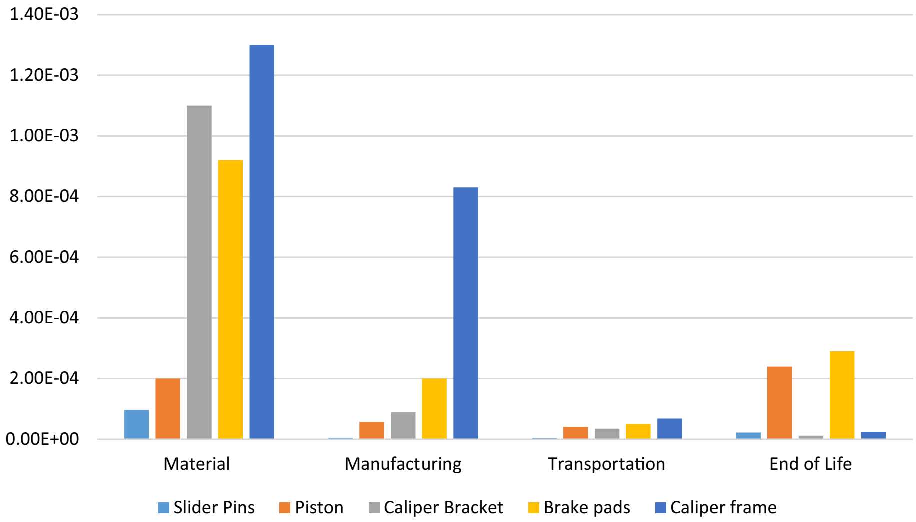


Fig. 9 Emission of PO_4 at each life cycle stages of the brake caliper

emissions of PO_4 at different life cycle stages. From Fig. 9, it can be inferred that Caliper frame has major emissions at material, manufacturing and transportation stage as compared to other components. Table 7 lists water eutrophication (WE) values for different components of brake caliper at each stage of life cycle.

Figure 9 shows emission values of PO_4 at for different components of the brake caliper at each stage of life cycle.

4.5 Overview of sustainability analysis

Table 8 lists values for consolidated sustainability analysis data of brake caliper.

Figure 10 shows the overall sustainability analysis of brake caliper.

From the data obtained from overall sustainability analysis (Fig. 10) and RQFD Table 8, an inference can be made that caliper frame has greatest environmental impact compared to other components of the brake caliper with 8.9 kg CO_2e of carbon footprint, 100 MJ of energy consumption, 0.058 SO_2e air acidification and 2.20E-03 PO_4e. Thus, the critical component mapped out of RQFD and sustainability analysis is 'caliper frame'.

Table 8 Consolidated sustainability analysis data of brake caliper

Component	Carbon footprint CO_2e kg/kg	Total energy consumption MJ	Air acidification SO_2e	Water eutrophication PO_4e
Caliper frame	8.9	100	0.058	2.20E-03
Caliper bracket	5	60	0.038	1.30E-03
Brake pads	1.9	22	0.011	1.50E-03
Piston	1.2	15	5.60E-03	5.30E-04
Dust bellows	0.049	0.9	1.10E-04	2.30E-05
Slider pins	0.129	1.6	5.60E-04	1.30E-04

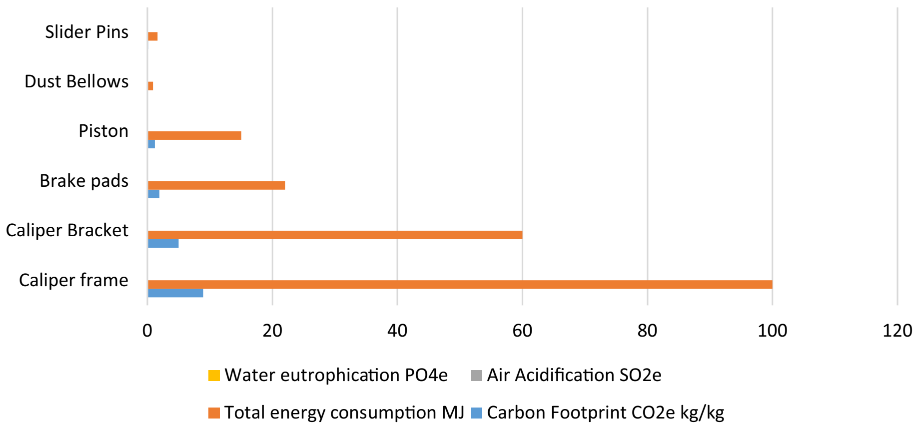


Fig. 10 Overall sustainability analysis of brake caliper

5 Sustainability orientations

Three orientations were performed on the critical component in order to bring modification in the critical component ‘caliper frame’ so that environmental impact could be controlled. The orientations being that of material change, design change and process change.

5.1 Design change of caliper frame (Orientation 1)

The study carried out for design change emphasize on improving sustainability by considering 6R tools. The design change is carried out on the critical component which is the caliper frame. The functionality of the caliper after the design change is not hampered as the focus has been on eliminating redundancy in the design by weight reduction. Two elements of 6R have been deployed in this study which are reduce and redesign. Reduction in the material of caliper frame is associated with a less CO_2 footprint throughout its life cycle. Reduction in material leads to a reduction in weight per component, thereby improving the efficiency of the brake caliper and reduction in carbon emission by the vehicle. Figure 11a illustrates the original design of caliper frame, and Fig. 11b shows the modified design after the changes made in the original design of the caliper frame.

