

Review Article

TRIZ or DFMA Combined With QFD as Product Design Methodology: A Review

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ABSTRACT

Quality Function Deployment (QFD) is a structured methodology that uses customer and technical requirements for designers and manufacturers to provide better products. Many researchers combine or integrate the technique of QFD with other methodologies such as Theory Inventive of Problem Solving (TRIZ) or Design for Manufacture and Assembly (DFMA) to optimise product design innovation and improvement. The combined methodologies are even used to solve process problems. Initial literature review of the application of stand-alone QFD poised several problems. Combining QFD with other techniques, such as TRIZ and DFMA, has helped to address these issues and forms the basis of future research. The integrated methods can solve main contradictory problems more precisely from product demand analysis to product design, production and application. Review work of the literature, specifically that on research and development of QFD, TRIZ and DFMA, showed that the said methodologies have been widely and successfully implemented in several practical applications such as resolving conflicts between customer and technical/engineering requirements and reducing production cost. This review work provides an in-depth analysis of identifying and finding issues of strengths, weaknesses and outcomes of the QFD when combined with TRIZ and also of QFD integrated with DFMA.

Keywords: Product design, QFD TRIZ, DFMA.

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INTRODUCTION

Many companies have tried various new approaches in product design to stay competitive. With globalisation, enterprises have to compete with both local and international companies. Many of them are adopting quality as a source of competitive

advantage so as to achieve a greater number of satisfied customers (Lai *et al.*, 2007). Therefore, having products which continuously meet customers' or users' needs is top priority in the product development process. Every stage of product design and manufacturing is meticulously done to ensure that the products meet users' needs (Luo *et al.*, 2012). According to Sakao (2013), several design guidelines have actually been developed, while a large number of individual design methods and tools have been generated, of which some were implemented as a standard part of design activities.

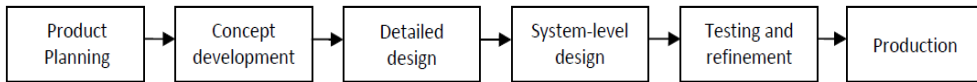


Fig.1: Product development process (Ulrich & Eppinger, 2008).

Fig.1 shows a generic model of the product development process consisting of a few linear steps (Ulrich & Eppinger, 2008). In actuality, the process is more complicated as different properties of the product (technical, economic, ergonomic and environmental) need to be considered simultaneously and this requires involvement of experts from various disciplines and departments. Most of the products consist of a variety of parts and subsystems and for this reason, different levels of product design need to be combined (e.g. components, parts and complete product).

Quality Function Deployment (QFD) is one of the widely used approaches today. It can drive a product development process from conception to manufacturing. It is a well-structured methodology and technique tool that combines customers' requirements with technical requirements that aid designers and manufacturers to produce better products, enhance their competitiveness in the marketplace and increase customer satisfaction (Prasad, 1998; Chan & Wu, 2002a; Mendoza *et al.*, 2003; Lai *et al.*, 2012; Farsi & Hakiminezhad, 2012). Van de Poel (2007) stressed that the main goal of QFD was to translate customers' demands into target values for the engineering characteristics of a product. By systematically and quantitatively employing the relationship between customers' demands and engineering characteristics, those engineering characteristics that are most promising for improving customer satisfaction can be selected, while target values can be set (Lai *et al.*, 2012). Initial in-depth review of articles is to categorise problems pertaining to using QFD in product design. The categories of the QFD problem are depicted in Table 1.

These problems or drawbacks prompt the need for other approaches to be added when applying the QFD method. There are many different methods for generating new ideas and selecting the ideas in order to create a new design or to improve existing ones. In general, researchers tend to focus only on one aspect of the design process, that is, either on the concept generation method or on the concept selection method (Claudio, 2010). Combining QFD with other techniques helps to address these drawbacks and can form the basis of future research. The integrated innovation method, which combines QFD with other technique tools, can precisely solve main contradictory problems in the process from the stage of product demand analysis to that of product design, production and application. However, there is a need to establish the conditions under which the given combinations of particular methods are useful.

TABLE 1 Literature Survey of QFD Problems

QFD Problems	References
Customers' needs may be confused with technical responses, conflicts between technical measures and the House of Quality (HoQ) may be too large and confusing with excessive detail.	Chan & Wu (2002a)
Problems associated with 'working in teams', maintaining a commitment to the methodology and an unsuitable 'organizational culture'	Martins & Aspinwall (2001)
Problems related to organisational conditions such as project definition and project management, as well as team selection and building.	Govers (1996)
Complex and very time consuming	Büyükoğkan et al. (2007); Mak (1999)
Size of the matrices may be too big and complex.	Franceschini & Rossetto (1998); Temponi et al. (1999)
Often difficult to reach agreement on conflicting technical requirements	Balthazar & Gargeya (1995); Lai & Chang (1999)
Difficult to meet the needs of different customer groups or segments	Kim et al. (1998); Partovi & Corredoira (2002)
Customers' needs, correlation among technical requirements and the relationship between customers' needs and technical requirements are often expressed informally in subjective and vague terms and linguistic variables	Zhou (1998); Kim et al. (2000); Fung et al. (2005)
The voice of the customer (VOC) is dynamic in nature and listening to the current VOC is insufficient	Fung et al. (2005)
Manual input of customer survey into the House of Quality (HOQ) is time-consuming and difficult	Bouchereau & Rowlands (2013); Karanjekar (2013)

This paper focuses specifically on the following areas:

- Analysis and identification of (investigates, analyses and reviews) the finding issues, particularly when QFD is combined with TRIZ and QFD is integrated with DFMA.
- Advancement of theory and practices directed to the combination/integration of the QFD method with TRIZ and DFMA approach are discussed and identified.
- Provision of a high-level overview of the current model of the combined QFD methodology in product design, as well as identifying current strengths, weaknesses and outcomes.

