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Exploring the Design Tool Attributes with regards to Sustainability Perspective: A Review

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Abstract

The inclination of global manufacturing competitiveness has shown a noteworthy shift from profit- and customer-driven business to a more holistic sustainability paradigm. This new direction, which accentuates the interests of three pillars of sustainability, i.e., social, economic and environment dimensions, has changed the ways products are designed. Therefore, the roles of design tools in the product development stage of manufacturing in adjusting to the new approach are essential and increasingly challenging. This paper aims to review the literature on the attributes of design tools with regards to the sustainability perspective. Five well-established design tools are selected, namely Quality Function Deployment (QFD), Failure Mode Element Analysis (FMEA), Reverse Engineering (RE), Design for Six Sigma (DFSS) and Design for Environment (DfE). By analysing preceding studies, the main attributes of each design tool and its benefits with respect to each sustainability dimension throughout four stages of product lifecycle are discussed. This study indirectly shows the strengths and weaknesses of the design tools. Consequently, the prospective of improving and optimising the design tools is projected, and the possibility of collaboration between the different tools is discussed. Finally, the potential of developing a new design tool to respond to the call for sustainability is also explored.

Keywords: *product design; design tools; sustainability benefits; product lifecycle*

Introduction

In the wake of globalisation, the manufacturing sector continues to grow and remains critically important to most developed and developing countries. The strategy and approach of the main players in manufacturing, however, have shown a gradual change in term of product development by moving from performance focus into more sustainability criteria (Hosseinpour, 2013). This new paradigm of so-called sustainable manufacturing is a response to the imbalance between economic growth and social well-being as well as environmental preservation. Sustainable manufacturing is also created to holistically address the increasing negative impact on the global environment.

The traditional practice of manufacturing is obviously biased towards the economic dimension. The stimulus behind product development and operation is how to retain market share and become more competitive. In addition, the demand of the government as well as society is motivated by modernisation and physical development. As a result, products are normally designed based on the perspective of the users and with a strong consideration on the return on investment. In doing so, the focus of product design is to improve the product quality, shorten the manufacturing time and reduce the operational cost. To achieve these objectives, numerous design tools have been successfully developed and are widely practiced in the industry. Since the introduction of sustainable development and sustainable manufacturing, another criterion that has been taken into account in product design is environmental performance. Hence, numerous design tools are also created to facilitate the design tasks.

In this study, five design tools are selected to be analysed, namely Quality Function Deployment (QFD), Failure Mode Element Analysis (FMEA), Reverse Engineering (RE), Design for Six Sigma (DFSS) and Design for Environment (DfE). These design tools have been selected as it is becoming increasingly difficult to ignore them; they are well-established in the industry globally due to their unique attributes with regards to their customer-driven approach, failure risk analysis, reverse and redesign approaches, improvement in manufacturing process variation, and eco-performance focus, respectively. In the literature, the design tools have been defined specifically: QFD refers to a powerful customer-driven and market-oriented method (Sharma, Rawani, & Barahate, 2008); FMEA is an effective analysis and solution of a potential failure modes tool (Ben-Daya, 2009); RE is a reverse and rapid approach to develop new products by replicating and modifying existing products via the use of computer-aided equipment and software (Zhang, Ajmal, & Yang, 1995); DFSS is a comprehensive tool created under the Six Sigma umbrella to design products and processes to achieve greater variations (Gremyr & Fouquet, 2012); while DfE is a systematic approach to improve the environmental performance of products (Hauschild, Jeswiet, & Alting, 2004). Firstly, the background and approach of each design tool are studied. Next, by analysing their attributes, their contribution to the three dimensions of sustainability, namely, social, economic and environment, throughout the product lifecycle are analysed. There are four stages of the product life cycle, starting with engineering, where the product is designed, followed by production, use and finally end of life or disposal. Since sustainability is a vast framework, the focus of this research is limited to the attributes of the design tools related to the customers and manufacturers only. For instance, for both social and economic dimensions, only users and manufacturing players will be considered; meanwhile, the benefits of the design tool with respect to the government, stakeholders, etc., will not be taken into account. Through this mapping activity, the strengths and weaknesses of the design tools with regards to the sustainability performance are exposed indirectly. Finally, the prospect of collaborating the design tools with other tools and the potential of developing a new design tool are also discussed.