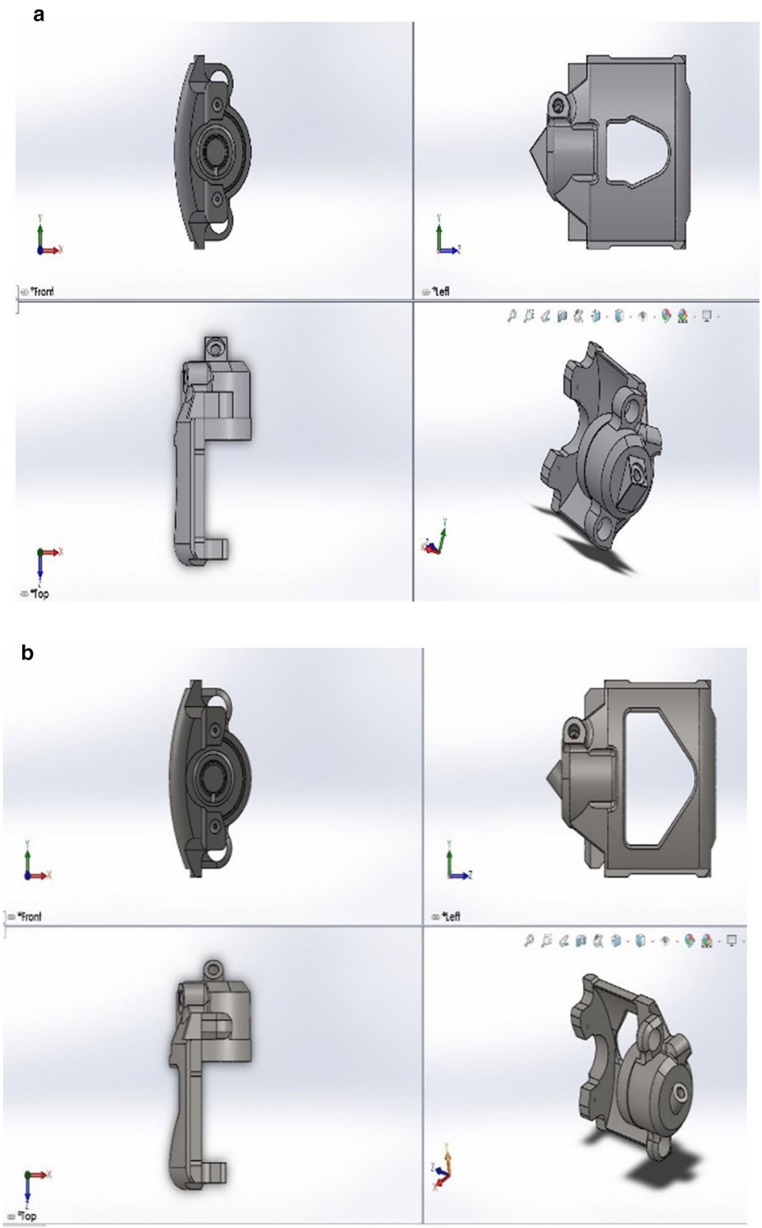


Fig. 11 **a** Original design of critical component **b** Modified design after design change operation

5.2 Material change of caliper frame (Orientation 2)

The base (original) material of the caliper frame is taken as Al 356. The aim is to find a suitable substitute for Al 356 while improving its sustainability and without compromising on its functionality. According to Oder (2009), high stiffness, fatigue strength and toughness against Fracture during frequent operation is the key determinant in the selection of the brake caliper. These forces are the resultant forces when the braking force is applied by the caliper piston on the brake pads. The material selection is performed in CES Edupack 2009—Level 3. For the graph plot of $\{K_{1c}/\rho\}$ and $\{\sigma_e/\rho\}$ (Refer Fig. 12), the following limits are considered:

1. Maximum service temperature 400 °C (upper limit)
2. Transparency—opaque
3. Flammability—non-flammable
4. UV radiation—excellent tolerance
5. Oxidation at 500 °C—acceptable and excellent tolerance
6. Casting energy—21.4 MJ/kg (upper limit)
7. Casting CO_2—14.14 kg/kg (upper limit)
8. Material recyclable
9. Water (salty)—limited use, acceptable and excellent tolerance
10. Water (fresh)—acceptable and excellent tolerance

where K_{1c} is the fracture toughness at 10^7 cycles (Pa $m^{0.5}$); σ_e, the fatigue strength (Pa); ρ, density (kg/m^3).

The graph of $\{K_{1c}/\rho\}$ and $\{\sigma_e/\rho\}$ is plotted by using the above-mentioned limits. The result shows all the materials from the database that have passed the limit. In the above case, a total of 485 out of 2920 materials have passed the limits that have been decided. The passed materials include gold, titanium, carbon steel, low alloy steel, etc. Although this result passes the criteria set for material selection, this result alone is not sufficient to finalize the material selection. Hence, further selection is considered on the basis of the economic feasibility of the material along with its environmental impact. The following