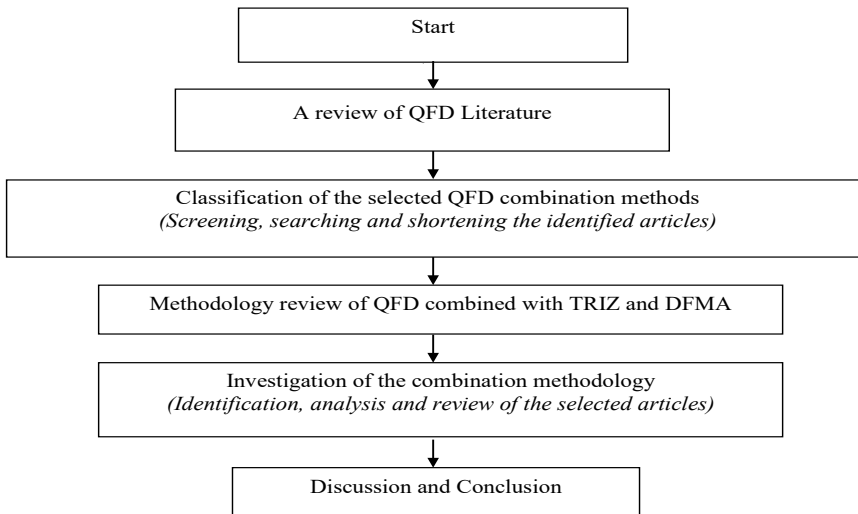


Fig.2: Flowchart of the methodology.

RESEARCH METHODOLOGY

The initial step of the process is to define the context of the literature survey based on the combination of the QFD methodology with TRIZ and DFMA. Fig.2 shows a flowchart of the methodology used to provide the literature review of the study. The work was divided into six sections. The parameters taken into consideration included:

- Product planning and development methods,
- Method of use and time boundaries (year of publication).

A table was used to record and classify the articles being reviewed. It is important to note that this paper focuses on and considers only journal articles whose goal was to either develop theoretical-conceptual work or reviews of the literature or a case study or theoretical modelling (keywords in the title, abstract, introduction were analysed). Even though the above identification methods were used during the searching process, the number of published articles is quite large; hence, it was not possible to analyse all the articles. In order to reduce the possibility of missing the latest developments, the emphasis of the analysis was on the literature published mainly within the last 20 years (1993 to 2014).

A screening process was needed to restrict the articles pertaining to combined QFD with TRIZ and/or DFMA approaches. As a result, a total 28 articles (out of 80) were selected from the following 13 journals, reviewed and further analysed: Production Research Journal, Institute of Electrical and Electronics Engineers Journal, Journal of Applied Operational Research, Science and Business Journal, Science and Agriculture Journal, Industrial Management Journal, International Journal of Operations and Production Management, Computers and Industrial Engineering Journal, International Journal of Ergonomic, Management and Development Journal, Journal of Engineering Education, International Journal of Collaborative Enterprise and Advances in Environmental Biology Journal.

The first and second sections present the Introduction and Research Methodology. Section 3 gives an overview of the QFD methodology and its applications. Section 4 and 5 discuss the combined methods of QFD with TRIZ and QFD with DFMA, as well as finding issues in depth-analysis of the combined methodology. Finally, discussion and conclusions are presented in Section 6.

Overview of Quality Function Deployment Methodology and Its Applications

Quality Function Deployment (QFD) is recognised as an effective method for integrated product and process development (Yang *et al.*, 2012). It was developed by Yoji Akao, who described QFD as a “method to transform user demands into design quality, to deploy the functions forming quality, and to deploy methods for achieving the design quality into subsystems and component parts, and ultimately to specific elements of the manufacturing process.” In other words, QFD is a tool for transforming the ‘Voice of Customer (VOC)’ to product design (Felice, 2010). QFD is a general concept that provides a method for translating customers’ requirements into suitable technical requirements in each stage of product development and production (Shih & Chen, 2013). Fig.3 shows the translation between both requirements.

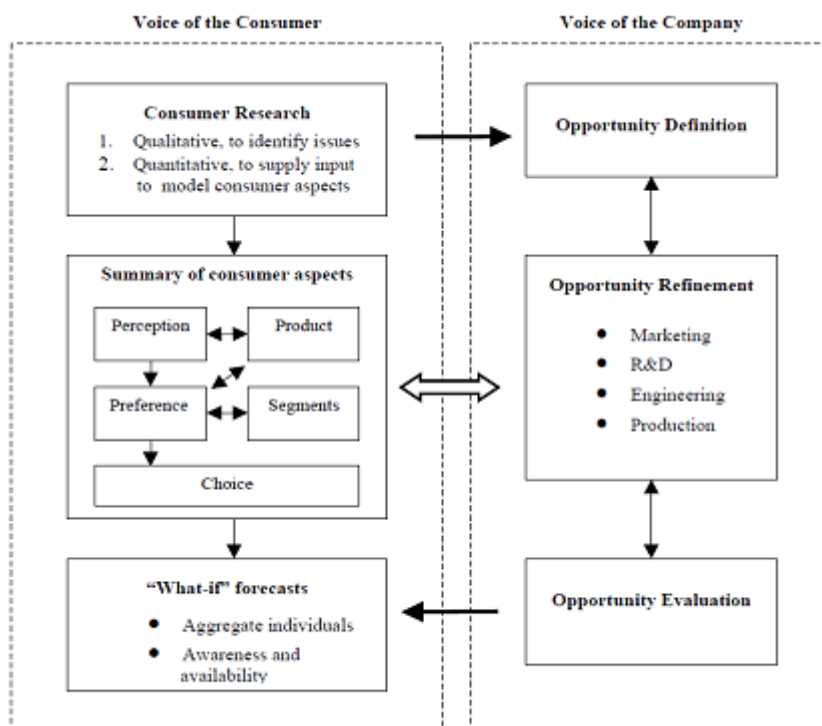


Fig.3: Phases of customer-orientated product design (Urban & Hauser, 1993).

