Application of integrated environmentally failure modes and effects analysis and environmentally conscious quality function deployment for sustainable product design

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Abstract: The necessity to consider the environmental measures in the early product development promotes the concept of sustainable product design. The purpose of this study is to develop sustainable products by an integrated framework using environmental failure mode effective analysis (EFMEA), environmentally conscious quality function deployment (ECQFD) and life cycle analysis (LCA). EFMEA was used to conduct an environmental defective analysis and ECQFD was used for integrating the environmental aspects and expectations of the customers from that product. Based on the results of ECQFD the components were redesigned and subjected to a simple CAD model-based LCA using solid works sustainability Xpress, considering the environmental factors for the analysis. Finally, using an overflow valve as a case product the integrated model was demonstrated to understand the practical applicability. The environmental impacts caused by the redesigned overflow valve were less than the existing valve confirming the viability of the proposed integrated model.

Keywords: environmental failure mode effective analysis; EFMEA; environmentally conscious quality function deployment; ECQFD; life cycle analysis; LCA; sustainable product development; overflow valve; integrated framework; green products; environmental impacts; sustainability analysis; product design stages.

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1 Introduction

In recent years, competition among industries has been grown tremendously which makes them put forward their efforts and produce high-quality products at low cost and with less consumption of time with taking care of all the environmental issues. Due to the trend of market globalisation, companies are developing new products to keep their organisation in the profit zone. Also, in recent decades, people started showing interest in sustainable products. Due to the limited availability of resources and stringent environmental regulations, industries are improving their process with environmental concerns (Qi et al., 2010). Further, Younesi and Roghanian (2015) highlighted the increase in awareness among consumers in developed and developing countries. Thus, the manufacturing organisations are forced to include the environmental criteria in the early stages of product design so that they would not come across huge losses (Singh et al., 2016). This forms the reason for the global acceptance and attention to the concept of sustainable product design (Deng, 2015). While the manufacturing industries carry out the product design there are several parameters to be considered such as raw material, processing technology, statutory and regulatory body requirements along with the customers requirements (Ocampo et al., 2020). The consideration of environmental criteria should not affect the quality as well as product cost. There are several existing tools such as quality function deployment (QFD), ECQFD, life cycle analysis (LCA), TRIZ, and certain MCDM techniques, which use minimal product information in terms of either cost, quality, or environmental aspects in an attempt to improve product sustainability (Singh and Kumar, 2013). The works carried out by Amini et al. (2019) shows the benefits of using integrated tools for analysis and prioritisation of the list of parameters which were contributing to the subject matter.

This study aims at developing an innovative sustainable product using environmental failure mode effective analysis (EFMEA) and environmentally conscious quality function deployment (ECQFD) along with the application of product sustainability framework. Based on the analysis considering the detailed information about product failure and effects, the critical aspects are prioritised. With the information, ECQFD is used to propose improvements in terms of environmental performance without compromising quality and cost. Finally, sustainability analysis is conducted for the improved design to quantify the improvement in environmental indicators. failure mode effective analysis (FMEA) is one of the methodologies for identifying all potential failures within the process. Analysing the results or outcomes of the failures are referred to as effect analysis (Parsana and Patel, 2014). Customer satisfaction is improved by attempting the process FMEA step where the product/process is improved progressively (Thakore et al., 2015). Increasingly, present-day environmental studies focus upon the internal and external environmental effects of a product right from the decision on product pattern, its cost of production, its environmental issues, during the product development stage, thus minimising undesired environmental consequences in the most effective manner. FMEA clearly describes the causes and effects of failures and that it includes solving, searching for apt decisions towards applying the suitable action.

Thakore et al. (2015) indicated FMEA is a systematic approach used to analyse failure modes of different parts, their effect on the system, and the method to avoid the failure. Based on the risk priority number (RPN), FMEA prioritises the failure modes but using FMEA alone the failures cannot be eliminated, additional activities are required. FMEA should improvise regularly so that new potential modes of failure can be recognised and corresponding plans for the framework could be invented.

QFD helps in recognising and clustering customer requirements (voice of customer – VOC's), prioritise the identified end-user needs, and translates them into engineering metrics (EMs) corresponding to the respective customer requirements. It also helps in correlating the objectives and priorities of the product design requirements (Vinodh and Rathod, 2009). To meet the complex requirements of the emerging world, the research methodologies also being developed over the long period with innovative approaches such as integration of several tools, enhancing the tool by adding another dimension to the conventional tool to meet the demands of customers and manufacturers yet in an environmentally friendly manner, studies of the evolvement of QFD has been reviewed to analyse the areas of application.

The most promising use of FMEA is that it can be used at both macro and micro-level, while QFD has always been used to produce products that outfit customer needs by effective production control. For the successful practice of QFD in any organisation, it should promote innovative initiations, teamwork and provide platform information and knowledge sharing (Buchert and Kaluza, 2014). Literature review carried out by Tosun et al. (2020) shows the insights of the application of hybrid technologies for various problem-solving tools. Another study carried out by Chaudhuri et al. (2020), also shows that the multi objective programming methodologies supports the manufacturing industries as well to solve the problems with multiple parameters involved in it.

Imbibing sustainability in the early stages of product development ensures the sustainability of the products, making them ecological benign. This includes a wide variety of ideas, ranging from environment-friendly high-tech industrial advances to socially suitable and acceptable scientific paths towards sustainable development. The sustainable design intends to "eliminate negative environmental impact through skillful, sensitive design." The sustainability of the product has to be considered across its life cycle where it will range from few seconds to many years depending on the nature of the product. The product/process design should anchor people to the habitual environment in such a way that it has a minimal footprint on the environment and harvest renewable resources to become a sustainable design (Latif and Gopalakrishnan, 2017) since 33% of the energy consumption and CO_2 emission is linked to the manufacturing industries as well (Saxena et al., 2020).

The scope of this study is to introduce an innovative redesigned product that is environmentally and economically better than the existing product. If this technique is applied in the design sector, it can also be used to optimise the product/process in various sectors in different stages. The objectives of the study are:

RO1 To introduce a hybrid technique of EFMEA and ECQFD for detecting failures in earlier stages.

RO2 To incorporate QFD in an environmentally concentrated technique called ECQFD and to transfer VOC as EM for redesigning of the overflow valve.

The paper is structured in seven sections; initially, the literature on the FMEA, QFD and sustainability are reviewed. Later, a case study is conducted on a product and the environmental impact of the product as per current design is studied using the sustainability analysis simulation. Further, the novelty of the framework proposed and key gaps identified are presented. The possible failure modes of the product on the environment are determined and ranked by calculating the RPN. Based on the RPN, the VOC's identified using QFD are addressed for the higher RPN parameters. Finally, the design of the product is modified and sustainability analysis is made for comparing the environmental impact.

