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An Eco-Innovative Green Design Method by QFD and TRIZ Tools- A Case Study of Brass-Ware Manufacturing

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ABSTRACT

Eco-design is an advanced method for product and process to achieve sustainability. For sustainability, manufacturing companies should contemplate and encourage eco-design products and processes. Brass-ware manufacturing involved excessive energy consumption and material wastage, which makes the process unsustainable. The purpose of this study is to develop a systematic-innovation methodology for the eco-design process in brass-ware manufacturing by considering the eco-efficiency parameters based on Quality Function Deployment (QFD) approach and Theory of Inventive Problem Solving (TRIZ) tools. QFD is used for translating customers' requirements into manufacturing standards. TRIZ laws are used to solve the eco-contradiction matrix, which finds solutions to make the process eco-efficient and sustainable. On solving the eco-contradiction matrix generic solution is obtained such as '31 Porous Materials', '15 Dynamics', '10 Preliminary Action', and '40 Composite Material'. The application of the proposed method has been demonstrated by a case study of the brass-ware manufacturing process in India. This method may be useful and used as a potent tool for design engineers to invent new, robust, and eco-friendly products and processes.

Keywords: Eco-design, eco-innovation, quality function deployment, theory of inventive problem solving

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INTRODUCTION

In today's world, environmental problems, namely global warming (Houghton et al., 2001), pollution, and the waste disposal problem (OECD, 2001) have become a serious issue. Post the industrial revolution and rapid strides in technology; manufacturers have not focused on the environment, thereby present systems become environmentally unsustainable. In fact, environmental issues have become critical for manufacturers. To make an environmentally friendly product and processes is becoming a major issue for the manufacturing companies. In the present scenario, it is required that every organisation/industry should be reducing environmental impacts caused by their products or process and also should be competitive to market; this activity is called eco-design. Hence, it has increased awareness among manufacturers for making environmental friendly process and products which would meet both customers demand and environmental requirements.

Systematic innovation for eco-design is an important step in the manufacturing organisation. To produce an eco-friendly product and process, the manufacturer should consider systematic innovation concept and environmental aspect in the early phase of design. Over the years the Indian brass-ware products have gained prominence throughout the world. A large number of individuals are employed in this sector. However, the methods and process involved in brass-ware manufacturing have not improved over the years. It is essential to develop a practical systematic-innovation method for eco-process design. In this context, the objective of this paper is to analyse and improve the process of brass-ware manufacturing, which should be eco-friendly and cost-effective. This study develops a systematic-innovation methodology for the green process by considering the eco-efficiency parameters based on QFD-I approach and the TRIZ tools.

Eco-friendly technologies are necessary to meet customer demand and environmental sustainability. The eco-friendly concept has been studied by many authors such as selection and design of sustainable transportation channels (Rajak et al., 2018) and design of circular production system (Vimal et al., 2019). Eco-innovative green materials have been considered by several authors (Ilyas et al., 2018a; Ilyas et al., 2018b; Ilyas et al., 2018c; Abral et al., 2019; Sanyang et al., 2018). A study carried out a detailed literature analysis on eco-design methods for developing new products based on QFD (Puglieri et al., 2011). In Ferrer et al. (2012), a technological eco-innovation preliminary design based on a computer-aided model for chemical engineering had been developed. Various methods have been considered to obtain the best results for eco-design (Kobayashi, 2006). Karlsson and Luttropp (2006) emphasized that eco-design produced an effective system solution, smart design of products, and methods. A recent study highlights environmental aspects into product/process development by using six sigma (Pusporini et al., 2013a). Later, a combination of six sigma and TRIZ has been presented by Wang et al. (2016) for the development of the new product. A study by Pusporini et al. (2013b) used green-QFD along with fuzzy logic to obtain an eco-friendly product. Environmental requirements and metrics have been used by Masui et al. (2013). Alemam and Li (2014) proposed an eco-design method by integrating QFD and Functional Analysis (FA) at the early stage of design. Chen and Liu (2003) presented an eco-innovative design method of products by considering the relationship between green-QFD, eco-efficiency, and TRIZ engineering parameters. The drawback of this paper is that they considered only for a product not for a process. Dehariya and Verma (2015) used green-QFD and House of Quality (HoQ) for designing an air-conditioner. A paper by Romli et al. (2015) presented an IEDM methodology formed from three stages namely, Life Cycle Assessment (LCA), eco-design process model, and enhanced eco-design QFD. A special eco-design HoQ is used to analyse the sustainability of manufacturing processes, product usage, and end-of-life strategy. Kobayashi (2005) introduced the software tool with a suitable parameter of the life cycle of the product to analyse the eco-design concept of the life cycle of the product. Alemam and Li (2016) dealt with the application of quality management systems for eco-design concepts. The paper used morphological charts, relation matrices as well as QFD for concept generation in eco-design. A study of the University of Taiwan developed an effective method for obtaining green products by integrating the green-QFD (Ko et al., 2016).