The Call for Sustainable Manufacturing

Sustainable Manufacturing Framework

Since the 1990s, the efforts to face the ever-growing global treats of climate change have shown a significant increase, especially from the manufacturing sector (Ocampo & Ocampo, 2015). Manufacturing activities, from the acquisition of land, consumption of natural resources and energy, production operation, followed by the consumption by end-users and finally, disposal activities have collectively and largely contributed to the alarming global warming as well as various deleterious environmental problems. In response to this concern, sustainable manufacturing, as a component of the sustainable development paradigm, has been introduced to offer a holistic solution from the consumer level, manufacturing players, and authorities up to the international level.

The universally accepted concept of sustainable manufacturing is “the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound” as defined by the U.S. Department of Commerce (The Organisation for Economic Co-operation and Development (OECD), 2011). This conception renders the role of engineering in product development more difficult and challenging. Besides retaining the efforts to develop products be achieved by applying the most efficient mechanisms in energy consumption and materials selection from the earth’s limited resources as well as minimizing waste and pollution through any means throughout the products’ lifecycle. To respond to the call, therefore, it is crucial and more beneficial to integrate the characteristics for sustainability at the early stage of product development (Cramer, 1997; Fargnoli & Kimura, 2006; Schöggl, Baumgartner, & Hofer, 2016) to ensure that the sustainability attributes are fixed as much as possible before the final design is delivered to the production (Byggeth, Broman, & Robèrt, 2007). Indeed, most of the costs (Mascle & Zhao, 2008) and the environmental impact (Schöggl et al., 2016) throughout most of a product’s life cycle are critically determined at the design stage. For that reason, the roles of design tools to provide optimal support during the design stage are vital and should be improved continuously.

Well-Established Design Tools in the Industry

Over half a century ago, various design tools were developed and successfully applied in the manufacturing industry. In general, the function of the design tools is to support the design team in finding solutions to address specific design problems with regards to quality (e.g., performance, safety, reliability), cost (e.g., materials, waste) and time (e.g., design process, production). Hence, the design tools contribute significantly in improving the competitiveness of the product. For instance, Design for Assembly (DFA) was introduced to simplify the assembly task. By minimising the number of separate parts and improving the assemblability of the remaining parts, DFA leads to the simplification of product. As a result, this method not only reduces the assembly cost but offers a significant reduction in overall manufacturing costs (G. Boothroyd, 1987). A number of well-established design tools applied in manufacturing are shown in Table 1.

Table 1. Well-established design tools in industry.

No.	Design Tool	Year Developed	Main Attributes	References
1	Reverse Engineering (RE)	In the 1940s	Acquire design recovery from existing products for redesign purpose.	(Kumar, Jain, & Pathak, 2013)
2	Value Engineering (VE)	In the late 1940s	Increase values of products/components whilst costs are reduced/retained.	(Dhillon, 2006)
3	Failure Mode and Element Analysis (FMEA)	In the early 1950s	Identify, prioritise and address potential failure modes.	(Dhillon, 2006)
4	Robust Design Methodology (RDM)	In the 1950s	Minimise the effects of variation by making products or processes insensitive to noise.	(Hasenkamp, Arvidsson, & Gremyr, 2009)
5	Design for Manufacturing (DFM)	In the late 1960s	Simplify production processes and minimise production time and cost through design.	(Bogue, 2012)
6	Kansei Engineering (KE)	In the early 1970s	Design products based on the customer's psychological emotion and needs.	(Nagamachi, 1995)
7	Quality Function Deployment (QFD)	In the 1970s	Translate the customer requirements into engineering characteristics.	(Akao & Mazur, 2003; Sharma et al., 2008)
8	Design for Assembly (DFA)	1977	Simplify assembly processes and reduce assembly time and cost through design.	(Geoffrey Boothroyd, 1983)
9	Tool for Inventive Product Solution (TRIZ)	1950s to the 1980s	Introduce problem-solving tools to address inventive problems and design contradictions.	(Moehrle, 2005)
10	Design for Environment (DfE)	In the early 1990s	Improve eco-performance of products and minimise manufacturing impacts on the environment.	(Hauschild et al., 2004; US Environmental Protection Agency, 2016)
11	Design for Remanufacture (DfRem)	In the 1990s	Improve remanufacturing efficiency through design.	(Hatcher, Ijomah, & Windmill, 2011)
12	Design for Six Sigma (DFSS)	In the late 1990s	Integrate design approach to allow for greater variation without compromising performance.	(Gremyr & Fouquet, 2012; Watson & DeYong, 2010)
13	Design for Sustainability (D4S)	In the late 1990s	Incorporate all three pillars of sustainability-social, economy and environment into design.	(Clark, Kosoris, Hong, & Crul, 2009)