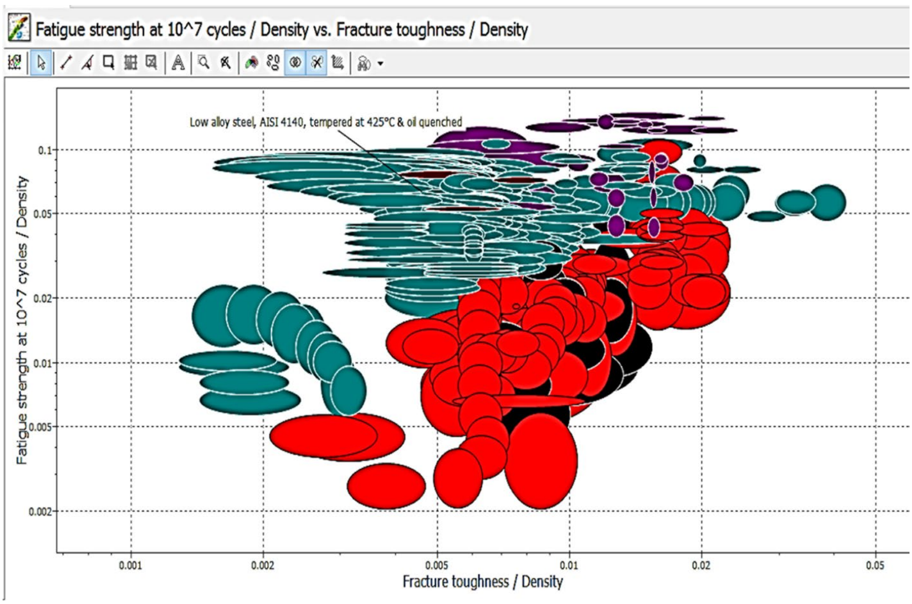


Fig. 12 $\{K_{1c}/\rho\}$ versus $\{\sigma_e/\rho\}$

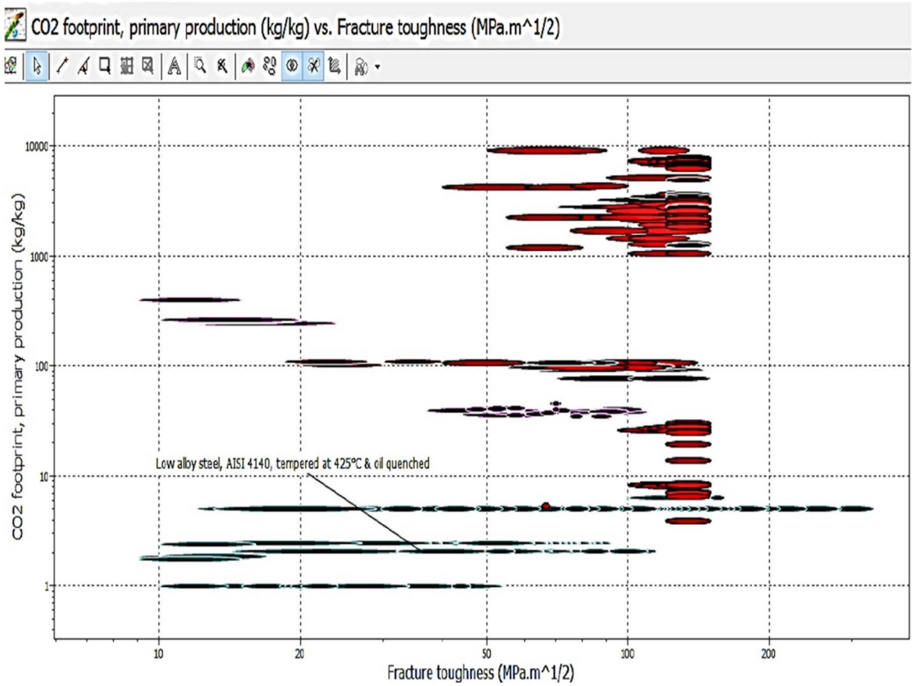


Fig. 13 CO_2 footprint primary production (kg/kg) versus σ_e

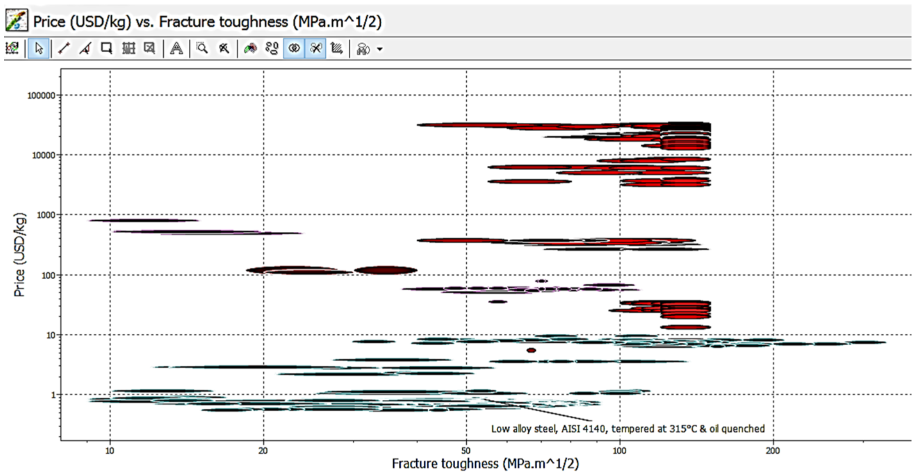


Fig. 14 Price versus σ_e

graphs are considered for further selection (with the same limits) CO_2 footprint, primary production (kg/kg) versus σ_e (Fig. 13) and price versus σ_e (Fig. 14).

Figures 13 and 14 show the material selection based on economic viability and less environmental impact and hence the target material has to be the one with a less CO_2 footprint at primary production and less price. Considering the limits and criteria set along orientation 1 and Figs. 13 and 14, the change in material is inferred as low alloy steel, AISI 4140, tempered at 315 °C and oil quenched. Figure 13 illustrates CO_2 footprint primary production (kg/kg) versus Fracture Toughness and Fig. 14 shows plot for Price versus Fracture Toughness.

5.3 Process change of caliper frame (Orientation 3)

Figure 15 illustrates process flow for manufacturing Al 356 caliper frame. The process change orientation is carried out using GaBi LCA software. The process flow of manufacturing of aluminum A356 caliper frame (original caliper frame material) is carried out, and LCA analysis is performed. The manufacturing of caliper frame made of Al 356 is carried out using permanent mold die casting. The manufacturing is divided into various stages. Stage 1 is the die preparation. This stage consumes in a total of 4.1 MJ of energy. Die-cast mold design and production consume 3.5 MJ out of the 4.1 MJ of energy. 1.47 L of naphtha is also consumed. Die-cast mold installation consumes 0.2 MJ energy, and die lubrication consumes 0.4 MJ of energy. 0.23 L alkyl benzene sulfonate is also consumed in this process. Outputs like NO_x, CO, SO_x and machining waste are given out at this stage.