House of Quality (HOQ) is a structure with interrelated matrices that can convert every customer’s requirements into several technical requirements at all levels (Kao *et al.*, 2002; Hung *et al.*, 2007; Kao *et al.*, 2010; Lai *et al.*, 2012). Fig.4 illustrates a generic HoQ.

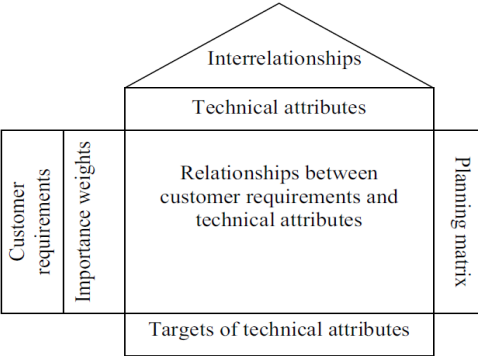


Fig.4: Matrix of HOQ (Cohen, 1995).

QFD also uses some principles from Concurrent Engineering (CE) because cross-functional teams are involved in all phases of product development (Cohen, 1995; Jaiswal, 2012). The QFD process involves four phases, as follows:

- Product planning; house of quality;
- Product design: parts deployment;
- Process planning;
- Process control (quality control charts).

A chart (matrix) represents each phase of the QFD process. The complete QFD process requires at least four houses to be built that extend throughout the entire system’s development life-cycle (see Fig.5). Each of the four phases in a QFD process uses a matrix to translate customers’ requirements from initial planning stages through production control. Bouchereau and Rowland (2000) stated that the starting point of any QFD project is the customers’ requirement, which is often referred to as non-measurable. These requirements are then converted into technical specifications, referred to as the engineering characteristics or measurable. Each phase or matrix can represent more specific aspects of the product’s requirements. Relationships between the elements were evaluated for each phase; however, only the most important aspects were deployed into the next matrix.

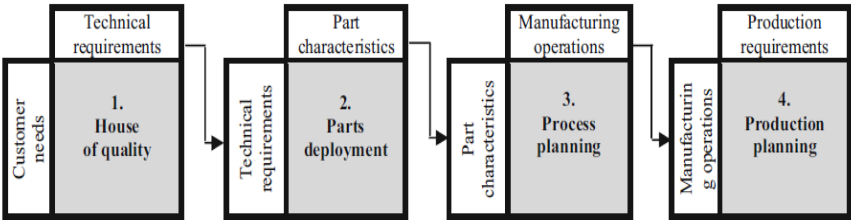


Fig.5: The QFD matrix phases (Hauser & Clausing, 1998, as cited in Kazemzadeh *et al.*, 2009).

QFD with TRIZ and/or DFMA

Several optimisation approaches have been applied in QFD analysis in recent years. Due to the complexity of deployment, various quantitative methods have been suggested to improve the reliability and objectiveness of QFD (Chan & Wu, 1998). Benchmarking is also used to

determine an objective set of technical attributes in QFD (Shen & Tan, 1998). Meanwhile, Kazemzadeh and Behzadian (2009) analysed 650 articles on QFD and grouped them according to their content and came up with four broad categories, which are, general introduction, functional field, industrial application and theoretical development. They also discussed some benefits and common implementation problems. Their findings indicated that a particular weakness of QFD is that it is only suitable for specific applications.

The performance of QFD can be improved by combining it with product design tools. Fig.6 demonstrates how QFD can be used as a framework for product development processes (Sasananan, 2008). The most common method to improve QFD performance to prioritise customers' requirements is to link it with TRIZ and DFMA approaches. The combination of QFD with TRIZ is the most commonly used technique when dealing with incomplete and imprecise information pertaining to customers' requirements (Owlia & Aspinwall, 1998; Ngai & Chow, 1999; Pelt & Hey, 2010; Farsijani *et al.*, 2013a). The combination of QFD-DFMA, on the other hand, can be used to improve the design quality of products during the product concept stage (Bahill & Chapman, 1993; Bergquist & Aberyskera, 1996; Bush & Robotham, 1999).

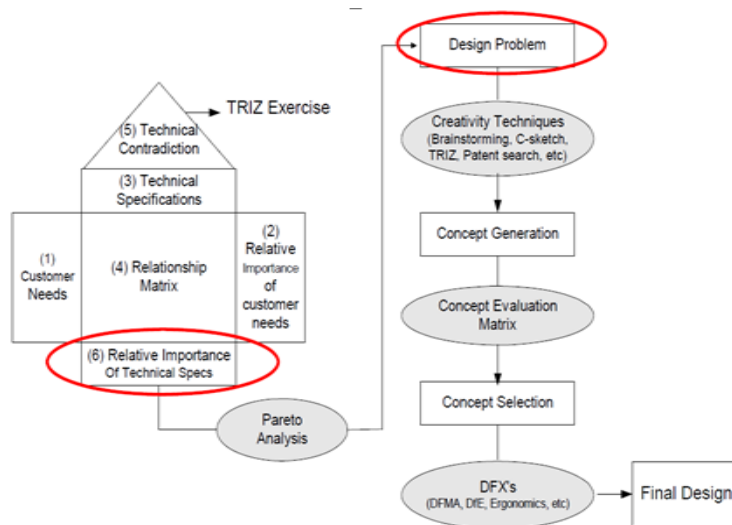


Fig.6: A conceptual model of how QFD is integrated with other methods for product design (Sasananan, 2008).

The findings showed that only two journal articles summarised the topic of QFD combination. Other topics that are commonly focused on in the literature are investigation and analysis of the application of QFD with TRIZ combination and application of QFD with DFMA combination. The common sectors where the combinations are applied include higher education, both large and medium-sized manufacturing, logistics, ergonomics, eco-design and product service. Meanwhile, the common product biased application areas are on product design, product design process, redesigning process, product development, redesigning product, product design cost, analysis cost and product cycle time. Table 2 lists some relevant literature on sector and applications in relation to the type of combinations.