From the sustainability perspective, the previous work on product development is not well-covered with respect to all dimensions (Gmelin & Seuring, 2014). In other words, most of the design tools may consider only certain aspects of the sustainability criteria. For instance, Ecodesign tools may be excellent in offering solutions and alternatives for environmental performance. However, Byggeth and Hochschorner (Byggeth & Hochschorner, 2006) revealed that existing Ecodesign tools "lack a goal defined by principles for ecological and social sustainability and strategic principles for sustainable development". Moreover, analysis and evaluations on the existing design tools for the purpose of improvement and complementation are unfortunately still lacking (Baumann, Boons, & Bragd, 2002). Furthermore, there is an obvious dearth of methods or tools that have specialty in developing a sustainable sound product (Byggeth et al., 2007).

Attributes of Design Tools in Response to the Sustainability Call

In this section, analysis of each of the selected design tools is conducted to identify its main attributes and benefits with respect to each sustainability dimension throughout the product lifecycle. The criteria that will be taken into account in this study for each phase of product life cycle and sustainability dimension are shown in Table 2.

Quality Function Deployment (QFD)

Originally developed in Japan in the 1970s (Akao & Mazur, 2003), QFD is a customer-driven quality tool for new product development that has the unique capability of systematically bridging and communicating the demands of customers with the engineering characteristic of a product to finally produce a more competitive product as an outcome. From a larger perspective, QFD effectively allows the communication of three entities, namely, the Voice of Customer (VoC) as the dominant component, Voice of Business (VoB), and Voice of Engineer (VoE) (Sharma et al., 2008), using a series of matrices called House of Quality (HoQ), throughout the product development and production stages. The three voices deal with the requirements and constraints from customers (e.g., quality, functionality, budget), organisation (e.g., resources, profit) and technical components (e.g., technology, manufacturing facilities), respectively (Sharma et al., 2008). After being successfully implemented in Japanese companies, in 1983, QFD then was introduced in the USA and Europe (Akao & Mazur, 2003). Since then, QFD began to spread worldwide and has become increasingly popular in various sectors and companies globally (Sharma et al., 2008).

Previous studies show that QFD dominantly contributes to both social and economic dimensions, especially in engineering, production and usage phases. In the product development and production phases, QFD promotes active communication between customers, design teams as well as the management of the company, consequently leading them to achieve the expected results (Bicknell & Bicknell, 1994). The human resources in the company, in particular, are optimised by stimulating cross-functional communications (Griffin & Hauser, 1993) and teamwork (Bossert, 1991; Hill, 1994), for instance, between marketing, design and production teams throughout all four phases of QFD. The party that enjoys the social benefits the most is understandably the customers. After providing inputs regarding their demands and feedback on the product in the design stage, the requirements are subsequently translated into engineering characteristics throughout the product development and production phases.

QFD also provides significant economic benefits. Although the QFD process involves many parties and phases, it is capable of shortening the design cycles with fewer and earlier design changes, reducing lead time and start-up costs (Bossert, 1991; Hauser, Griffin, & Robert, 2010; Hill, 1994) as well as improving documentation and operational procedures (Bicknell & Bicknell, 1994). Bicknell & Bicknell (1994) even claim that if QFD is utilised properly, the company can shorten the design cycles by 30–50%, achieve a reduction in design changes by 30–50% and enjoy 20–60% lower start-up costs. Furthermore, due to its effectiveness, QFD can develop superior product designs which simultaneously eliminate waste in the form of unnecessary characteristics and features in the product. If we analyse them further, these attributes are consistent with the Crosby's definition of quality: conformance to requirements, i.e., the final design and product possess the criteria that customers want most. As a result, these advantages as a whole are translated into the reduction in both development and production costs and finally result in improved products with more competitive prices (Bicknell & Bicknell, 1994; Hauser et al., 2010). Manufacturers can benefit from this financial gain due to fewer warranty claims (Bicknell & Bicknell, 1994), while end users benefit from the value for money. In addition to the aforesaid benefits, by implementing QFD properly, manufacturers may significantly improve their competitiveness in the market (Chan & Wu, 2002), which can be translated into an increase in loyal and new customers, and most importantly, increase in revenue and market share. Meanwhile, there is no strong assertion to support the contribution of QFD at the end of life phase of the product, be it socially and economically, even though the benefits may have been indirectly created.