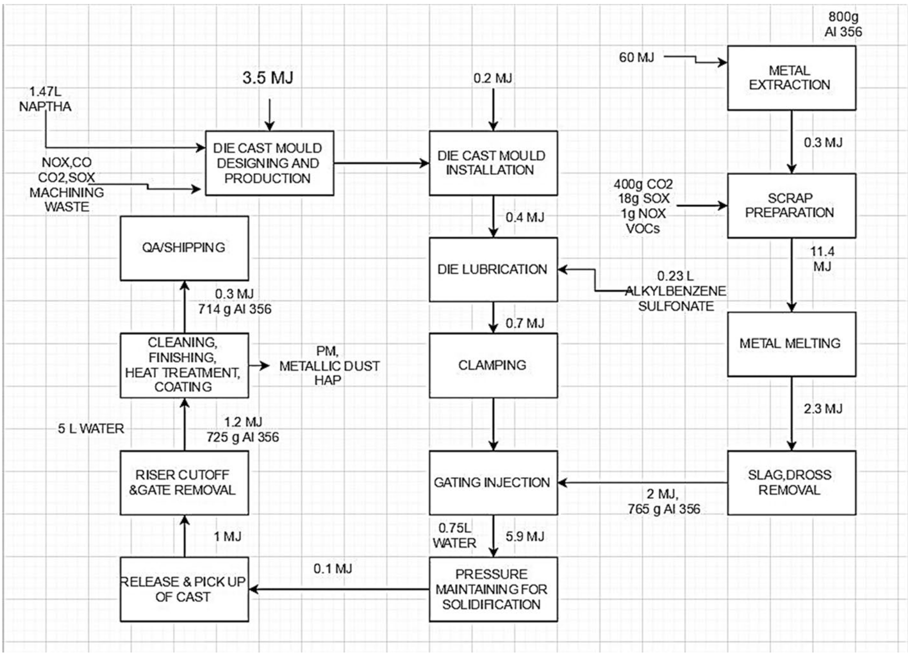


Fig. 15 Process flow for manufacturing Al 356 caliper frame

Stage 2 of caliper frame production involves metal preparation process. 800 gm metal extraction of Al consumes 60 MJ energy. 0.3 MJ energy is consumed in scrap preparation. Metal melting is carried out which consumes 11.4 MJ of energy along with the output of a high amount of CO_2, 1.8 gm SO_x, 1 g NO_x and certain VOC's. After this step, slag removal is done which consumes 2.3 MJ which gives the remainder metal of 765 gm Al 356. Metal preparation stage in total consumes 74 MJ of energy. Step 3 in manufacturing caliper frame is casting where the metal prepared is poured into the die cast. The clamping of the die prepared requires 0.7 MJ of energy. The metal prepared is injected into the cast consuming 2 MJ energy in that process. 0.75 L of water per part is circulated for cooling.

Pressure is maintained for some time to solidify the cast. For this 5.9 MJ of energy is required. 0.1 MJ of energy is required for release and pick up of the cast. The casting stage in total consumes 8.7 MJ of energy. Stage 4 consists of finishing and inspection. This stage in total consumes 2.2 MJ of energy. Out of the total energy consumed, 1 MJ is utilized in riser cut-off and gate removal process. The weight of the caliper frame after this step reduces to 725 gm. 5 L of water along with 1.2 MJ of energy is needed in cleaning, finishing, heat treatment and coating process. The weight of the casted part, caliper frame, is 714 gm. The output of this process includes PM, metallic dust and HAP. The last stage in the manufacturing process includes quality assurance and shipping of the product to the required destination. This step-in total consumes 0.3 MJ of energy. The whole process of manufacturing caliper frame, including the various stages, of Al 356 material requires 90 MJ of energy.

Figure 16 illustrates process flow for manufacturing AISI 4140 caliper frame. After the material selection is done, the material chosen to be more sustainable is AISI 4140. The process flow of manufacturing AISIS 4140 is compiled, and LCA is done for the

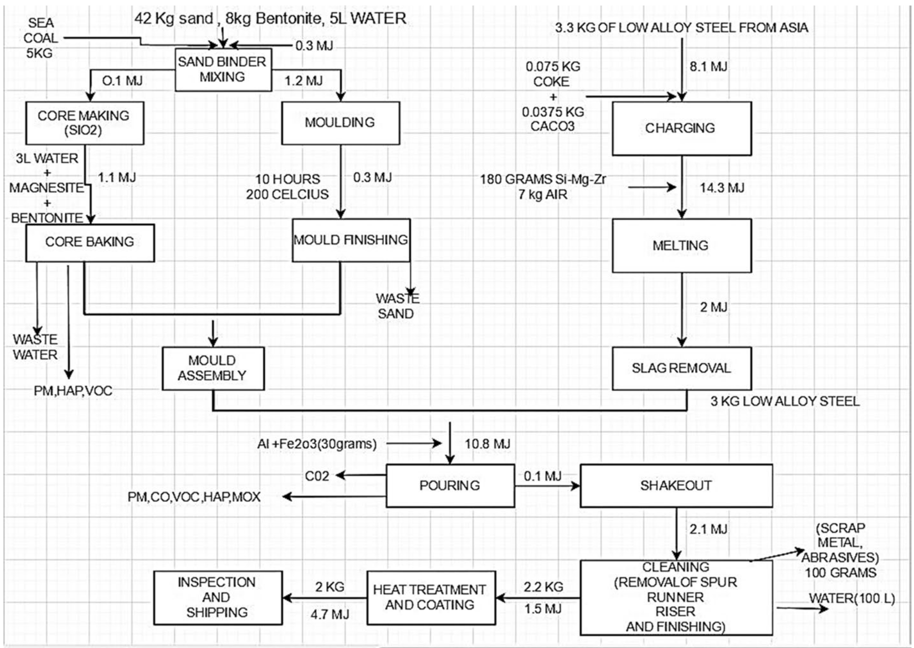


Fig. 16 Process flow for manufacturing AISI 4140 caliper frame

same (Fig. 16). The process for manufacturing A356 caliper is permanent mold die casting, whereas the manufacturing process for AISI 4140 caliper frame is sand casting. This manufacturing process has five stages. Stage 1 is the mold preparation stage. For making caliper frame, green sand molds are used. In this stage, the core and the mold were prepared which is further used for the casting process. For preparing core and the mold for this particular component, we need 42 kg of sand + 8 kg bentonite and 5 L water to form a sand binding mixture. 5 kg of seacoal is also added. This requires an energy consumption of 0.3 MJ. Mold assembly contains of two separate process for making the mold and the core. Initially, 0.1 MJ of energy is supplied for core making using SiO2. Further, 3 L water + magnesite and bentonite are added, with a consumption of 1.1 MJ, for core baking. This operation is 10 h long carried at 200 °C. The by-products of core baking are wastewater and gaseous waste like PM, HAP and VOC.

For molding 0.3 MJ of energy is supplied, and to obtain a better quality of the product, mold finishing is done, which involves putting the mold under heat torches for 10 h at 200 °C to remove moisture. The consumption of energy involved is 1.2 MJ for mold finishing process. Waste sand is the by-product of mold finishing. Putting together the mold and core forms the mold assembly. The total energy involved in the whole mold preparation stage is 3.3 MJ (or 7% of the 46.9 MJ energy required for overall manufacturing of caliper frame). Stage 2 includes metal preparation stage. For making caliper frame, air coupler furnaces are used assuming that manufacturing happens in Asia. The raw material of 4.5 kg steel is fed to the furnace as a charge alone with certain additives like 0.075 kg of coke and 0.0375 kg of limestone as a flux. The energy used up in charging is approximately 8.1 MJ. The metal is now melted in the melting stage where around 7 kg air is used for this particular component for cooling. Dolomite refractory is also added in negligible amount along with 180 gm of Si-Mg-Zr for proper melting. The energy involved in the melting stage is 14.3 MJ. Gases PM, NOx, CO and SO_2 are released as by-products. Slag removal is also an essential part in the process which consumes 2 MJ of energy.