Table 1 Literature review for FMEA

S. no.	*Title*	*Author(s)*	*Inference*
1	Application of FMEA to an automotive leaf spring manufacturing organization	Vinodh and Santhosh (2011)	FMEA is applied to an automotive leaf spring manufacturing organisation and results indicated that the actions lead to improvement in design, key decision factors apart from conventional factors.
2	A case study: a process FMEA tool to enhance quality and efficiency of bearing manufacturing industry	Thakore et al. (2015)	The potential problem for the manufacturing process of bearing is concentrated and eliminated using FMEA. Based on the parameters, some of the suggestions are proposed for avoiding the possible risk and ultimately decrease the loss to the industries in terms of money, time and quality.
3	Improving product quality based on QFD and FMEA theory	Tan and Xiong (2020)	The study has been carried out with a specific focus on improving the product quality by integrating the FMEA and QFD yet lead to the significant improvement in design and manufacturing efficiencies as well. The study evidence that the tool can be used seamlessly for all sorts of technical requirements as well.
4	Block printing process performance evaluation and improvement using FMEA and Taguchi loss function for selecting print paste suppliers in apparel industry	Nupur et al. (2020)	The study shows the application of the integrated FMEA in the apparel industry where the feasibility of the suggested solutions for the root cause analysis has been evaluated.
5	A case study: a process FMEA tool to enhance quality and efficiency of manufacturing industry	Parsana and Patel (2014)	Here, the problems from a manufacturing process of the cylinder head in the company are identified and eliminated and reliability of subsystems is also improved and the prevention suggested in this paper can considerably decrease the loss to the industry in terms of both money time and quality.
6	PFDA-FMEA, an integrated method improving FMEA assessment in product design	Aguirre et al. (2021)	An integrated approach of FMEA, PFS and DA is carried out to cover the gap of non-addressed parts of FMEA. The study has shown the integrability of FMEA with various other tools.
7	A combined analysis method of FMEA and FTA for improving the safety analysis quality of safety-critical software	Han and Zhang (2013)	Safety-critical software is analysed for quality using a combination of FMEA and FTA. Potential errors of software are detected at the early stage and a semi-auto analysing tool was developed to carry the process and comparison experiments were carried out to testify the effectiveness of this method.
8	Automated model-based FMEA of a braking system	Struss and Fraracci (2012)	Automation of FMEA is applied to the hydraulic part of a vehicle braking system, the essential parts of models of hydraulic components suitable to generate the predictions needed are generated based on constraints rather than simulation. Based on one global integration step deviations from the nominal functionality of the device are determined.
9	Design and failure mode and effects analysis (FMEA) of a vehicular speed advisory system	Nagel (2015)	Using D-FMEA and FTA a vehicular speed advisory system is developed. This GLOSA system displays speed advice that a vehicle should drive to pass an upcoming traffic light at the green. The reliability and possible failures are analysed.

Table 1 Literature review for FMEA (continued)

S. no.	*Title*	*Author(s)*	*Inference*
10	FMEA analysis for reducing breakdowns of a sub system in the life care product manufacturing industry	Rakesh et al. (2013)	Further FMEA is used in reducing breakdowns of a subsystem in the life care product manufacturing industry where FMEA is applied to analyse automatic plastic welding machines used for the production of blood bags in a life care manufacturing company. The preventions suggested in this paper can considerably decrease the loss of production hours in the industry due to the breakdown of the machine.
11	Fuzzy FMEA application to improve purchasing process in a public hospital	Kumru and Kumru (2013)	In this study, the purchasing process of a public hospital is improved by the application of fuzzy FMEA, and also the problems arising from conventional FMEA are discovered and the stability of process assurance is provided.
12	Detecting groan sources in drum brakes of commercial vehicles by TVA-FMEA: a case study	Karabay et al. (2013)	The environmental conditions causing the groan were identified and the groan was reproduced. Vehicle tests were performed both at the factory and in traffic. To conclude the planned study, total value analysis (TVA) and failure mode and effects analysis (FMEA) methods were used effectively. A strategy to determine the root causes was planned and implemented systematically to eliminate the secondary and tertiary effects of brake groan problems.
13	An ISO 9001 based approach for the implementation of process FMEA in the Brazilian automotive industry	de Aguiar et al. (2015)	This study performs, through a case study in the incoming inspection of raw material, the comparison of a conventional application of the process FMEA with a proposal based on the concepts of process approach defined by ISO 9001. This paper shows a simple way to better structure process FMEA, facilitating meetings with multidisciplinary teams.
14	Enhancing FMEA assessment by integrating grey relational analysis and the decision making trial and evaluation laboratory approach	Chang et al. (2013)	They proposed a novel approach, integrating grey relational analysis (GRA) and the decision-making trial and evaluation laboratory (DEMATEL) method, to rank the risk of failure, wherein the GRA is used to modify RPN values to lower duplications and the ordered weighted rule is followed; then, the DEMATEL method is applied to examine the direct and indirect relationships between FMs and CFs, giving higher priority when a single CF causes FMs to occur multiple times.
15	Fuzzy assessment of FMEA for rotary switches: a case study	Vinodh et al. (2011)	In the case study reported in this paper, the fuzzy FMEA of a rotary switch was analysed, starting from its components to subsystems. Failure modes were identified and the effect of these modes was studied, then the results before and after taking actions were compared.
16	Fuzzy FMEA model for risk evaluation of ship collisions in the Malacca Strait: based on AIS data	Zaman et al. (2014)	In this paper, an investigation of sea traffic is carried out using AIS data and the geographic information system (GIS). The proposed fuzzy failure mode and effects analysis (FMEA) method for the evaluation of Ship-collision risk is described. Finally, the risk evaluation results are discussed.
17	Improving overall equipment effectiveness (OEE) through integration of maintenance failure mode and effect analysis (maintenance-FMEA) in a semiconductor manufacturer: a case study	Chong et al. (2015)	This paper presents the implementation of maintenance-FMEA to improve OEE in a semiconductor manufacturing firm. The FMEA was conducted by using five steps approach on a bottleneck process. Results from the FMEA provide a list of prioritised corrective actions which the plant manager can implement to improve equipment OEE.

Table 2 Literature review for QFD and sustainability in manufacturing

S. no.	*Title*	*Author(s)*	*Inference*
1	Integration with QFDs, TRIZ and FMEA for control valve design	Hu et al. (2014)	This paper proposes how QFDs, TRIZ integration with FMEA may arise, and making the control valve in the design concept and manufacturing development stages to amend the main issues to have front-end prevention.
2	Development of integrated ECQFD, LCA and sustainable analysis model	Vinodh and Jayakrishna (2014)	In this article, an attempt has been made to develop an integrated model encompassed with environmentally conscious quality function deployment (ECQFD), LCA and sustainability analysis module. The model has been tested with automotive assembly development and manufacturing.
3	Integrated multiphase sustainable product design with a hybrid quality function deployment – multi-attribute decision-making (QFD-MADM) framework	Ocampo et al. (2020)	The article shows that the research was carried out to use the QFD-MADM approach in all the phases of product development unlike only up to the design phase as in most of the studies.
4	Environmentally conscious quality function deployment – a new approach for green manufacturing	Francis (2009)	Environmental metrics are used in the application of ECQFD as evaluation criteria for customer requirements before any design concepts are being developed. In this paper, these environmental metrics are used to evaluate the relationship between technical characteristics and the environment.
5	Integration of ECQFD in conceptual design activities for enabling environmentally conscious design	Hassan et al. (2016)	In this study, the recently developed environmentally conscious quality function deployment (ECQFD) approach is applied for enabling the environmentally conscious design of a new product concept by integrating it in the conceptual design activities. Based on the ECQFD decision, a list of suggestions is referred to in the generation of new concepts and evaluation using a weighted decision matrix based on criteria in Phase III of ECQFD.
6	Methodology for sustainable product design: a review and direction of research	Hassan et al. (2014)	In this paper, various methodologies for producing a sustainable product design are reviewed and directions for future research are discussed. The sustainability of product design is based on three crucial requirements: social, economic and environmental.
7	Integration of ECQFD and LCA for enabling sustainable product design in an electric vehicle manufacturing organization	Rathod et al. (2011)	The EMs are used to evaluate the customer requirements (EM-CRs) and the technical requirements (EM-TRs) on their environmental impact perspective. In this case study, the integration of ECQFD and LCA has been done to an electric vehicle for enabling sustainability in the process of product development.