As for the environment, the authors notice that it seems to be given less attention in each phase of the product life cycle and may rely solely on the standard practice and regulation as well as initiative of the design team to incorporate the environmental characteristics in the HoQ matrix. For example, in order to fulfil the customers' needs, the design team may opt to select renewable and environmentally friendly materials that offer better eco-performance of the product. There is also no specific attributes of QFD that are noticeable in offering alternatives to minimize environmental impact in the usage and end of life phases.

Table 2. (a) Criteria of Sustainability Performance for each phase of the Product Life Cycle—Phase 1 & 2; (b) Criteria of Sustainability Performance for each phase of the Product Life Cycle—Phase 3 & 4.

(a)					
Phase 1: Engineering			**Phase 2: Production**		
Social	**Economic**	**Environment**	**Social**	**Economic**	**Environment**
Manufacturers: ▪ Development of experts (e.g., design team) ▪ Communication, integration and collaboration between inter functional units Users: ▪ Communication with manufacturer	Manufacturers: ▪ Product Development cost ▪ Utilisation of facilities and technology ▪ Design cycle ▪ Time to market ▪ Documentation ▪ Design optimisation (functionality, materials etc.)	▪ Selection of Materials (e.g., environmentally friendly/renewable materials) ▪ Waste reduction (functionality, materials, etc.)	Manufacturers: ▪ Development of experts and skilled workers ▪ Safety & Heath (employees) ▪ Comfort and satisfaction (employees) ▪ Communication, integration and collaboration between inter functional units	Manufacturers: ▪ Production cost ▪ Effectiveness and efficiency of manufacturing processes, assembly and testing ▪ Operation cost (electricity, water, etc.) ▪ Utilisation of facilities and technology ▪ Defect reduction ▪ Waste reduction (materials, defects, etc.)	▪ Consumption of raw materials ▪ Efficiency of operation (electricity, machines, water, etc.) ▪ Minimising wastages and pollution (air, water, sound) ▪ Utilisation of green energy and technology
(b)					
Phase 3: Use			**Phase 4: End of Life**		
Social	**Economic**	**Environment**	**Social**	**Economic**	**Environment**
Manufacturers: ▪ Competent staff for service after sales (e.g., repair) Users: ▪ Safety & Health ▪ Ergonomic & Comfort ▪ Aesthetic & Perceived Quality ▪ Satisfaction	Manufacturers: ▪ Warranty ▪ Maintenance (spare parts, service, etc.) Users: ▪ Value for money ▪ Operation cost ▪ Maintenance cost ▪ Protection of product (from theft, corrosion, dirt, flood, etc.) ▪ Resale value (if applicable)	▪ Efficiency of operation (electricity, water, fuel, etc.) ▪ Minimising wastages (e.g., spoiled parts) ▪ Minimising pollution (air, water, sound) ▪ Utilisation of green energy and technology	Manufacturers: ▪ Develop expertise in disposal science (e.g., adverse effect of plastic materials on animals, plants) Users: ▪ Awareness/training to reuse products/parts or send for recycling remanufacture	Manufacturers: ▪ Remanufacture & reuse products/parts Users: ▪ Conserve by reusing products/parts	▪ Reusable, recyclable & remanufacturable products/parts ▪ Efficient waste management ▪ Minimising pollution (air, water, sound) ▪ Efficient and environment friendly disposal

Failure Mode and Element Analysis (FMEA)