After slag removal 4.2 kg of steel is left which is to further proceed to casting. The metal preparation stage involves around 24.4 MJ of energy (or 52% of the whole process). Stage 3 is casting of the caliper frame. To get the shape of caliper frame, the molten metal is poured into the mold assembly along with additives like $Al + Fe_2O_3$ (30 g) for generating extra heat. The casting is allowed to solidify for some time. Gases like carbon dioxide, PM, CO, VOC, HAP and MO_X are the b-products of this stage. After solidification, shakeout of the sand happens on the casting using hydraulic core knockout. Around 50 L of pressurized water is used in this process. Around 0.1 MJ is the energy consumption of shakeout process. The casting stage in total requires 10.81 MJ of energy (or 23% of the whole process). The pre-final stage includes finishing. Machining is used in this process for the removal of spur, runner and riser and also for finishing purpose to make the caliper frame dimensionally accurate. After the removal of reductant steel, the weight of the cast drops to 3.5 kg. Wastewater and scrap metal abrasives are by-product of this process. Heat treatment is done for assuring required functioning of the caliper frame. Due to the coating the weight increases to 3.6 kg. PM is also released in the air. Total energy involved in this stage is 2.1 MJ (or 8% of the whole process). The final stage is shipping and inspection. Inspection checks are carried out to ascertain the quality of the product. Now the caliper frame is to be shipped to North America which is our target market for the company. The total energy involved in this stage is 4.7 MJ (or 10% of the whole process).

The results obtained are based on parameters like global warming potential (CO_2 emission), abiotic depletion fossil (MJ), water depletion (m^3) and metal depletion (kg of Fe equivalent).

6 Results and discussion

This discussion is important in design, material and process perspective and its corresponding sustainability analysis are discussed in the following subsections.

6.1 Design change and sustainability analysis

The design change has been brought about using SolidWorks software. Before the design change, the weight of the Al-356 caliper frame of the brake caliper was 715 g. After design change, the weight was reduced to 654 g. Sustainability analysis on the original and new part of the design change has shown that carbon footprint has reduced from 8.9 to 8.1 kg/kg for its life cycle. Also, the energy consumed in the life cycle has dropped from 100 to 91 MJ. There is considerable reduction shown in air acidification values also. This validates the fact that using 6R tools like reduce and redesign, the sustainability of the product has increased.

Figure 17 shows the comparison of crucial environmental factors before and after design change.

It can be deduced from Fig. 17 that all the changes that have been brought during the design changes are sustainable and have lesser values of crucial environmental factors when compared to the original design. There is a decrease of 9.1% in carbon footprint and total energy consumption for the new design with respect to the original design.

6.2 Material change and sustainability analysis

Material selection for caliper frame was carried using CES Edupack-2009. The most important criteria for material selection was to decrease carbon footprint without compromising on the functionality. The material selected is AISI 4140. The SolidWorks sustainability analysis was done on caliper frame after the material change. The CO_2 emission as a measure of carbon footprint decreased dramatically from 8.9 kg/kg for Al-356 material to 4.3 kg/kg for AISI 4140. Also, the energy consumption over caliper frame's life cycle dropped from 100 to 44 MJ. The values of air acidification and water eutrophication were also acceptable causing negligible impact by material change. Hence, material

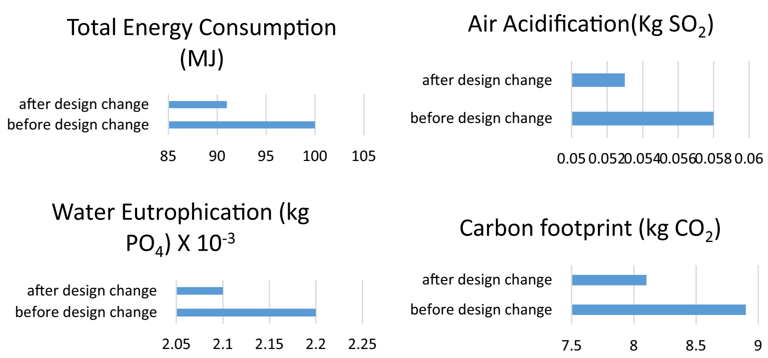


Fig. 17 Comparison of crucial environmental factors before and after design change

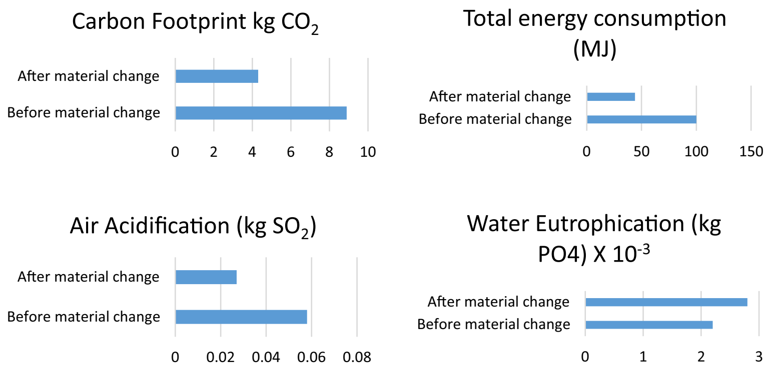
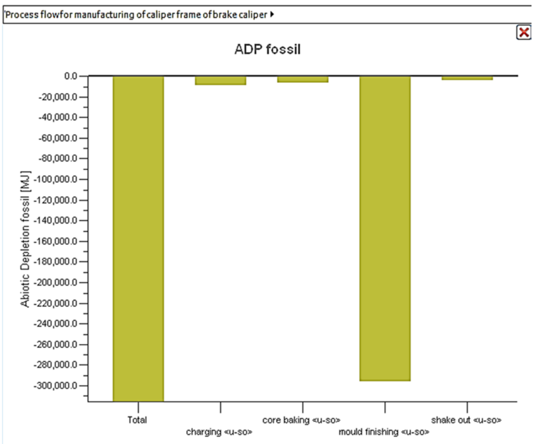


Fig. 18 Comparison of crucial environmental factors before and after material change

Fig. 19 Abiotic depletion fossil at various stages in manufacturing of AISI 4140 caliper frame



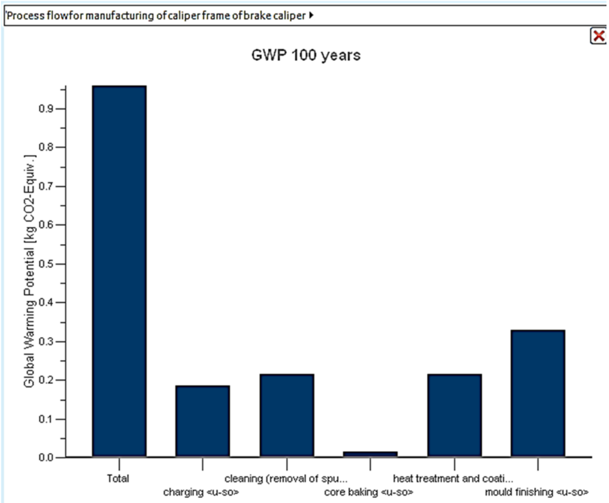
change activity shows highly positive result toward attaining sustainability for brake caliper in general. Figure 18 shows the comparison of crucial environmental factors before and after material change.