The 'Theory of Inventive Problem Solving' also known as TRIZ was developed by a Russian scientist Genrich Altshuller in the 1940s. It is a systematic thinking tool that can help to improve 'systems' in an innovative way. TRIZ is a potent tool to solve the inventive problems and has been used by many authors' over the past decade (Chen & Jiao, 2014; Pokhrel et al., 2015; Russo et al., 2015). A systematic literature survey based on TRIZ for transforming technical knowledge into a product concept has been conducted by Fiorineschi et al., (2018). TRIZ tool has been used by several authors such as the design of automotive parking brake lever (Mansor et al., 2014), for green supply chain problem (Moussa et al., 2017). A study discussed the guidelines needed to be taken into consideration for implementing the TRIZ laws of evolution for eco-design (Russo et al., 2011). Numerous design method and techniques, TRIZ tools, and eco-efficiency parameters to obtain desired results have been developed to support systematic innovation, which is summarised in Table 1.

Table 1
Different tools and techniques used for eco-design

Sl. No.	Tools	References
1	QFD	Kobayashi (2005); Puglieri et al. (2011); Pusporini et al. (2013a); Dehariya and Verma (2015); Romli et al. (2015); Alemam and Li (2016); Ko et al. (2016).
2	Morphological Charts	Alemam and Li (2016).

Table 1 *(Continued)*

Sl. No.	Tools	References
3	Matrix-Based Correlation	Alemam and Li (2014).
4	TRIZ Laws	Chen and Liu (2003); Russo et al. (2011).
5	Life Cycle Planning (LCP)	Kobayashi, (2005).
6	Life Cycle Assessment (LCA)	Kobayashi (2005); Dehariya and Verma (2015).
7	IEDM	Dehariya and Verma (2015)
8	Fuzzy Logic	Pusporini et al. (2013a)
9	Green- QFD	Chen and Liu (2003); Pusporini et al. (2013a); Alemam and Li (2014); Ko et al. (2016).
10	House of Quality (HoQ)	Pusporini et al. (2013a); Ko et al. (2016).

Based on the literature review, to the best knowledge of the authors, it has been found that researchers have successfully integrated QFD and TRIZ Laws for eco-design of products. However, no significant methodology has been developed for systematic and innovative eco-design of a process. Moreover, no concrete research has been carried out to obtain the green process for brass-ware manufacturing. This paper aims at the integration of Green-QFD, TRIZ tools, and eco-efficiency parameters for obtaining a green process for brass-ware manufacturing. Further, the rest of the paper has been organized as follows: The methodology has been described in Section 3. In Section 4, a case study of the brass-ware manufacturing process is introduced. Results and discussion are shown in Section 5. Finally, Section 6 concludes the paper with future works.

METHODOLOGY

In order to develop an eco-friendly process, a systematic-innovation eco-design concept was used by integrating QFD-I and TRIZ tools. The QFD-I method can be used to systematically design the problem, analyse the technical feasibility, and validate the design solution by using the House of Quality (HoQ). TRIZ is a systematic method for creating innovative resolutions. In this paper, the blend of QFD-I and TRIZ method has been used to construct a framework for the new eco-design process. QFD-I has been adopted to analyse the manufacturer's need and transfer the problem into requirements. TRIZ is used to establish an eco-contradiction matrix, which can be used to identifying the conflict between customers' need and eco-efficiency elements for deriving TRIZ invention principles.