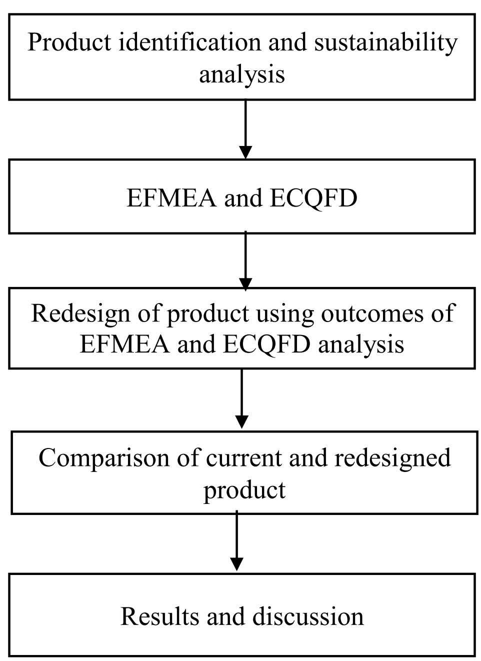
Table 2 Literature review for QFD and sustainability in manufacturing (continued)

S. no.	*Title*	*Author(s)*	*Inference*
8	Sustainability assessment for manufacturing operations	Saxena et al. (2020)	The study is focused solely on the sustainability part of the manufacturing process where unlike other studies, the author has carried out the research by integration of information from the computer aided technologies.
9	Application of ECQFD for enabling environmentally conscious design and sustainable development in an electric vehicle	Vinodh and Rathod (2013)	This study focuses on the application of the ECQFD technique to an electric vehicle. The study results indicate that it could be applied in the early product design and development stages for ensuring sustainability. To practically validate the effectiveness of applying a questionnaire-based validation was conducted with the executives of EMV.
10	Integration of ECQFD and LCA for sustainable product design	Vinodh and Rathod (2009)	This study reports research carried out for ensuring sustainable product design by the integration of environmentally conscious quality function deployment (ECQFD) and life cycle assessment (LCA) approaches. The methodology of sustainable product design is practically feasible and compatible. The findings and contributions of this research would be useful to the majority of the organisations situated in the world.
11	ECQFD & LCA based methodology for sustainable product design	Wang et al. (2010)	This paper proposed a methodology that is based on the environmentally-conscious quality function deployment (ECQFD) and product life cycle assessment (LCA) for the product designers. The case study is conducted in an electronics switches factory, and the result of the implementation shows the effectiveness and worth of the proposed method.
12	A review of engineering research in sustainable manufacturing	Haapala et al. (2013)	This study gives a review of discussions made on manufacturing and sustainability. Sustainability necessitates the need for a performance level that may be contrary to humanity's rational desire for continuous development and growth. It also defines the metrics for a potential sustainable manufacturing process. It also states some of the important manufacturing impact areas in environmental orientation.
13	Sustainable manufacturing and design: concepts, practices and needs	Rosen and Kishawy (2012)	This case reports the importance of integrating sustainability with manufacturing and design, along with other objectives such as function, competitiveness, profitability and productivity. It is concluded that more extensive research and collaboration are needed to improve understanding of sustainability in manufacturing and design and to enhance technology transfer and applications of sustainability.

2 Literature review

Literature review was made with the context of FMEA and QFD. Table 1 shows the literature survey of FMEA, certain key papers are Vinodh and Santhosh (2012), de Aguiar et al. (2015) and Chang et al. (2013) where the FMEA was applied in various fields of applications such as enhancing quality and efficiency of the process, automotive part manufacturing, healthcare and risk analysis. Table 2 shows the literature review for QFD and sustainability in manufacturing with key papers such as Vinodh and Jayakrishna (2014), Francis (2009) and Rathod et al. (2011) where integration of ECQFD with sustainable analysis model, green manufacturing, eco-friendly design process, development of electric vehicle is discussed. The literature gap indicates that no work was has been made in EFMEA and ECQFD sector and also the necessity of integrated frameworks to get better outcomes by considering the other stakeholder's requirements as well in the product design phase unlike only considering the VOC's (Ocampo et al., 2020; Tan and Xiong, 2020). Hence, this case attempts a hybrid technique by integrating FMEA and QFD for significant improvement in product quality, design and manufacturing process. Focusing on the environmental considerations for sustainability using LCA makes this framework, a novel along with the integrated approach of FMEA and QFD.

Figure 1 Methodology adopted



3 Proposed methodology

Figure 1 shows the methodology adopted in this study. This study proposes an improved industrial overflow valve both environmentally and economically. CAD model has been developed for the existing component and the sustainability analysis has been conducted. Using EFMEA, the components which contribute more towards negative environmental impacts were found using the RPN calculated and ECQFD analysis has been made where the VOC is converted as EM and the top prioritised components are determined. Using the results of the ECQFD chart the components were redesigned and sustainability analysis was also conducted for the redesigned component and the results are compared with the existing component report.

Figure 2 EFMEA process flow

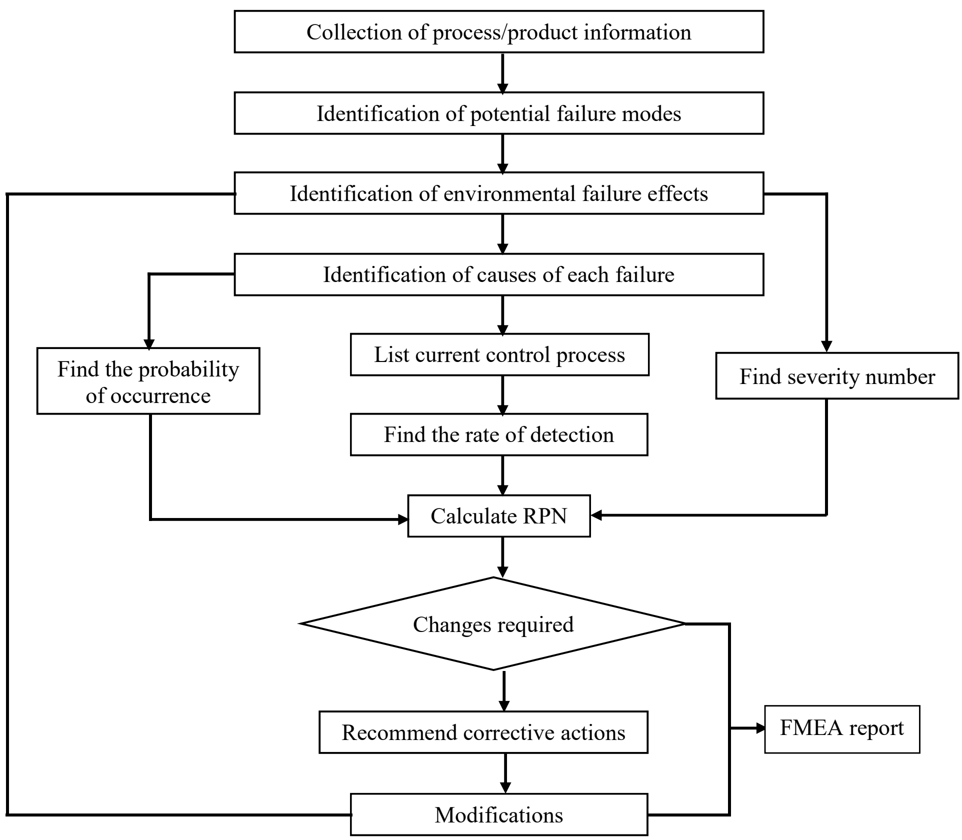


Figure 2 depicts the flowchart of executing the FMEA process. Initially, the process/product information is collected and tabulated. All the possible failure modes in the process/product and the effects of the corresponding failure were determined and a severity (S) rating was assigned to it. The reasons for each of the identified failure modes to occur are determined and the rating (O) has been given based on the probability of occurrence. The control point being followed currently for identifying the failure mode is listed down and the detectability (D) rate is also assigned. Finally, RPN will be calculated with the S, O and D values. A cross-functional team was formed consisting of members from manufacturing, design, and environmental safety departments with experience of 8 to 12 years in their respective fields. The values of S, O, and D are assigned based on the discussion with the cross-functional team members by conducting brainstorming sessions. With the resultant RPN value, the process is decided whether any change in the process requires or not. If any corrections are required, they are mentioned and the FMEA report can be generated, if no corrections are required then the process is repeated for different failure effects.

3.1 Occurrence (O)

The number of times that the identified reason for the failure occurring is rated as occurrence. Probable causes for the failures are pointed out and documented in technical terms.

3.2 Severity(S)

Upon determining all the conceivable failure modes and the impact of those failures on the product/process, the rating will be given based on its rigorousness on the result of the product/process (Chang et al., 2013).

3.3 Detection (D)

The probability of the number of times that the failure mode being spotted in the product/process before it reaches the end-user is taken as the detection value.

3.4 Risk priority number

RPN for the failure mode will be arrived at by multiplying the rated S, O and D of the failure mode. The failure modes are sorted in the decreasing order of RPN and an action plan for eliminating/reducing the RPN value with higher RPN failure modes is carried out.

3.5 Rating table

The rating scale utilised for determining the S, O and D of the failure modes are depicted in Table 3.