TABLE 2 : Selected Literature Survey of QFD Combined with TRIZ

References	QFD combined	Method Applied in
Clarke (2000)	TRIZ	New product design development
Green & Bonollo (2002)	DFMA	Innovative conceptual idea
Yamashina et al. (2002)	TRIZ	Innovative product development
Suk & Kyeong (2003)	TRIZ	Product design
Mendoza et al. (2003)	DFMA	Product design
Marsot et al. (2004)	TRIZ	Product design
Estorilio & Marcelo (2006)	DFMA	Product design
Chuan & Chun Yu (2007)	DFMA	Product design
Bohm et al. (2008)	TRIZ	New product process and development
Su & Lin (2008)	TRIZ	Product development
Horak & Timar (2008)	DFMA	Product design process
Shang Liu et al. (2009)	TRIZ	Product design
Boppana & Azizi (2009)	DFMA	Product planning, conceptual design
George et al. (2009)	DFMA	New product development
Tseng et al. (2010)	TRIZ	Redesigning process
Claudio et al. (2010)	TRIZ	Redesigning product
Butdee & Trakunsaranakom (2010)	TRIZ	QFD (E), TRIZ
Yeh et al. (2011)	TRIZ	Innovative product design
Johangir & Noraddin (2012)	DFMA	Developing new service
Rau & Tse Fang (2012)	TRIZ	Design Improvement
Sojung & Byungun (2012)	TRIZ	Product and service components
Melgozaa et al. (2012)	TRIZ	Product Design
Yihong et al. (2012)	TRIZ	New Product Design
Farsijani et al. (2013)	TRIZ	Product designation processes
Sakao (2013)	TRIZ	Product planning
Shih & Chen (2013)	TRIZ	Product Design
Mayda & Borklu (2014)	TRIZ	Product Design
Vinodh et al. (2014)	TRIZ	Product Design and Development

Combination of QFD and TRIZ

QFD should not only address product functions but also quality requirement. This can be met by considering generated contradicting effects and evaluating improvement options. Tools on quality requirement in QFD alone are rather weak. The TRIZ methodology can better support designers to find such improvement solutions; hence, it is deployed together with QFD. This is because the tools and techniques of TRIZ, based on the integrated innovation methods, can be organised in many ways. The flowchart in Fig.7 illustrates the TRIZ systemic innovation knowledge. It is useful for the understanding of the integrated innovation methods (see Fig.7), particularly the tools and how they are related (Yihong *et al.*, 2012). The synergy attained between the four phases of QFDs and TRIZ is a powerful tool to enable development

of breakthrough in products because it emphasises on error prevention practices (Yeh *et al.*, 2011). The attained synergy can detect problems such as quality characteristic conflicts in target specifications and also negative interactions between product structures, materials, manufacturing processes and shop floor control requirements.

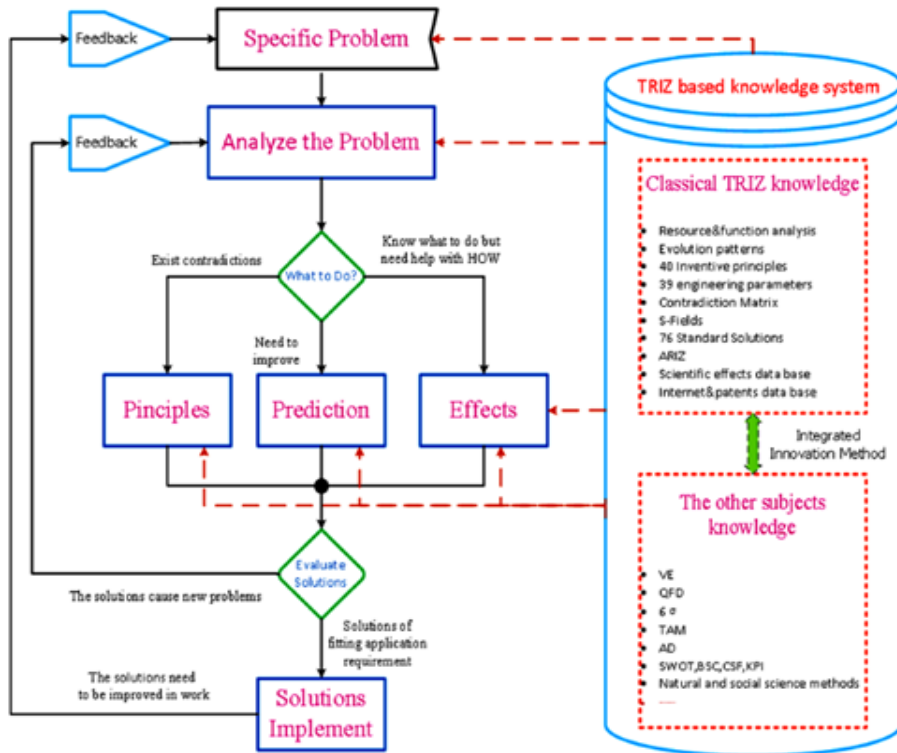


Fig.7: TRIZ problem solving flow chart with integrated innovations tools.