Systematic-Innovation Design Process

Product design engineers must consider both technical innovation and environmental consideration while designing innovative product and processes. Seven principles have been identified by the World Business Council of Sustainable Development (WBCSD) to develop eco-friendly product or processes to reduce the environmental impact, which is as follows:

(i) Material reduction- a reduction of the material intensity of its product, processes, and services.

(ii) Energy reduction- a reduction of energy intensity of its product, processes, and services.

(iii) Toxicity reduction- reduction in the dispersion of any toxic materials.

(iv) Material retrieval- enhancing the recyclability of materials.

(v) Resource sustainable- maximize the sustainable use of renewable resources.

(vi) Product durability- extend the durability of its products, processes, and services.

(vii) Product service- Increasing the service intensity of its product, processes, and services.

The proposed method had been divided into three phases. In the first phase, the seven eco-efficiency elements for the design of a product or process were defined and assigned respective TRIZ numbers. In the second phase, customers' need and quality characteristics had been identified using the QFD-I method. In the third phase, the standard solution of the problem had been obtained by using the eco-contradiction matrix and TRIZ inventive principles. The proposed method might be helpful for the design engineer to produce novel solution idea for the eco-design of product and processes.

QFD-I Approach

Any organisation aims to produce quality products and services. In today's competitive environment, quality is a requirement that customers expect. QFD is a critical aspect of the quality control policy of an organisation. QFD is a very powerful tool as it incorporates customer needs into the design parameters so the final product will be better designed to meet customer expectations. The main concept of traditional QFD-I is to consider four relationship matrices that included product planning, part planning, process planning, and production planning matrices, respectively. Each translation uses a matrix, also called the House of Quality (HoQ). In this paper, the product planning matrix was constructed to obtain the desired quality characteristics.

Eco- Contradiction Matrix

The steps of the eco-contradiction matrix are shown as follows:

STEP 1: Quality characteristics are placed in the improving column and the eco-efficiency elements into the worsening row.

STEP 2: Quality characteristics and eco-efficiency elements are replaced with standard features in TRIZ intuitively.

STEP 3: Set contradiction marks (X) between the technical terms in TRIZ.

STEP 4: Derive invention principles based on the TRIZ contradiction matrix.

STEP 5: Develop eco-innovation product concept based on the invention principles.

CASE STUDY

Problem Environment: Application of the new Method on Brass-Ware Manufacturing Process

Brass-ware product manufacturing has been prevalent in India since times immemorial. Brass–ware manufacturing has many key parameters that affect the end product. These include energy, labour, processes employed, and machinability. In addition to these, the economical sourcing of raw materials as well as minimize environmental effects plays a vital role in brass–ware manufacturing. Therefore, the manufacturing of brass-ware incorporates all areas which would have a bearing in green manufacturing.

The problem environment was studied to convert a traditional brass-ware manufacturing process to a green process by applying QFD-I coupled with the TRIZ laws. The environmental concern was to identify the key parameters such as product volume, labour requirement, and reusability that would help in making the brass-ware manufacturing process sustainable without impacting the quality and uniqueness of the products.

Steps to carry out the analysis were as follows: -

- House of Quality (HoQ): - This step involved identifying what's (Environmental Requirements) and how's (Engineering Metrics) that would affect the brass–ware manufacturing. The what's are the parameters to make the process green and the How's are the factors that can be changed by the manufacturer to make the process green. Both the what's and how's were selected as presented by Masui et al. (2013) for environmental requirements and engineering metrics. Once the metrics were identified, the 9–3–1 weighting method was used to signify the correlation between the what's and how's with respect to making the process green. For example, the 'Weight of the Product' was strongly correlated with 'Less Material Usage,' and hence the weight of '9' had been assigned. These weights were obtained by gaining insights about the brass- ware manufacturing process using literature review as well as in discussion with industry experts and decision makers. Using the weight, the raw score was calculated, which was done by multiplying the weights of each what's with the weights of the respective how's and adding the same. The raw score was indicative of the importance of the quality characteristics of making the process green. For better understanding, a relative score was calculated. The higher the relative score, the more important the engineering metric and that makes the process green. QFDE for the brass-ware manufacturing process is given in Table 2. The relative score has been computed as:

$$\text{Relative Score} = {}^{\text{Raw Score}}/_{\sum \text{of Raw Scores}} \tag{1}$$