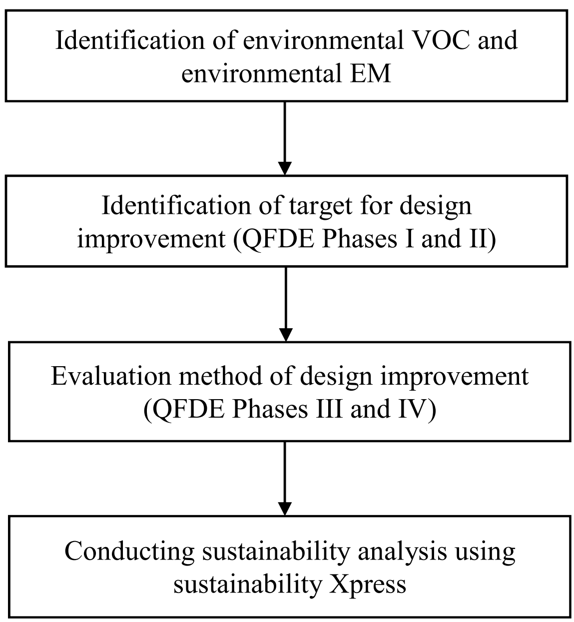
As this study is environmentally concentrated, the VOC collected is not only based on raw material and energy consumption but also the factors contributing to environmental degradation and market cost. EMs have been deployed based on the VOC obtained. The EMs are identified and assigned to the VOC based on the discussions with industrialists and quality control division managers who are experienced with the operations.

Figure 3 shows the ECQFD process flow. The areas which require design improvements are identified in Phase I and Phase II. The RPN value from Table 4 is used as customer weight in ECQFD Phase I by which the EFMEA and ECQFD techniques are integrated which makes it a hybrid and new technique for product/process quality improvement environmentally.

Table 3 Rating scale for EFMEA chart

Rate	*S*	*O*	*D*
1	No	Almost never	Almost certain
2	Very slight	Remote	Very high
3	Slight	Very slight	High
4	Minor	Slight	Moderate high
5	Moderate	Low	Medium
6	Significant	Medium	Low
7	Major	Moderately high	Slight
8	Extreme	High	Very slight
9	Serious	Very high	Remote
10	Hazardous	Almost certain	Almost impossible

Figure 3 ECQFD process flow



In Phase III and Phase IV, the target areas identified in Phase II are evaluated for design improvement based on the relative weights obtained from Phase I and Phase II. In Phase IV, the improvement rate of customer requirement and its effect are determined. After implementing the identified design changes, sustainability analysis has been conducted for the redesigned product.

Table 4 List of environmental failure effects and its causes

No.	Component or process	Function	Failure modes	Failure effects	C	Failure causes	Failure prevention		Failure detection	S	O	D	RPN
1	Honing bore in mounting nut	Stock removal Ensure bore diameter 6.000 + .008 Form parameter 1 Circularity 2 Straightness 3 Cylindricity 4 Parallelism 5 Roughness (Rz < 2)	Bore rough inconsistency to RZ	Noise pollution, chips and waste coolant with toxicity	C	Honing sticks 1 Quick wear or short tool life 2 Uneven wear 3 Broken edges	Optimum grit size and bond strength 1 Ensure proper stone preparation specification 2 Prevent overloading	1	Check tool after machining 500 pieces for tool wear (limit sample of the tool should be provided)	7	5	3	105
								2	Check after 500 pieces for even wear in tool	7	3	3	63
								3	Check once in 2,500 parts for broken edges in the tool (limit samples to be provided)	7	3	3	63
						Particle suspended freely	1 Optimised particle size 2 Optimised bonding strength	1	Check after 100 pieces of the finished bore for dig marks (limit sample of components to be provided)	7	3	5	105
						Loading of abrasive – sticks	1 Assure rake angle of each particle 2 Exposing of the abrasive particle after considerable cycles	2	Check-in 500 pieces for chip loading (limit samples of tool to be provided)	7	3	4	84
						Abrasive chip off	1 Bonding strength even throughout the abrasive layer 2 Even distribution of abrasive particles	3	Check once in 1,500 pieces for abrasive chip off in tool (limit samples for tool to be provided)	7	3	3	63
2	Supporting stones	Support cutting stones during cutting	Chip-off of supporting stones	Air pollution due to vaporisation of cutting tool material and also contributes for global warming	C	Solder strength is not enough	Ensure sufficient soldering	1	Check after 500 pieces in a tool (limit samples to be provided)	7	3	3	63
						Edge of supporting stones	Chamfering of edges in supporting stones	2	Check after machining 500 pieces in a tool (limit samples to be provided)	7	3	3	63

Notes: S = significance of failure effect (severity), O = failure occurrence probability and D = failure detection probability.
Risk priority number (RPN) = S × O × D.

Table 4 List of environmental failure effects and its causes (continued)

No.	*Component or process*	*Function*	*Failure modes*	*Failure effects*	*C*	*Failure causes*	*Failure prevention*	*Failure detection*	*S*	*O*	*D*	*RPN*
3	Lubricant oil	(Support) lubricate stone during cutting action	High temperature	Susceptibility to microbial growth and formation of biofilms; formation of oil mist leading to air pollution.	C	Thermal expansion of tool and workpiece	Ensure optimum lubricant oil temperature	Check the temp of the thermostat for once in 1 hour	2	3	3	18
4	Moulding	Premix bond	Wrong blend, no-material, wrong soil	Emissions of magnesium oxides and metallic fumes, particulates, metal oxide fumes, carbon monoxide, organic compounds		Bad blending	Reviews sample of material before receiving	Check the blending composition every time before pouring molten metal	5	4	4	80
5	Mulling	Sand temperature	Hot sand	Toxic lead, barium-cadmium, tin and calcium-zinc are exposed to atmosphere		Low sand to metal ratio	Production scheduling monitored to equal tonnage poured	Check the sand temperature for every 1 hour	4	2	3	24
6	Pouring	Inoculation	Scales-off tare weight off not placed in stream	Emission of CO, CO_2, NH_3 to atmosphere due to decomposition of resins		Calibration got-off improperly trained personnel	Scheduled calibration, lead man oversees operation during production	Use more effective pouring equipment	8	5	3	120
7	Solidification	The temperature of molten metal reduces and component gets solidified	Improper solidification of the casting	Defective casting		Improper chemical composition	Proper weighing of materials added in the furnace during melting	Measure input material composition	6	3	4	72
			Waste gas emission	Environmental pollution	C	Use of toxic Chemical additives in die preparation	Using of non-reactive materials for die preparation	Implement legislation on air pollution	8	10	9	720
			Si dust emission	Corrosion of surrounding machines and equipment		Emission of SO_2 into the atmosphere	Using the furnace in an effective method to minimise the usage time	Take control measures of filtering the air emitted before releasing it into the atmosphere				
			Odour and oil formation	Air pollution, smog formation, the mix of toxic substances to the environment, deposits of fine dust particles in surrounding objects	C	Due to melting operation in an electric arc furnace, induction furnace	Using dust arresters		7	8	6	336
8	Melting	To melt the raw materials	Non-uniform fuel flow rate to the furnace	Emission of products of combustion, oil vapours, particulates, metal oxide fumes	C	Non-working temperature sensors, flow gauges	Use of better working temperature sensors	Periodically maintain the flow valves, sensors, gauges and calibrate them	6	7	5	210

Notes: S = significance of failure effect (severity), O = failure occurrence probability and D = failure detection probability.
Risk priority number (RPN) = S × O × D.

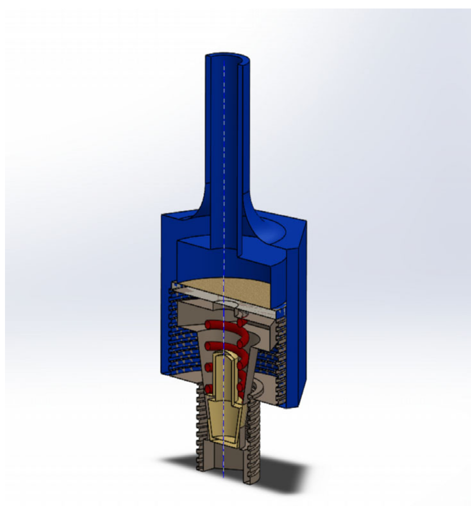
4 Case study

The study was aimed to develop an innovative design of the product with low environmental impact and at low cost. A hybrid combination of EFMEA and ECQFD is attempted to get more optimal failure causes.