It can be deduced from Fig. 18 that the new material chosen for brake caliper shows a 52% reduction in carbon footprint along with 56% and 53% reduction in total energy consumption and air acidification, respectively (Fig. 18).

6.3 Process change and LCA using GaBi

The process change of caliper frame is validated using GaBi LCA software. The results obtained show the lesser value of AISI 4140 caliper frame for the parameters global warming potential (CO_2 emission), abiotic depletion fossil (MJ), water depletion (m^3) and metal depletion (kg of Fe equivalent) as compared to A356 caliper frame. This shows the successful implementation of sustainability tools to make the manufactured product more environmentally friendly. Figure 19 shows the Abiotic depletion fossil over the LCA of caliper frame manufactured by using sand casting process. The result shows that mold finishing yields the maximum contribution toward total abiotic deletion.

Fig. 20 Global warming potential for various stages in manufacturing AISI 4140 caliper frame



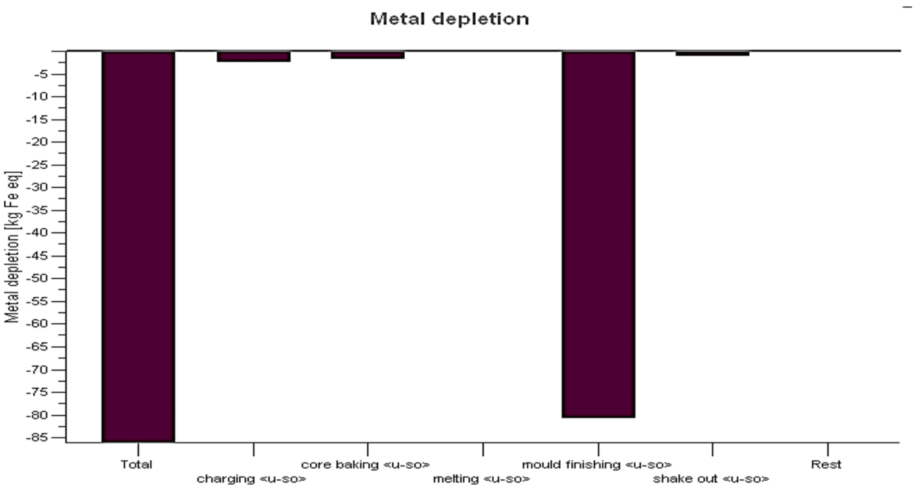


Fig. 21 Metal depletion for various stages in manufacturing AISI 4140 caliper frame

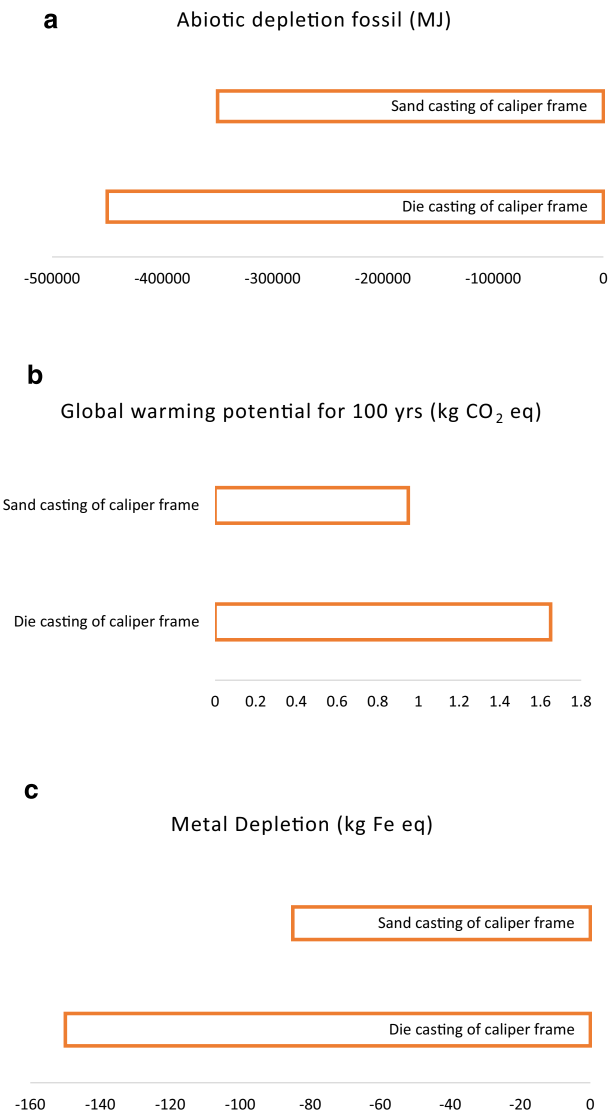
Figure 20 shows the global warming potential over 100 years, for every stage of manufacturing caliper frame using casting process. Charging and mold finishing steps cover the maximum of global warming potential.

Figure 21 shows metal depletion for various stages in manufacturing AISI 4140 caliper frame.

Figure 22a, b, c presents the results of process change using GaBi analysis (LCA Tool).

It can be inferred from Fig. 22a, b and c; The LCA (using GaBi software) comparison of the sand casting process and permanent die mold casting process for manufacturing brake caliper reveal that abiotic deletion fossil is less for sand casting as compared

Fig. 22 **a**, **b**, **c** The results of process change using GaBi analysis (LCA Tool)



to die casting process. The die casting of caliper frame has 1.7 kg CO_2 eq as compared to 0.9 kg CO_2 eq for sand casting. Also, metal depletion over LCA is less for sand casting as compared to die casting. This indicates that sand casting process using AISI 4140 is a better-suited process as compared to die casting using A356 material for manufacturing caliper frame.