Table 2

QFDE for brass–ware manufacturing process

		How's (Engineering Metrics/Quality Characteristics)								
What's (Environmental Requirement)	Importance to Manufacturer (Weights)	The weight of the product	The volume of the product	Number of Parts	Number of Types of materials	Hardness	Physical Lifetime	Amount of energy	Rate of Recycled	Biodegradability
Less Material Usage	9	9	9	9						3
Easy to transport and retain	9	9	9	9	3		3		1	
Easy to process and assemble	9	3		9	3		1	9	3	
Less energy consumption	9				3	3	9	9		
Ease to disassemble	3	9	9	9	3				3	
Easy to clean	3									
Less labour	9	3	3	9				3		
Easy to reuse	3								9	
Safe to incinerate	1									
Safe to landfill/dispose easily	9	9			3					9
Harmless/safe emission	3								3	
Raw score		324	216	351	90	27	117	189	72	81
Relative score		0.22	0.15	0.24	0.06	0.018	0.08	0.13	0.05	0.06

Using the Relative Scores, the following quality characteristics were selected:

- Product weight
- Number of parts
- Product volume
- Amount of energy consumption
- Physical lifetime
- Eco-Contradiction Matrix: - The top five relative scores obtained were then used to make an eco–contradiction matrix. Each of the five-engineering metrics obtained from the HoQ were given respective TRIZ number. Similarly, the seven eco-efficiency parameters were assigned respective TRIZ number. Thus, the contradiction matrix was formed and solved using the 40 inventive principles. Explanation of each contradiction is given as follows:
  - X1: - 'Product Weight' is strongly correlated with 'Material Reduction,' which means that if the product weight increases, the quantity of material used per unit service increases, that makes the product less eco-friendly.

- X2: - Increasing the number of parts would lead to increase in product durability. If the number of parts increases, the reliability of the product may decrease, leading to the failure of the product.
- X3: - 'Product Volume' is strongly correlated with 'Material Retrieval,' which means that as the volume of the product increases, the amount of material that can be recycled will be less, making the product less eco-friendly.
- X4: - As Energy Consumption Increases, the product becomes less eco-friendly.
- X5: - Increasing the lifetime of the product has a direct correlation with the 'Product Service.'

All the above correlations had been solved using an eco-contradiction matrix. Each contradiction had been solved using the 40 inventive principles. The TRIZ eco-contradiction matrix is shown in Table 3.

Table 3
TRIZ eco-contradiction matrix

Eco-Contradiction Matrix				**Worsening Parameters** Eco-Efficiency Elements						
				A. Material Reduction	B. Energy Reduction	C. Toxicity Reduction	D. Material Retrieval	E. Sustainable Resource	F. Product Durability	G. Product Service
		Item	TRIZ No.	23	20	31	2	34	27	33
Improving Parameters	Quality Characteristics	Product Weight	1	X1						
		Number of Parts	4						X2	
		Product Volume	8				X3			
		Amount of Energy Consumption	20		X4					
		Physical Lifetime	27							X5

RESULTS AND DISCUSSIONS

Table 4 was obtained on solving the eco-contradiction matrix. Each solution of the five contradictions had been explained.