4.1 Case product details

For this case study, industrial overflow valve (Figure 4) was considered as the case product. The overflow valves help to avoid damages to the pumps and other plant systems due to high pressure, by maintaining and controlling the pressure of liquids or gases. In this case product, spring and locating cap mechanism is used where the diaphragm will be torn by the locating cap when the pressure surpasses the limit.

Figure 4 Industrial overflow valve (see online version for colours)



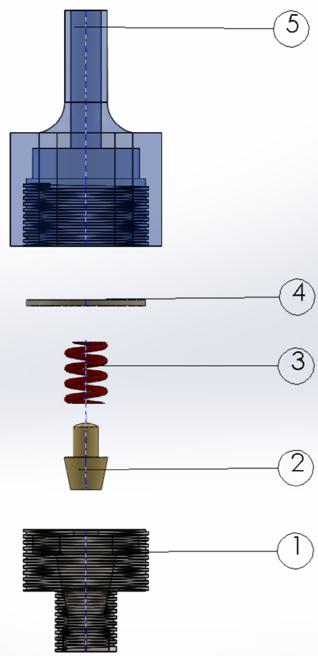
The parts of current overflow valves in the industries use diaphragms and are made of grey cast iron. The casting process is costly as well as generates high environmental impacts. Higher replacement costs in case of valve failure are also a major concern for the need of redesigning the valve.

4.2 Initial sustainability analysis

Environmental sustainability can be defined as upholding the amount of renewable resource usage, contamination creation, and reduced consumption of non-renewable resources (Brown et al., 2009). The impact of the product/process on the environment and the developments made to it by humans are analysed concerning the material, recyclability, and contamination absorbing tendency of nature (Zhang et al., 2010).

Sustainability Xpress module in the Solidwork's software helps the product designers to analyse the effect of their product design (CAD model) and manufacturing process on the environment and the ways where the cost and material are being reduced. A sustainability analysis has been made for the existing component, with India as a manufacturing region since the case organisation is situated in India. The manufacturing region also plays a vital role in the analysis process for determining the product lifecycle (Miguel, 2013).

Figure 5 Exploded view of industrial overflow valve (see online version for colours)



ITEM NO.	PART NAME	QTY.
1	Mounting nut	1
2	Locating cap	1
3	Spring	1
4	Diaphragm	1
5	Body	1

Sustainability evaluation has been carried out considering the below-mentioned factors:

- *Carbon footprint:* The amount of carbon being released into the environment due to the process carried out is considered a carbon footprint. The combustion of fossil fuel is the major reason for the rise of CO_2 level in the atmosphere which most of the studies show. Due to the increased greenhouse gases in the atmosphere, global warming also increases.
- *Total energy consumed:* The amount of energy utilised during the process/product by the organisation/individual/community is accounted as total energy consumed. The efficient use of energy makes the organisation more sustainable. 32% of the energy is utilised by the manufacturing sectors in the USA as per the National Association of Manufacturers (Gillingham et al., 2009). In this study, the energy used in the mainstream, as well as the downstream process, are considered.
- *Air acidification:* Acidification of air by the increased emission of SO_2 into the atmosphere causes acid rain which in turn acidifies the lakes and soil and causes toxic inhalation to the human being. Due to such a vital role of the SO_2 content, this parameter is also considered as a part of the analysis.

- *Water eutrophication:* Eutrophication occurs when there is an increased level of nutrients in the water content. The oxygen level in the water reduces when water eutrophication occurs, leading to disturbance in the aquatic ecosystem and the food chain (Rosen and Kishawy, 2012).

Figure 6 depicts the outcomes of the analysis. It is observed from the results that the high environmental impact is from the body and the mounting nut part, 0.425 kg CO_2e of 0.78 kg CO_2e and 4.3 MJ of 8 MJ of energy is from body part due to which it is considered as a highly ranked component for modifying the design/process parameters followed by the mounting nut with 0.318 kg CO_2e of 0.78 kg CO_2e, 3.2 MJ of 8 MJ of energy.

Figure 6 Sustainability analysis of existing component (component wise) (see online version for colours)

Component	*Carbon*	*Water*	*Air*	*Energy*
Body	0.425	2.7E–4	2.6E–3	4.3
Mounting nut	0.318	2.0E–4	1.9E–3	3.2
Locating cap	0.012	7.7E–6	7.5E–5	0.124
Spring	7.6E–3	4.8E–6	4.6E–5	0.077
Diaphragm	2.0E–4	2.3E–7	8.2E–7	3.5E-3

4.3 EFMEA

Failure mode effect analysis identifies the possible ways in which a design or process could fail, together with their causes and effects. FMEA is a successful tool being used across different levels of requirements right from customer complaints analysis up to the military's problems (Tan and Xiong, 2020). This method is accompanied by a weighting process to factors such as severity (S), occurrence (O), detectability (D), necessary processes and units to perform corrective actions (Flores and Malin, 2013). Since the failures are focused on the environment, it is termed as environmental failure mode effect analysis. EFMEA identifies and assesses the significant potential environmental impact of a product during the early stages of product development by which failures can be prevented by using different materials or processes, due to which loss of money, time, material, space can be avoided, etc.

FMEA method's application can be segregated into three stages:

- Qualitative analysis, where all potential failure modes, causes, and its belongings are recognised (Struss and Fraracci, 2012).
- Quantitative analysis, given the assessment of the RPN list (Thakore et al., 2015).
- Corrective analysis, by actualising the improvement procedures distinguished with a specific end goal to lessen the hazard level.

The EFMEA chart has been made for the product and the chart is shown in Table 4. From the EFMEA chart, the factors contributing to environmental impacts are prioritised and the topmost factors that occur during product manufacturing are solidification, melting and boring operations.

Sample calculation

The sample calculation is shown for the failure mode of waste gas emission where gases such as SO_2 are emitted which causes environmental pollution.

- severity(S): 8
- occurrence (O): 10
- detection (D): 9

$$\text{RPN} = \text{S} \times \text{O} \times \text{D}$$

$$\text{RPN} = 8 \times 10 \times 9 = 720.$$

4.4 ECQFD

QFD technique is used to improve the product/process design at early stages by transforming the user requirement to corresponding engineering parameters (Wang et al., 2015). Yoji Akao, the father of QFD, has done vast research in QFD. QFD is one of the most welcomed tools for the professionals where the area to be focused on for having the customers satisfied is known easily and without any vague assumptions, the product can be developed (Tan and Xiong, 2020). In this case study, the ECQFD approach has been proposed to integrate the conceptual design activities to improve the product in terms of environmental aspects which help in the reduction of various environmental issues causing loss to us. New frameworks are developed for organisations to have VOC as environmentally conscious and integration of ECQFD with sustainable analysis has shown the way for the development of products with the consideration of environmental aspects (Vinodh and Jayakrishna, 2014). The product features can be made sustainable during the design phase itself by employing the ECQFD technique (Rathod et al., 2011).

4.4.1 Identifying the target for design improvement

ECQFD undergoes four phases and determines the area which requires development.

4.4.1.1 ECQFD Phase I

Table 5 shows the assignment of VOC against the EM for the design of the overflow valve as Phase I of the ECQFD application. Based on the market poll, 12 criteria of VOC's have been identified and all of those are related with seven items of EM. Each criterion from the VOC is weighed based on the market survey. The important relation of VOC and EM has been indicated and determined by the designer using a scale, '9' indicates strong, '3' indicates moderate, and '1' indicates low.