Figure 23a shows sustainability parameters for different components for original design of brake caliper (before design change). Figure 23b shows sustainability parameters for different components for modified design of brake caliper (after design change). Figure 23c shows sustainability parameters for different components for original material of brake caliper (before material change), and Fig. 23d shows sustainability parameters for different components for new material of brake caliper (after material change).

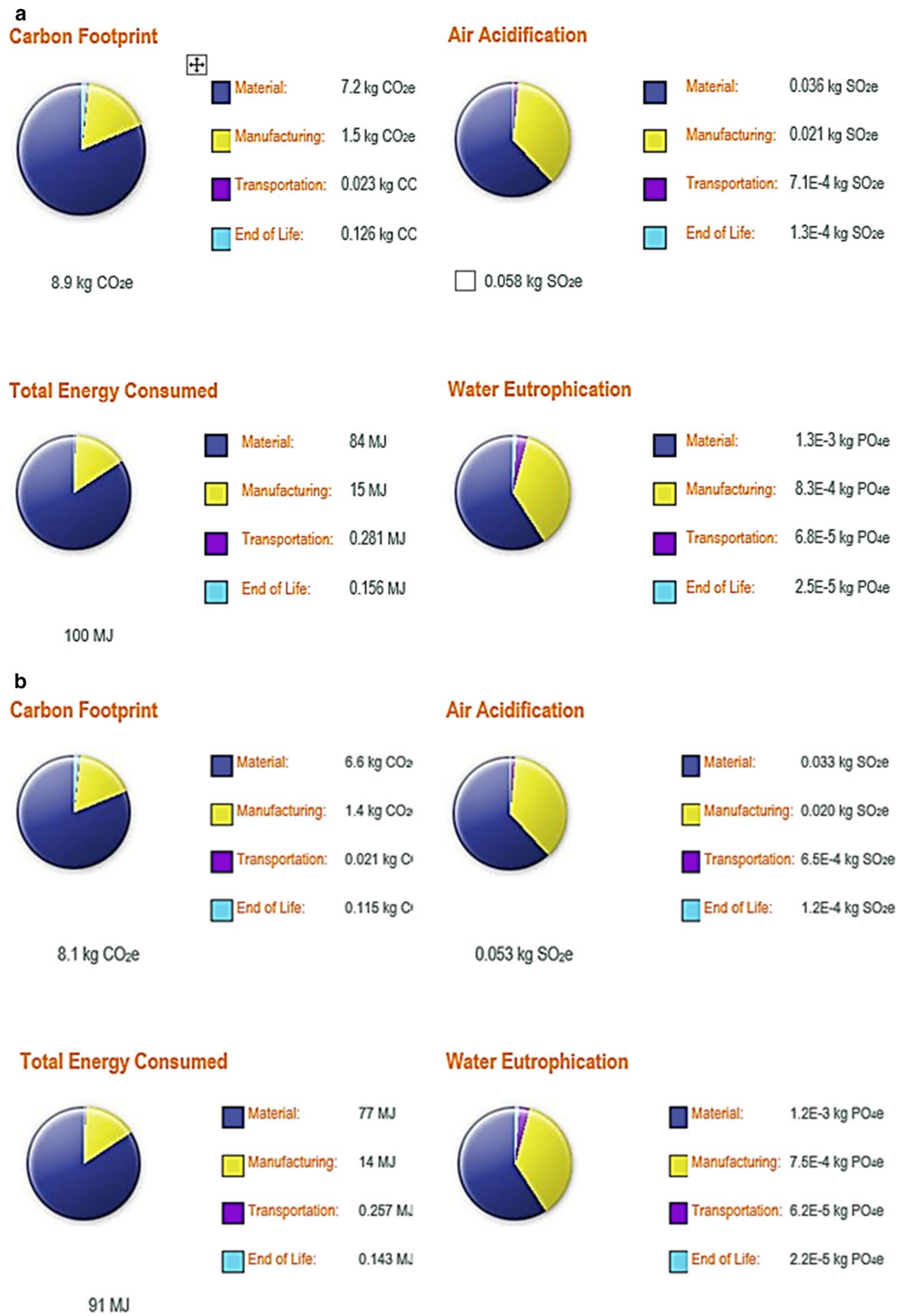


Fig. 23 **a** Sustainability parameters before design change. **b** Sustainability parameters after design change. **c** Sustainability parameters before material change. **d** Sustainability parameters after material change