TABLE 3: Some Identified Literature Reviews on Combination of QFD and TRIZ

References	Selected Variables	Identified Outcomes
Clarke (2000)	Engineering characteristics	TRIZ and QFD has synergies that can be used for a wide range of innovative problem solving
Hajime et al. (2002)	Customers requirement and quality characteristic	Product development process carried out systematically with the integration of QFD and TRIZ
Hong Suk & Kyeong (2003)	Eliminating stool, bowl flushing, odour prevention, rinsing reduces sound	Flexible rubber and operation using TRIZ, which is applied to dipper in toilet, thus reducing water consumption in buildings (from 13 to 3 litres).
Marsot et al. (2004)	Voice of customer and engineering characteristic	Integration of FA, QFD and TRIZ can be used to create ergonomic products

TABLE 3: (Continued)

References	Selected Variables	Identified Outcomes
Liu et al. (2009)	Voice of customer, engineering characteristic	The Integration of QFD and TRIZ and non-linear programming can produce simulation design products that meet consumers' satisfaction with cost minimisation and elimination of contradicting technical characteristics.
Tseng et al. (2010)	Priority technical characteristics in product design	The combined QFD-TRIZ can be applied to determine sequence of technical characteristics and correlations between them.
Yeh et al. (2011)	Customer and environmental requirements, technical product characteristics, QFD contradictions	QFD supported TRIZ to translate Notebook's customers' needs into required design attributes, components/modules, process operations and production, concurrent with the desire to realise high applicability and innovation in products.
Rau & Fang (2012)	Packaging weight, size, prices, resilience, handling costs, resistance of moisture, vibration, pounding, pressure and durability wrapping	The proposed QFD was combined with the TRIZ approach to survey design requirements and attributes and their weights in terms of importance for notebook computer packaging design; a fuzzy QFD matrix was constructed, and it was found that the results were highly practical, extensible and applicable.
Yihong et al. (2012)	External variables, motivation (perceived usefulness, consumers' taste perception, behaviour, habits) and actual system used	With the integrated innovation method of QFD, TAM and TRIZ combined, the company's new wall material products are designed, and green, environmental, economic series wall material products have been designed and marketed in China
Sakao (2013)	Customer and environmental requirements; Technical attributes	The methodology supporting the effective planning in term of product cost and environment

TABLE 3: (Continued)

References	Selected Variables	Identified Outcomes
Mayda & Borklu (2014)	Capacity, weight, simple design, ergonomics, human effort, safety, durability, and dimensions	The applicability of the proposed model is demonstrated through a case study. The case study shows that the proposed model allows designers to find easily innovative and customer-centred solutions. Based on Altshuller's levels of innovation, the effectiveness of the proposed model was evaluated, and high innovative solutions were obtained.
Vinodh et al. (2014)	Durable, easy to operate and cost effective.	The results of this study highlight the practical feasibility of the integrated model of QFD combined with TRIZ, which includes a VOC translation mechanism, an innovative design tool, and an MCDM framework for innovative and sustainable product development.

Table 3 lists the works pertaining to the combination of QFD with TRIZ in the literature in chronological order. It shows the variables or sector that are being applied and the identified outcome of each work.

Many researchers have worked on the QFD and TRIZ combination and deployed TRIZ to address QFD problems and shortcomings. For example, Wang *et al.* (2005) identified contradictions within TRIZ by defining rules based on HOQ (House of Quality) in QFD. Several main parameters can be extracted and used to resolve conflicts and contradiction in QFD (Lu *et al.*, 2006). Regazzoni *et al.* (2010) pointed out that taking an innovative, active and prospective approach is much more effective than showing passive reactions in preventing product collapse during its initial designation stages. TRIZ instrument was implemented to resolve these conflicts by translating the technical requirements into 39 designation parameters.

In the contradiction matrix, ameliorating parameters in rows and deteriorating parameters are arranged in columns. As QFD reveals the “what’s” of required operations, TRIZ instrument determines the “how’s” of the required operations (Hassan Farsijani *et al.*, 2013). Sakao (2013) presented TRIZ as a set of technology trends related closely to quality control. The purpose is to help designers to become more efficient in making improvements to their designs. Designers need only to focus on more influential components to improve the quality of a product. This is because QFD reveals the “what” of the required operations, while the TRIZ instrument determines the “how” of the required operations. Farsijani *et al.* (2013) addressed the combination of QFD and TRIZ as seen in Fig.8.

Many researchers have also developed models or algorithms based on the QFD and TRIZ combinations. For example, Su and Lin (2008) developed a model based on the TRIZ

methodology to generate creative solutions using Fuzzy QFD to improve service quality by examining the service quality determinant and analysing the correlation between imprecise customer requirements and service quality determinants. Meanwhile, Yeh *et al.* (2011) proposed and developed using the four phases of QFD to translate customers' needs into required design attributes, components/modules, process operations and production into TRIZ inventive principles and a contradiction matrix. The purpose was to achieve green-design solutions. The software of the TRIZ matrix was developed based on the algorithm. Kim and Yoon (2012) implemented the TRIZ and QFD instrument to resolve the conflicts between production and consumption requirements in 500 automobile factories in the world.

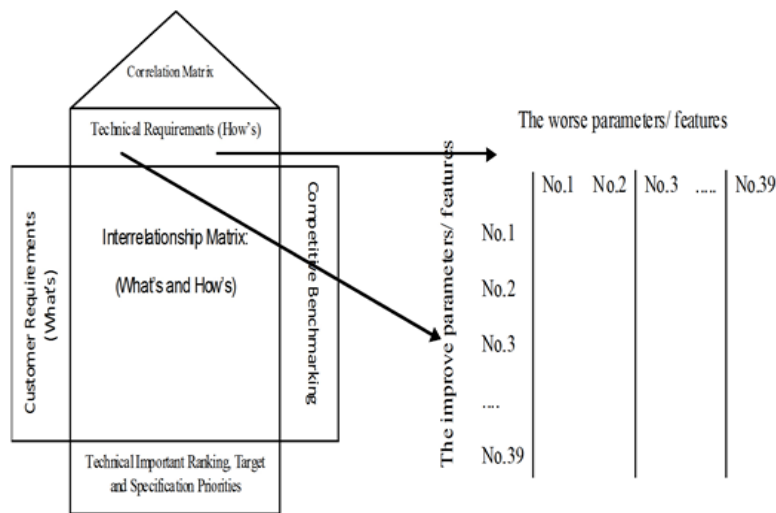


Fig.8: A conceptual model of how QFD was integrated with other methods (Hassan Farsijani et al., 2013).

Analysis of the QFD Combined TRIZ

This section reviews the analysis of the case studies applying the combined QFD-TRIZ. Fifteen case studies were selected for analysis in this section (see Table 3). Cases 1 to 7 are categorised as development and improvement of the combined QFD-TRIZ, cases 8 to 18 are categorised as application, and cases 19 and 20 are the fuzzy version of the combined QFD-TRIZ.