Table 5 ECQFD Phase I of overflow valve

Voice of customer	*Customer weight*	*Engineering metrics*						
		Machining parameters	*Temperature control*	*Raw material selection*	*Employee training*	*Emission control*	*Inspection*	*Tool selection*
Quick wear of honing sticks	1.05	6						
Broken edges of honing sticks	0.63	4					3	
Free suspension of particles	1.05					4		
Abrasive chip-off	0.63	4					5	2
Weak solder strength	0.63				3		6	
Thermal expansion of workpiece	0.18	5	7				3	3
Low sand to metal ratio	0.24				7			
Untrained personnel	1.2				5	3		
SO_2 emission	7.2			7		6		
Si dust formation	3.36			6		4		
Odour	3.36			7				
Toxic additives in sand	0.72			5		7		
Raw score		*12.24*	*35*	*97.68*	*15.13*	*65.28*	*9.36*	*1.8*
Relative weight		*0.0517*	*0.1479*	*0.4130*	*0.0639*	*0.2760*	*0.0395*	*0.0076*

4.4.1.2 ECQFD Phase II

The seven EM's considered for this study are associated with the case product components in Phase II of ECQFD and the weights attained in Phase I are used for each EM. Similar to Phase I, the connection between EM and parts of the case product is made. Table 6 shows the components of the valve. Based on the calculations, 'body', 'mounting nut', and 'locating cap' are identified as the highest weighted value components.

Table 6 ECQFD Phase II of overflow valve

Engineering metrics	*Phase I relative weight*	*Component characteristics*				
		Body	*Mounting nut*	*Spring*	*Diaphragm*	*Locating cap*
Machining parameters	0.0517	4	5			3
Temperature control	0.1479					
Raw material selection	0.4130	6	5		7	4
Employee training	0.0639					
Emission control	0.2760	5	5		6	
Inspection	0.0395			3	8	
Tool selection	0.0076			2		
Raw score		*4.0654*	*3.7041*	*0.1339*	*4.8641*	*1.8074*
Relative weight		*0.2789*	*0.2541*	*0.0091*	*0.3337*	*0.1240*

4.4.1.3 ECQFD Phase III

In this phase, the effect of design improvement of overflow valve components on EM is discussed as shown in Table 7 and Table 8. In Phase III, two options have been discussed, the first option relates to the requirement of the customer based on VOC. And the second option is by evaluating the most important components identified in Phase II. In this study, environmental aspects are playing an important role in the design improvement of components. Table 7 discusses the design improvement of the body, mounting nut, and locating cap and Table 8 discusses the design improvement of spring and diaphragm based on the relative weights obtained from Phase I. The two proposed options are:

Option I Raw material selection and emission control parameters are creating more impact on the environment. The components body, mounting nut, and locating cap require modifications.

Option II The emission control and inspection process affect the overall impact of the product on the environment. In this section, spring and diaphragm require changes.

Table 7 ECQFD Phase III Option I of overflow valve

Engineering metrics	*Phase I relative weight*	*Component characteristics*					*Score*	*From Phase III*	*From Phase II*	*Improvement rate of engineering metrics*
		Body	*Mounting nut*	*Spring*	*Diaphragm*	*Locating cap*				
Machining parameters	0.0517						0	0	0	0
Temperature control	0.1479						0	0	0	0
Raw material selection	0.4130	6	5			4	15	6.1956	9.0868	0.6818
Employee training	0.0639						0	0	0	0
Emission control	0.2760	5	5				10	2.7603	4.4165	0.6250
Inspection	0.0395						0	0	0	0
Tool selection	0.0076						0	0	0	0

Table 8 ECQFD Phase III Option II of overflow valve

Engineering metrics	*Phase I relative weight*	*Component characteristics*					*Score*	*From Phase III*	*From Phase II*	*Improvement rate of engineering metrics*
		Body	*Mounting nut*	*Spring*	*Diaphragm*	*Locating cap*				
Machining parameters	0.0517						0	0	0	0
Temperature control	0.1479						0	0	0	0
Raw material selection	0.4130				7		7	2.8912	9.0868	0.3181
Employee training	0.0639						0	0	0	0
Emission control	0.2760				6		6	1.6562	4.4165	0.375
Inspection	0.0395			3	8		11	0.4353	0.4353	1
Tool selection	0.0076						0	0	0	0

Table 9 ECQFD Phase IV Option I of overflow valve

Voice of customer	*Customer weight*	*Engineering metrics*							*Improvement rate of customer requirement*	*Improvement effect of customer requirement*
		Machining parameters	*Temperature control*	*Raw material selection*	*Employee training*	*Emission control*	*Inspection*	*Tool selection*		
Quick wear of honing sticks	1.05	6							0	0
Broken edges of honing sticks	0.63	4					3		0	0
Free suspension of particles	1.05					4			0.5952	0.6250
Abrasive chip-off	0.63	4					5	2	0	0
Weak solder strength	0.63				3		6		0	0
Thermal expansion of workpiece	0.18	5	7				3	3	0	0
Low sand to metal ratio	0.24				7				0	0
Untrained personnel	1.2				5	3			0.1953	0.2343
SO_2 emission	7.2			7		6			0.0910	0.6555
Si dust formation	3.36			6		4			0.1961	0.6590
Odour	3.36			7					0.2029	0.6818
Toxic additives in sand	0.72			5		7			0.9009	0.6486
Improvement rate of engineering metrics	0	0	0	0.6818	0	0.6250	0	0		3.5045

Table 10 ECQFD Phase IV Option II of overflow valve

Voice of customer	*Customer weight*	*Engineering metrics*							*Improvement rate of customer requirement*	*Improvement effect of customer requirement*
		Machining parameters	*Temperature control*	*Raw material selection*	*Employee training*	*Emission control*	*Inspection*	*Tool selection*		
Quick wear of honing sticks	1.05	6							0	0
Broken edges of honing sticks	0.63	4					3		0	0
Free suspension of particles	1.05					4			0.3571	0.3750
Abrasive chip-off	0.63	4					5	2	0	0
Weak solder strength	0.63				3		6		0	0
Thermal expansion of workpiece	0.18	5	7				3	3	0	0
Low sand to metal ratio	0.24				7				0	0
Untrained personnel	1.2				5	3			0.1171	0.1406
SO_2 emission	7.2			7		6			0.0478	0.3444
Si dust formation	3.36			6		4			0.1014	0.3409
Odour	3.36			7					0.0946	0.3181
Toxic additives in sand	0.72			5		7			0.4879	0.3513
Improvement rate of engineering metrics	0	0	0	0.3181	0	0.375	0	0		1.8704

4.4.1.4 ECQFD Phase IV

Phase IV for overflow valve is shown in Table 9 and Table 10 is to convert the effect of design improvement on EM into environmental considerations. Based on the calculation, it is found that the quantum of change impact of client necessity, the Option I of Phase IV is higher than Option II, where Option II is 3.504. Meanwhile, Option II is 1.87. The requirement from Option II cannot be accepted because it has less environmentally friendly features.

Sample calculation

Phase I

The sample calculation was made for VOC of an abrasive chip off which has an EM of machining parameters.

$$\text{Raw score} = (1.05\times 6)+(0.63\times 4)+(0.63\times 4)+(0.18\times 5) = 12.24$$

$$\text{Relative weight} = \frac{\text{Raw score}}{\sum \text{Raw score}} = \frac{12.24}{236.49} = 0.0517$$

Phase II

$$\text{Raw score} = (0.0517\times 4)+(0.413\times 6)+(0.276\times 5) = 4.0654$$

$$\text{Relative weight} = \frac{\text{Raw score}}{\sum \text{Raw score}} = \frac{4.0654}{14.5751} = 0.2789$$

Phase III Option I

Improvement rate calculations.