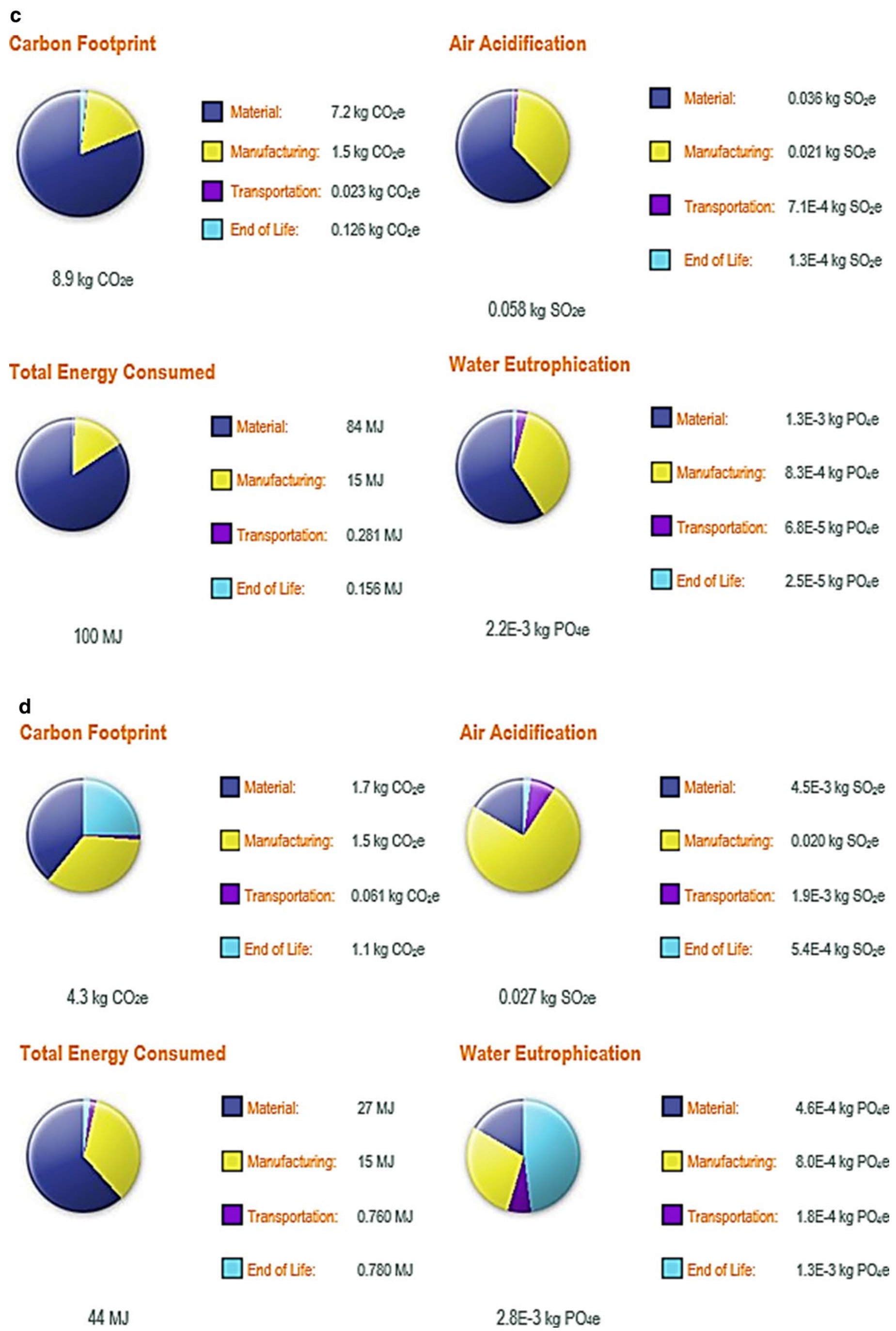


Fig. 23 (continued)

6.4 Impact on overall assembly

The combination of design changed and materially changed caliper frame was used to recreate the brake caliper assembly. The results obtained are a validation of obtaining a more sustainable brake caliper with less impact on the environment and greater efficiency. The sustainability analysis on the recreated brake caliper shows a steep reduction in negative impacts created on the environment by the critical component. The sustainable product development of caliper frame (the critical component) using 6R concepts and sustainability tools has reduced the overall impact that brake caliper causes on the environment in general. Table 9 illustrates the sustainability analysis of brake caliper assembly before 6R tools were used to improve sustainability.

After implementing 6R and sustainability tools on the critical part the overall assembly was evaluated for sustainability and the result is illustrated in Table 10.

7 Conclusions

The objective of the study was to consider sustainability tools to make any automotive component more sustainable. This framework has been adopted to study the brake caliper. To fulfill the objective, the study started with a review on QFD, ECQFD, GQFD, LCA, sustainability, remanufacturing and its benefits, end of life and their positive impact on environment and society. This was followed by the adoption of RQFD from literature along with identification of case product which is brake caliper. Remanufacturing VOCs and EM were studied and tabulated for RQFD. Sustainability analysis was performed on each component of brake caliper to map out the critical component which came out to be as caliper frame. This critical component was subjected to three orientations that were material, design and process change. Then this modified component was compared with the proposed component on the lines of sustainability, and a detailed

Table 9 Sustainability analysis data before modification

Component	Carbon	Water	Air	Energy
Caliper frame	9.3	1.9E-3	0.050	110
Caliper bracket	5.0	1.3E-3	0.037	61
Brake pads	2.2	1.7E-3	0.013	27
Piston	1.6	7.8E-4	0.010	20
Slider pins	0.165	1.5E-4	9.8E-4	2.0
Dust bellows	0.050	2.5E-5	1.1E-4	0.905

Table 10 Sustainability analysis data after modifications

Component	Carbon	Water	Air	Energy
Caliper bracket	**5.0**	**1.3E-3**	**0.037**	**61**
Caliper frame	**4.1**	**3.1E-3**	**0.024**	**41**
Brake pads	**2.2**	**1.7E-3**	**0.013**	**27**
Piston	**1.6**	**7.8E-4**	**0.010**	**20**
Slider pins	**0.165**	**1.5E-4**	**9.8E-4**	**2.0**
Dust bellows	**0.050**	**2.5E-5**	**1.1E-4**	**0.905**

discussion on result was done and inferences were derived. The main conclusions of this study can be summarized as follows:

- The unique feature of the project considers customer-focused product development at the design stage of product life cycle by using remanufacturing in QFD. The framework adopted in the study attempts to correlate customer needs with the 6R's as the engineering metrics of RQFD.
- Application of design change on the critical component considers redesigning of component and reduction of material. As a result, total energy consumed in the extraction of raw material and manufacturing of component is reduced per part. This will lead to lesser CO_2 emission and thereby make the caliper frame more sustainable.
- Application of material critical component considers various limits so as to take care of the functionality and also focus on sustainability. After the material change, the sustainability analysis of new material selected yields better results than the original material of the critical component.
- Application of all the three orientations of sustainable product development resulted in a brake caliper which had better sustainability as compared to the originally considered brake caliper component.

The proposed model has consequently achieved material and weight reduction by elimination of redundancy in design. This redesigned component thus has less CO_2 footprint throughout its life cycle and better efficiency with reduced cost. Also changed material is economically viable and has less environmental impact. It has also ensured employer safety. The service life is increased which is in the interest of consumers.

The approach undertaken in this project proved to be beneficial. This method can be used in the industry and it can help toward organization's sustainability initiatives of making product customer-focused and environment-friendly. As a policy recommendation, this proposed model will help organizations to achieve their sustainable development goals (SDG's) such as responsible consumption and production (SDG'12).

7.1 Limitations and future scope

In this study the work has been performed on one single automotive component at one single organization. The framework used in this study can be extended to other automobile components at various other organizations. More voice of customers can be included to get an even accurate result while compiling RQFD. This will help in finding critical parts of the automotive components under consideration. While selecting material using CES Edupack software, the study can consider greater number of functional limits to get a more focused material selection result. Also, the material accepted after the limit implementation gives multiple options for an engineer to choose from. The sustainability analysis can be done on similar material from the accepted pool of material so as to get a result according to the functional needs. If the requirement of the customer is focused more on some other parameter, for instance fatigue strength, then the framework proposed in this study allows flexibility for choosing the material according to the need of the manufacturer and customer. Alternate manufacturing processes can be tried apart from the ones used in the study so as find a more feasible and sustainable option for manufacturing if any.

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