Case 1. Clarke (2000). A new combined QFD-TRIZ approach was used to employ elements from the existing customer assessment from concept generation methods to concept selection methods. The TRIZ method was used to transfer the ideas generated through brainstorming into concepts and solutions. The result was to obtain and develop ideas in designing a product that is actually needed by customers. Unfortunately, the amount of ideas generated was insufficient to completely fulfil all customers' requirements.

Case 2. Yamashina et al. (2002). A new combined QFD-TRIZ approach was developed and named Innovative Product Development Process (IPDP). It systematically integrates QFD with TRIZ and enables effective and systematic technical innovation for new products. The IPDP was developed to assist engineers in finding innovative solutions during the technical

product development process. However, the work does not show the effectiveness of QFD and TRIZ integration as it lacks the concentration of an in-depth method. Other in-depth analyses in other literature also indicate that there are no other methods that can effectively show the integration of QFD and TRIZ.

Case 3. Su & Lin (2008). Their combined approach was used to identify critical determinants that pertain to customer satisfaction by analysing the correlation between imprecise requirements obtained from customers and determinants of service quality. The approach can be used to overcome both technical and non-technical problems. However, the applicability of the method is rather complex.

Case 4. Bohm et al. (2008). Their combined QFD-TRIZ approach covers the conceptual development of new products. The methodology was structured into several specific steps and used an IT tool. It provides the transition from isolated support tools to information management along all the phases of the conceptual development in an innovation process. The integration of KNOW-IT, HoQ and TRIZ can improve the overall process of new product development concepts and link it to integrated management information. The communication of each department in developing the product must be transparent when applying the methodology.

Case 5. Liu et al. (2009). Their integrated approach emphasises the contradictions between engineering characteristics rather than compromising trade-off during the early stage of product development. They suggested utilising TRIZ to solve contradictions as the first step. The second step is to amend the correlation matrix of engineering characteristics. The next step is to validate; this is followed by planning and executing IFR (ideal final result). However, they did not describe cost calculation optimisation in detail. MatLab was used for non-linear programming.

Case 6. Claudio et al. (2010). They proposed using the combined QFD-TRIZ approach to create a new design, right from the customer needs assessment to the final design. The methodology was created while a variable message-sign mounting device was designed. The methodology utilises elements from existing customer assessment tools, concept generation methods and concept selection methods.

Case 7. Tseng et al. (2010). They developed a new combined QFD-TRIZ model in terms of Prioritisation of Product Design Tasks. TRIZ was used to generate conflict problems arising from HoQ. DSM and the importance of ECs are applied to overcome the conflicting problems. The methodology of combined QFD, TRIZ and DSM provides ease in determining absolute priority importance in HoQ. However, its application is rather complicated for problem solving whenever simultaneous resource constraints exist.

Case 8. Lee & Won (2003). They used the combined QFD-TRIZ approach to find innovative conceptual ideas to develop a super water-saving toilet system. The physical contradiction in TRIZ with QFD was defined for the fixed ceramic S type trap for saving water while preventing a bad smell from the septic tank at the same time. The concept of using a flexible tube to save water was obtained by using the separation principle to resolve physical contradictions. The aim was to make the innovative concepts more structured so that the physical contradiction of every customer need can be eliminated. Unfortunately, identifying what customers desire using the approach is very difficult to do, and it is even more challenging to use it to generate creative ideas.

Case 9. Marsot et al. (2004). The QFD-TRIZ approach was used to design and produce an ergonomic boning knife. However, the advantages of the newly-designed product compared to the others were not mentioned to prove the effectiveness of their methodology.

Case 10. Tomohiko Sakao (2007). The combined QFD-TRIZ approach was utilised to support the product planning and conceptual design stages effectively. The author provided the concept of innovative product design and eco-friendly design. Nonetheless, it is difficult to quantify the environmental attributes into QFD using this particular concept.

Case 11. Butdee & Trakunsaranakom (2010). The combined QFD-TRIZ approach was used to support redesigning of the High Temperature Machine (HTM). Key TRIZ contradictions for HTM include power duration of action, quantity of substance in the water, as well as temperature and weight of major objects. This combination was used to design eco-friendly products. However, their paper does not describe the validation steps in TRIZ.

Case 12. Yeh et al. (2011). Their combined approach utilises a methodology that integrates TRIZ inventive principles and contradiction matrix to achieve green-design solutions for major contradictions. TRIZ was used to propose innovative methods to resolve problems. This helps designers to anticipate the end results of product development process, a result that is innovative and enhances the chances of product success. However, it is difficult to solve problems when there are simultaneous resource constraints.

Case 13. Kim & Yoon (2012). The combined QFD-TRIZ approach was applied to create product-service system (PSS) concepts by resolving contradictions between product and service components. They applied TRIZ's 40 inventive principles to PSS cases. QFD was adopted to identify critical features of products and services. Characteristics of good products and services were identified using QFD so that the resulting product could be appropriately generated. However, using a tool that is only used to reduce losses due to the product will not be able to prove or show the service quality of existing products.

Case 14. Melgozaa et al. (2012). The methodology they used is based on the synergy between several methods such as attribute listing, QFD and TRIZ to solve physical contradictions related to geometry and material used. Through the combination of QFD and TRIZ, physical contradictions related to geometry and material can be solved. This resulted in a form of stent that is approved by doctors. Although the device has been adjusted, the design techniques do not allow feature geometry to be detailed at this level.

Case 15. Yihong et al. (2012). Through the QFD combined TRIZ and TAM, a design of new building wall materials was achieved. Technical contradictions and physical contradictions at various stages of product design and production were resolved from the perspectives of a user survey, R & D design, manufacturing and marketing. On the other hand, some researchers claimed that TAM might be easy to use and a quick study it is less representative of the real problems of technology acceptance.