For raw material selection:

- from Phase III:

$$(0.4130\times 6)+(0.4130\times 5)+(0.4130\times 4) = 6.1956$$

- from Phase II:

$$(0.4130\times 6)+(0.4130\times 5)+(0.4130\times 7)+(0.4130\times 4) = 9.0868$$

$$\text{Improvement rate} = \frac{6.1956}{9.0868} = 0.6818$$

Phase III Option II

For emission control:

- from Phase III:

$$(0.2760\times 6) = 1.6562$$

- from Phase II:

$$(0.2760 \times 5) + (0.2760 \times 5) + (0.2760 \times 6) = 4.4165$$

$$\text{Improvement rate} = \frac{1.6562}{4.4165} = 0.375$$

Phase IV Option I

For SO_2 emission:

$$[\text{Relational strength} \times \text{Improvement rate}] = (0.6818 \times 7) + (0.625 \times 6) = 8.5227$$

$$[\text{Sum of relational strength} \times \text{Customer weight}] = (7 + 6) \times 7.2 = 93.6$$

$$\text{Improvement rate of customer requirement} = \frac{8.5227}{93.6} = 0.0910$$

Phase IV Option II

For toxic additives in the sand:

$$[\text{Relational strength} \times \text{Improvement rate}] = (0.3181 \times 5) + (0.375 \times 7) = 4.2159$$

$$[\text{Sum of relational strength} \times \text{Customer weight}] = (5 + 7) \times 0.72 = 8.64$$

$$\text{Improvement rate of customer requirement} = \frac{4.2159}{8.64} = 0.4879.$$

4.4.2 Outcomes

From the results of EFMEA and ECQFD, it is determined that the waste gas emission, Si dust emission, and melting processes that occurred in the manufacturing body, mounting nut, and locating cap of the valve contribute more towards the environmental pollution. From Table 8 of ECQFD, it is found that modifying/redesigning the body, mounting the nut, and locating the cap will reduce the environmental impacts (Vinayak and Kodali, 2013).

4.4.3 Development of redesigned overflow valve

Based on the outcomes of the EFMEA and ECQFD, the existing valve has been redesigned. The body, mounting nut, and locating cap of the valve were decided to be manufactured using ABS plastics instead of mild steel. Also, the diaphragm is found to fail often and it has to be replaced in case of failure, so it is replaced with a washer, knob, spring set whereas in case of failure only spring has to be replaced. These modifications reduce the cost incurred in the manufacturing process along with the material reduction and also the environmental impact caused. The redesigned valve is shown in Figure 7.

Figure 7 Cross-sectional view of redesigned overflow valve (see online version for colours)

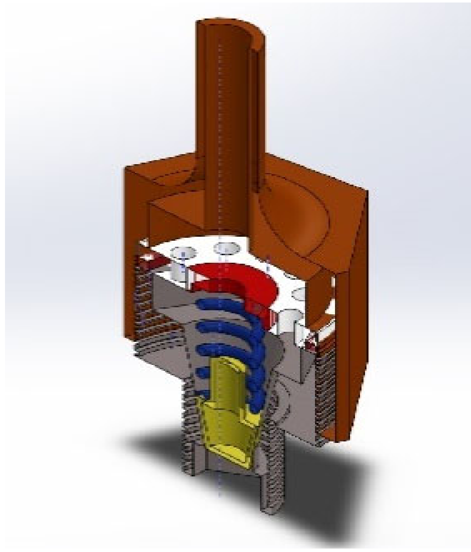
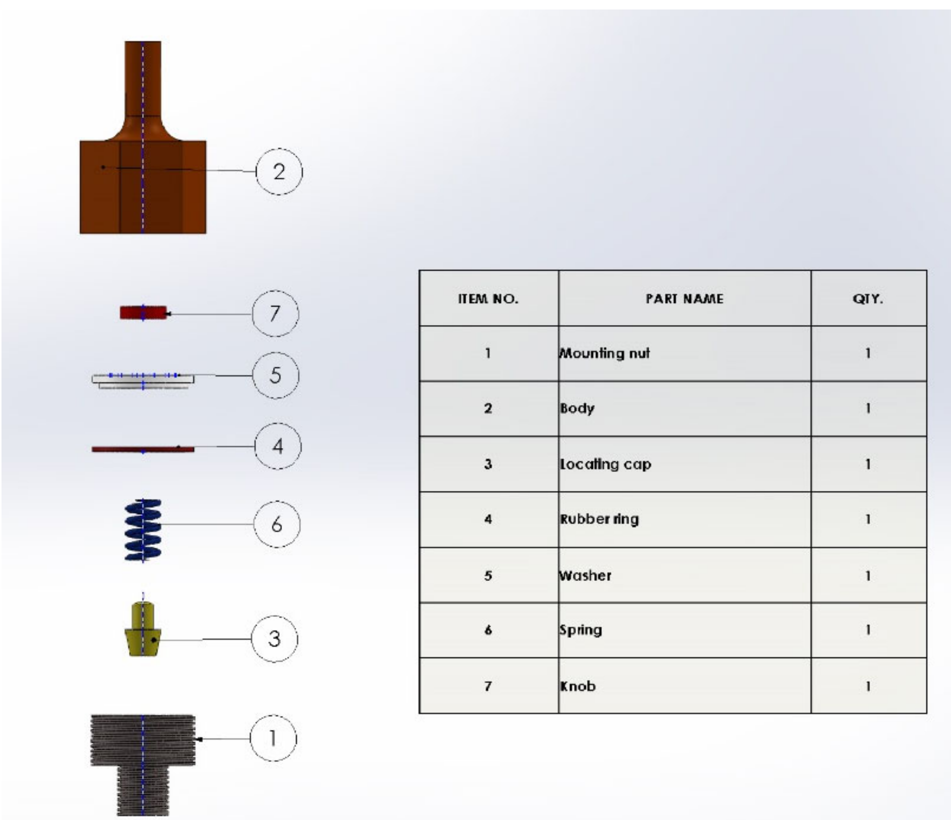


Figure 8 Exploded view of redesigned overflow valve (see online version for colours)

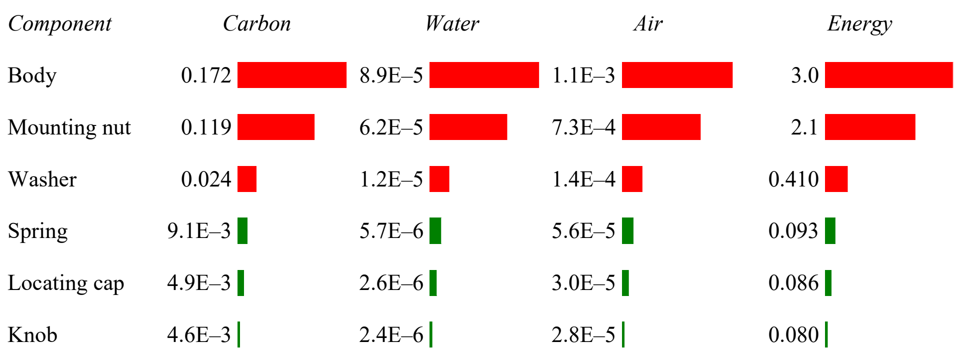


ITEM NO.	PART NAME	QTY.
1	Mounting nut	1
2	Body	1
3	Locating cap	1
4	Rubber ring	1
5	Washer	1
6	Spring	1
7	Knob	1

4.4.4 *Sustainability analysis of redesigned component*

From the sustainability analysis report of the redesigned component, the environmental impact caused by the valve is reduced and the results are shown in Figure 9.

Figure 9 Sustainability analysis of redesigned component (component wise) (see online version for colours)



The environmental impact is mainly related to the content of carbon, water toxicity, energy usage and air contaminations. In this case study, the carbon content and energy usage are considered on processes such as the combustion of fossil fuel. On comparing the sustainability analysis report of the redesigned component with that of the existing component the rate of carbon dropped down to 0.341 kg, energy to 5.8 MJ, air acidification to 2.1E–3 kg and water eutrophication to 1.9E–4 kg.

5 Results and discussion

The systematic methodology of integrating the EFMEA, ECQFD, and sustainability analysis for building up a product in an eco-friendly manner. Taking the environmental, economic, and social aspects into the account during product design phase makes it successful and sustainable. Based on the results of the sustainability analysis report of parameters such as carbon footprint, total energy consumed, air acidification, and water eutrophication the product is redesigned.

5.1 *Results of EFMEA*

From Table 4, compared to the other failure modes, it is found that the waste gas emission, odour, and oil formation were found to possess high RPN values which are considered as the potential failure modes and taken as VOC of ECQFD for further analysis.

5.2 *Results of ECQFD*

From Table 7, it is found that the body, mounting nut, and locating cap have more contribution on creating environmental impact. So, these parts were redesigned and a new overflow valve has been made.