Table 4
Results of the eco-contradiction matrix

Contradiction	Invention Principle	Generic Solution
X1= (1,23)	(3,5,31,35)	31. Porous Materials
X2= (4,27)	(15,28,29)	15.Dynamics
X3= (8,2)	(10,14,19,35)	10.Preliminary Action
X4= (20,20)	-	-
X5= (27,33)	(17,27,40)	40.Composite Material

- X1 is the contradiction of "increasing the weight of the product without affecting the material reduction." Four main solutions are available to solve this contradiction:

1. Local quality (3)
2. Merging (5)
3. Porous materials (31)
4. Parameter changes (35)

On analysing each solution, the most suited is **"porous material."**

"Porous Material "can be explained as:

Make an object porous or add porous elements (inserts, coatings, etc.). Example: - Drill holes in the structure to reduce weight

Additionally, if the product is porous, one can use the pores for some useful function.

In the brass-ware manufacturing process for statues, use of investment casting instead of sand casting is an anticipated solution for making the process green. It helps in obtaining a smooth finish and reducing the weight of the product (Hollow).

- X2 is the contradiction of "increasing the number of parts without affecting the product durability."

Three main solutions are available to solve this contradiction:

1. Dynamics (15)
2. Mechanics substitution (28)
3. Pneumatics and hydraulics. (29)

On analysing each solution, the most suited is **"dynamics."**

Dynamics deals with designing the characteristics of the process in such a way that if the process is rigid or inflexible, it will make it movable or adaptive. It implies that as the parts increase, each part would be made movable/adaptive, ensuring that durability is not affected.

- X3 is the contradiction of "increasing the volume of the product without affecting the material retrieval." Four main solutions are available to solve this contradiction:

1. Preliminary action
2. Spheroidality
3. Periodic action
4. Parameter changes.

On analysing each solution, the most suited is **"preliminary action."**

Preliminary action can be explained as:

1. Perform, before it is needed, the required change of an object (either partially or fully). Example: - Sterilize all instruments needed for a surgical procedure on a sealed tray.
2. Pre-arrange objects such that they can come into action from the most convenient place and without losing time for their delivery.
   Example: - Kanban arrangements in a Just-in-Time (JIT) factory.

In the brass-ware manufacturing process, **"design for manufacturability"** is an anticipated solution for making the process green. It will help in:

1. Optimising all the manufacturing functions such as fabrication, assembly, test, procurement, shipping, delivery, service, and repair, and
2. Assure the best cost, quality, reliability, regulatory compliance, safety, time-to-market, and customer satisfaction

- X5 is the contradiction of "increasing product lifetime without affecting product service."

Three main solutions are available to solve this contradiction:

1. Another dimension
2. Cheap short living
3. Composite material.

The most suitable solution is the use of "**composite material"** to obtain the desired product lifetime. In brass-ware manufacturing use of corrosion-resistant brass for harsh environments is an anticipated solution for making the process green.

Many systematic innovation methods have been discussed in the literature, but these methods are only focused on eco-design of a product (Chen and Liu, 2003; Ko et al., 2016). The eco-friendly process is also an important aspect need to be explored by the design engineer in the starting phase of design, such as planning and conceptual design phases. Based on the literature survey, to the best knowledge of the authors, it has been found that no concrete research has been carried out for the eco-friendly process. In this context, this paper presents the eco-innovative green design method for brass-ware manufacturing.

CONCLUSIONS

In the pursuit of sustainable and green manufacturing, there is a need to examine the eco-design of both products and processes. The contradiction is the biggest impediment to a new generation of solutions. The design process integrating quality characteristics of QFD-I and eco-efficiency elements into the proposed eco-contradiction matrix has been established for solving eco-innovative design problem. In this paper QFD-I, TRIZ tools, and eco-efficiency parameters were effectively used to make brass-ware manufacturing a green process. After, solving the eco-contradiction matrix, it has been found that by considering the solution such as the use of porous material, dynamics, preliminary action, and composite material, brass-ware manufacturing process may be made green. A case study of brass-ware manufacturing demonstrated the applicability and feasibility of the systematic-innovation method. Further, the approach could be applied to any type of other manufacturing processes.

FUTURE WORK AND RECOMMENDATION

Future work for this method has the potential to be adopted for numerous applications. Various tedious processes can be easily analysed and made environment-friendly. Fuzzy logic, as well as LCA, can be applied to get better results. Besides the considered parameters, other parameters can also be taken into consideration, which would enhance the result.

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