Case 16. Shih & Chen (2013). They proposed the combined QFD, ANP and TRIZ to design a mobile healthcare device in the healthcare industry. The proposed process for designing a future mobile healthcare device points out some important features, meets the needs of customers and could be a future direction for the development of the healthcare industry. The concept of innovative ideas has become more structured. Therefore, physical contradiction of each customer's needs can be eliminated.

Case 17. Mayda & Borklu (2014). The proposed combination of QFD and TRIZ into Pahl and Beitz's conceptual design approach was used to design a punch according to two different design models: classical conceptual design process and TRIZ and QFD-assisted conceptual design. This was done to see the results of these designs.

Case 18. Vinodh et al. (2014). They applied fuzzy in their combined Fuzzy QFD-TRIZ approach to redesign the product packaging system. Requirements derived through fuzzy QFD were used to identify design attributes using the TRIZ method. This approach can eliminate the contradictions between material and technical features. However, determination of technical characteristics is still subjective. A combination of QFD and TRIZ can boost innovative thinking in the designing process. Moreover, the total time taken by QFD and TRIZ in assisting the designing process is significantly shorter compared to the classical design process. However, in this paper, QFD did not consider product life cycle but focused on what to do instead. The answer to the question of how to do it is not given, while the process of converting customers' desires into a characteristic technique cannot be defined as well.

Case 19. Rau & Fang (2012). They applied fuzzy in their combined Fuzzy QFD-TRIZ approach to redesign product packaging system. Requirement derived through the fuzzy QFD was used to identify design attributes by using the TRIZ method. This approach can eliminate the contradictions between material and technical features. However, determination of technical characteristics relationship is still subjective. QFD and TRIZ in synergy can save about 40% of time. In terms of cost, on the other hand, the negative effects can cause noise. There is an increase in the cost incurred, while operational complexity is also increased.

Case 20. Farsijani et al. (2013). The combined Fuzzy QFD-TRIZ approach was used to increase product designation efficiency. The researchers implemented the Fuzzy Analytic Hierarchical Process (FAHP) to weigh customers' requirements. Meanwhile, an advanced decision-making software was used to calculate adaption coefficients. The TRIZ instrument was used to resolve the conflicts between technical requirements in a short time based on priorities of customers' requirements. Data from consumers were collected indirectly. However, researchers did not focus on and make comparisons between competitors' products.

The QFD-DFMA Combination Methodology

Design for Manufacture and Assembly (DFMA) focused on operation issues during product design. According to Rajagopalan (2011), this can be critical even though design costs are just a small part of a product's total cost because wastage of raw materials or duplicating efforts could substantially cause negative impacts on any business's profitability. Silva *et al.* (2009) identified QFD as having a concept similar to that of the Design for Manufacturing (DFM) because it also attempts to integrate the relationship between product engineering, quality, marketing and customers. The systematic evaluation approach by DFMA tools provides critical insight into the strengths and weaknesses of the existing product design during its production life phase.

Designers will be led to focus on searching for new product concepts after using this evaluation method in combination with QFD's needs analysis and benchmarking exercises. The inadequacies highlighted by the QFD and DFMA evaluation will be resolved into a solution. It will form the basis of new product concepts with an improved design quality. This technique

also reduces total project time. Gupta and Okudan (2012) described QFD as a popular DFM tool that is used at the conceptual design stage to convert customers' demands into quality characteristics. Design for Assembly (DFA) is closely linked to DFM as it also attempts to reduce the total number of parts and also the total cost incurred. Ideally, DFA must be applied at the conceptual design stage to attain maximum effects. Thus, QFD and DFM promote integration between engineering, manufacturing and marketing by reducing the total cycle time of product development and implementing product quality to be in full compliance with customers' desires (Bush & Robotham, 1999). Table 4 shows the list of some literature related to the combined QFD-DFMA approach and the identified variables and outcomes.

TABLE 4 : Some Literature Reviews Related to QFD Combined DFMA

References	Identified Variables	Identified Outcomes
Green & Elivio (2002)	Conceptual and detail design	Provides solutions on the study guide to other researchers in product design
Mendoza <i>et al.</i> (2003)	Voice of customers, quality characteristic, cost, cycle time	This study shows the methodology used is more suitable for products in the early stages of product cycle.
Estorilio & Simiao (2006)	Cost, detail design	Application of QFD, DFMA and FMEA can be used to show the critical subsystems identified by using cost.
Chiu & Lin (2007)	Product design costs, analysis costs, product design stages	Integration of QFD-DFMA to streamline the design of the product by reducing cost and time in order to improve the quality
Horak & Timar (2008)	E s t i m a t i n g manufacturing costs, cost of assembling product	The application of DFMA has led to quantum leaps in productivity that are reflected in saving programme timing reductions of >50%, assembly time reductions of >63%, assembly defect reductions of >68%, separate part reductions of >50%.
Chowdary & Harris (2009)	Customers' needs, material selection, material assembly time	Product design concepts allow designs to be produced at lower costs and lower environmental impacts, thus enabling organisations employing these principles to become more profitable.
George & Vosniakos. (2009)	Product manufacturing, system simulation, parametric design	Combination of QFD-TRIZ allowed the designer a better control over the intermediate results, enhancing the ability to simulate and test more variations with built-in computerised decision making tools.
Farsi & Noraddin (2012)	Customers' needs and requirements	The technique of QFD, DFMA and VE in the design of product/service or production process is the selection of suitable alternatives that lead to increased value for the customers but does not increase product/service cost. In other words, improved product/service costs lead to greater customer satisfaction.

Analysis of the Combined QFD-DFMA

Eight works were studied for the combined QFD-DFMA approach. Cases 1 and 2 involved new developments and improvement to the combined approach while cases 3 to 8 were on the application of the combined approach.

Case 1. Green & Bonollo (2002). They proposed collaboration between QFD-DFMA and the Value Analysis (VA) approach as a means to improve both outcomes and quality of product design solutions. They explained and described in detail the knowledge and stages involved in the design methodology and also clarified the relationship design process stage. However, their explanation of the integration of product design development method with other methods is not detailed.