5.3 Results of sustainability analysis

Figure 9 shows the sustainability analysis report of existing components where carbon footprint, total energy consumed, air acidification, and water eutrophication are measured for individual components of the valve. In Figure 10, the results of sustainability analysis for the existing component are shown. Similarly, the redesigned product sustainability analysis has been conducted and the result is shown in Figure 11.

Figure 10 Sustainability analysis of existing component (environmental impact) (see online version for colours)

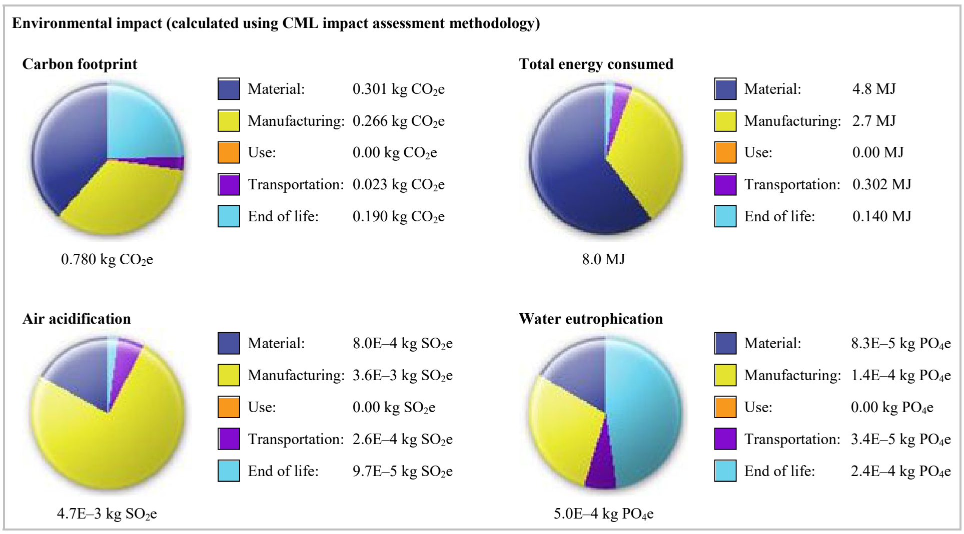
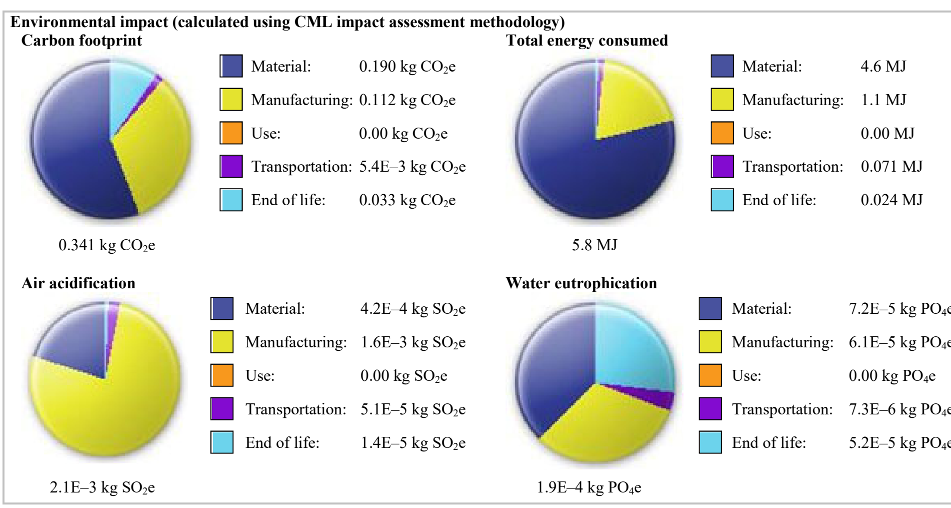


Figure 11 Sustainability analysis of redesigned component (environmental impact) (see online version for colours)



6 Theoretical and managerial implications

6.1 Theoretical implications

This framework has given contribution to the existing knowledge in the area of life cycle assessment of the product and integration of the environmental factors to the novel tools such as FMEA and QFD in particular. Another major outcome of the study is showing the seamless integration of EFMEA and ECQFD where only limited studies have been carried out by carrying out a case study in different fields. This study also paves way for linking the LCA and improving the sustainability of the product in the design phase itself with the use of EFMEA and ECQFD. In the case study of the research, various field expert's data is collected as inputs for the EFMEA and VOCs for the ECQFD as well, and using the sustainability Xpress software, the LCA of the product is simulated to arrive at the results. This work shows the researchers the sense of integration of different analytical tools to different requirements of the industries to meet the ever-growing demands.

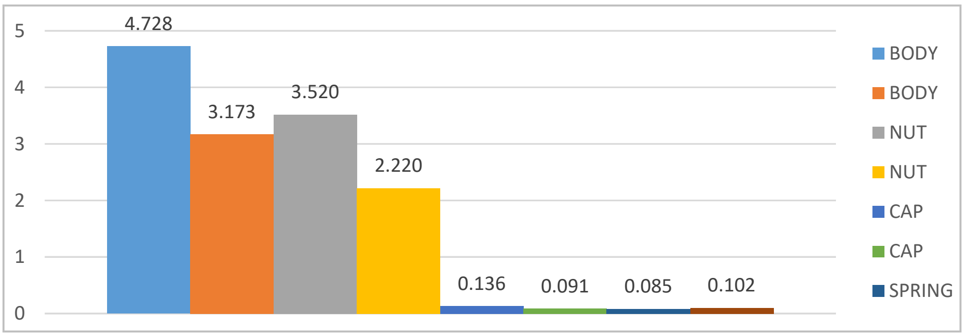
6.2 Managerial implications

This research gives insights to the managers/developers on how the quality tools can be used to improve the sustainability of the product in the design phase and analyse it as well with various iterations by considering the factors responsible to the sustainability in a systematically prioritised manner using the simulation rather than the real-time development. Usage of such methodologies by the industries will help to reduce the new product development time, cost savings and leads to increase the scope of opportunities by carrying out multiple iterations.

7 Conclusions

This study was aimed at developing an innovative sustainable product based on the results of the analysis made by EFMEA and ECQFD where the environmental impact is considered as an additional parameter. FMEA technique documents the failure modes and their causes and prioritises the most effective failure mode by calculating RPN values. The use of EFMEA has given the methodology of prioritising the environmental failure modes in the process. QFD converts VOC to EM and thereby improves the quality of the product by meeting the exact necessities of the customers, the effectiveness of the QFD usage is proven over a long time for developing a household product with energy-efficient, low cost with meeting most of the expectations of the customers (Yulianto et al., 2020). By considering environmental factors, QFD is made as ECQFD and the product can be evaluated at every stage of development. Conducting sustainability analysis provides the general impact of the product/process towards the environment by analysing the parameters such as carbon footprint, with these results the area which causes severe impact can be identified and improvement actions can be taken. Initially, sustainability analysis has been conducted for the existing product, using EFMEA the top components contributing to environmental impacts were determined and from the ECQFD the components which require modifications have been identified and the product has been redesigned. The existing and redesigned components are compared with the sustainability analysis report, from Figure 12. The environmental impacts caused by the redesigned component are less than that of the existing component. It has been verified through application to an example product. From the case application, it was proved that the proposed methodology supports effectively the wide range of product planning and conceptual design stages in the upper stream of eco-design. The environmental impact of carbon footprint, total energy consumed, air acidification and water eutrophication were found to be reduced.

Figure 12 Comparison of old and new design overall environmental effects (see online version for colours)



From the literature survey, it is evident that the FMEA and QFD techniques have a wide area of application, and considering the environmental factors in these methods will help to find out a solution for many ecological problems. This new hybrid technique of EFMEA and ECQFD with sustainability analysis paves way for prioritising the failure causes and determining the design improvements of process/product where the failures can be avoided at the early stages of product/process development. This hybrid technology will make the study more effective and the study can be taken further to the next level by applying this approach in different areas of problem in varied sectors in different countries.

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List of abbreviations

FMEA	Failure mode effective analysis
EFMEA	Environmental failure mode effective analysis
QFD	Quality function deployment
ECQFD	environmentally conscious quality function deployment
RPN	Risk priority number
VOC	Voice of customer
EM	Engineering metrics