Case 2. Chowdary & Harris (2009). They presented an integrated DFMA and DFE with the QFD method. In this regard, QFD aided DFMA and DFE in determining the limits of any design. The study also showed the connections between customers' needs and the metrics used to satisfy them. It also illustrated what the development team should focus on to produce quality products. Once a final concept is selected, two concept variants should be developed. The first variant is without the use of DFE and DFMA methodologies, while the second variant uses DFE and DFMA. However, their proposed combination methodology is only useful for reducing the time required for product design.

Case 3. Mendoza et al. (2003). They applied the combined QFD-DFMA and VE approach in five case studies, and showed that DFMA eased evaluation efforts in terms of information that was generated during the QFD/VE process. Through this combination, DFMA could be used to optimise design proposals. Information from the QFD/VE processes could then be used to evaluate the would-be impacts due to modifications suggested by the DFMA analysis of the product's performance. However, the results of the QFD process are not necessarily balanced because requests focusing on improving the performance of specific features may not be relevant to specific populations. Customers appeared to make assumptions about the products that were not immediately evident from their requests.

Case 4. Estorilio & Simiao (2006). They utilised the integrated QFD-DFMA approach to reduce assembly costs in a diesel engine model, thus making the engine economically feasible. They presented a detailed description of how the most critical engine subsystem was a delimiter by considering the cost and applying DFMA guidelines to the subsystem. Hence, it was concluded that QFD, DFMA and FMEA could be used to reduce the number of components when developing product design.

Case 5. Chiu & Lin (2007). The integrated concept of QFD and DFMA was used to produce low-cost products with high quality in a shorter lead time. Their concept could be used to reduce materials and energy usage, while reducing emissions. However, this integration has a major constraint in the form of the complexity of organising and analysing large-scale matrix relationships.

Case 6. Horak & Timar (2008). They applied the combined QFD-DFMA approach with FMEA to reduce assembly time, assembly defects and separate parts of the door-lock system of tractors in a DFMA laboratory. The combination of QFD, DFMA and FMEA could be used to reduce the number of components used in developing a product design. DFMA also aided DFE to reduce costs, develop future products and minimise the number of design errors.

Case 7. George & Vosniakos (2009). They applied the combined QFD-DFMA approach to examine the path of preliminary products and process development to detailed product design to manufacturing system design focusing on performance prediction. Emphasis was given to analysis-based configuration issues. Their methodology attempted to integrate several different tools within the context of concurrent product and manufacturing system development. Each tool has certain advantages and disadvantages. Holistically from an integration perspective, there are several areas that need attention. One area of interest is the methodology's sequential nature. The difference between the three phases is rather obvious even though there are instances of change in the feedback given and used for decision making.

Case 8. Farsi & Hakiminezhad (2012). They applied the combined QFD-DFMA approach with VE to reduce service/product costs without lowering its quality or performance. Their approach showed that the tools could be used to maintain the team's focus during the design process. They explained the stages involved in identifying processes that facilitated the designer to make inferences. Integration of the three methods simultaneously led to cost reduction and quick or instant improvement of the performance of services or products. However, the method has been presented as too complex to be integrated with other methods.

DISCUSSION AND CONCLUSION

The main objective of this work was to analyse and review several works in the literature on QFD methodology in combination with other techniques that were aimed to improve product design and perform designing tasks as quickly as possible during the product development process. The analysis focused on the combined use of three established methodologies of Quality Function Deployment (QFD), Theory of Inventive Problem Solving (TRIZ) and Design for Manufacturing and Assembly (DFMA).

For this work, journal articles pertaining to the combined QFD approaches from 1993 to 2014 were reviewed and analysed. The articles were distributed over 13 different journals. For this purpose, the initial screening process of relevant journal articles was done whereby 28 combination methods were identified. The combined methods were categorised and presented in two groups: one was based on their type and the other on their methodological characteristics. The categorisation was done for both the approaches of combined QFD-TRIZ and the combined QFD-DFMA.

The strengths and weaknesses of the combined methods and their application in the specific cases were also highlighted. The combined techniques were also analysed separately. This paper also elaborates on details of the combination methodology, specifically details related to both QFD combined with TRIZ and QFD combined with DFMA.

It was found that the QFD combination methodology could provide relevant guidelines and information pertaining to designers on matters to be considered during product design and development processes. The combined QFD-TRIZ and QFD-FMA approaches were the most commonly used techniques to deal with incomplete and imprecise information related to customers' and technical requirements. However, their shortcomings have also been encountered. Among these shortcomings were that many of the combination methods were classified under only one type; the combination methodologies were discussed separately and

compared with no integration; and systematic framework in combining the methods was not described in detail. DFMA could be used to optimise design proposals, while information from the QFD/VE processes could be used to evaluate the impacts the modifications might have on the product's performance, as suggested by the DFMA analysis.

This paper also reviewed the important benefits of the combined QFD-TRIZ and QFD-DFMA approach. Some of the benefits of the combined QFD approach obtained from the literature reviewed are listed below:

- The integration of with TRIZ improves the overall process of new product development, from concepts to integrated management information.
- Completion of the technical characteristics on the relationship in QFD's house of quality (HoQ) using TRIZ contradiction can result in cost optimisation.
- The combined QFD-TRIZ method easily determined absolute priority importance in HoQ.
- Contradictions in the requirements and technical features can be eliminated.
- With the QFD, customer's needs could be determined and attribute needs could be arranged systematically, while TRIZ resolved any contradictions that occurred.
- The combination of TRIZ and QFD can reduce flaws in product design.
- The combined QFD-DFMA can determine the limits of a design and relate customers' needs to the metrics used to satisfy them.
- QFD-DFMA could be used to reduce the components used during the product design development stage.
- QFD-DFMA with FMEA can reduce assembly time and assembly defects and also separate parts of products.

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