Initially introduced in the early 1950s in the US as a failure analysis method in the design of flight control systems (Dhillon, 2006), FMEA is a design tool for systematically addressing failure issues while simultaneously improving the reliability of product through design. The initial approach in the FMEA mechanism is to identify and prioritise potential failure modes in the critical parts, functions and components of products or processes. Subsequently, a decision is made on the appropriate mitigating actions to overcome the issues in order to avoid production loss and prevent failures from reaching the end users (Ebrahimipour, Rezaie, & Shokravi, 2010; Zheng, Kiu, & McMahon, 2010). By doing so, this will significantly improve the safety, quality and reliability characteristics of the product (Arabian-Hoseynabadi, Oraee, & Tavner, 2010). FMEA consists of four types: system, design, process, and service. These are associated with global system functions, components and subsystems, manufacturing and assembly processes as well as service functions (Ben-Daya, 2009). In normal practice, FMEA uses the Risk Priority Number (RPN) to prioritise the potential failure modes, which are computed by multiplying the occurrence, severity, and detection difficulty of the risk (Arabian-Hoseynabadi et al., 2010; Rhee & Ishii, 2003). Although initially used in the aerospace and automobile industry (Ben-Daya, 2009), nowadays, FMEA is widely applied in various industries such as the military, nuclear, healthcare, electronics and electro-technical industry (Arabian-Hoseynabadi et al., 2010; Zheng et al., 2010).

The speciality of FMEA is its capability to address product failure issues comprehensively where QFD or other tools may not offer a solution. In the design stage, FMEA is normally applied after the first matrix of QFD is completed. Similar to QFD, previous studies show that the benefits of FMEA applications are mostly associated with social and economic dimensions in engineering, production and usage phases of the product life cycle. In engineering and production phases, the application of FMEA may involve active communication and teamwork between the management, design team and production team as well as previous customers (Arabian-Hoseynabadi et al., 2010; Ben-Daya, 2009; Huang, Shi, & Mak, 2000) in order to identify, prioritise and finally overcome the potential risks. When the products reach the customers, the end users may enjoy the benefits mostly due to the fact that the probabilities of catastrophic failure of the product have been mitigated earlier, and as a result, the risks of death or injuries may be reduced as much as possible. On top of the safety enhancement, the improvement in quality and reliability characteristics also will increase the customers' satisfaction (Ben-Daya, 2009) and ultimately, their loyalty.

It seems that the economical dimension enjoys most of the benefits of FMEA, both for manufacturers and customers. FMEA approach increases the efficiency of product development and production in terms of implementation time and cost (Ben-Daya, 2009). Besides that, Huang et al. (2000) claim that industrial users of FMEA managed to improve product quality by around 15–45% as well as time to market. The introduction of FMEA application in most recent computer aided software such as Computer Aided Design (CAD) and Computer Aided Process Planning (CAPP) increases the effectiveness and efficiency of the risk assessment tremendously (Zheng et al., 2010). Furthermore, when the product reaches the end users, due to increased quality and reliability attributes (Huang et al., 2000), a lower number of failures is expected, hence the repair cost can be reduced. In addition, FMEA can be applied to optimise the maintenance by suggesting preventive maintenance (Arabian-Hoseynabadi et al., 2010; Ben-Daya, 2009); as a result, this will improve the lifespan of the product. We can conclude here that FMEA benefits end users due to higher reliability of product, meanwhile manufacturers enjoy lower warranty cost and fewer complaints, hence increasing their competitiveness. Besides that, FMEA can also be applied to address the potential risks associated with the negative impact on the environment (Ben-Daya, 2009). Nevertheless, the benefits of FMEA application in the disposal phase are scarcely found in the literature.

Reverse Engineering (RE)

Historically, RE was often used in the Second World War and the Cold War to imitate military equipment and technology (Kumar et al., 2013). Nowadays, with the increase in computer capability and the emergence of computer aided software, RE is widely accepted as a contemporary tool in product design and manufacturing processes (Sokovic & Kopac, 2006) in numerous industries such as manufacturing, industrial design, medical and jewellery design (Raja, 2008). In contrast with the traditional approach of product design, which follows a logical order from abstractions to physical implementation, RE is a design recovery strategy that started with extracting a geometric CAD model from existing products/parts; then, from the acquired digital data, improvement and enhancement of the products/parts attributes are conducted (Raja, 2008). In normal practice, RE involves three main steps, namely, (I) digitizing, (II) data collection and segmentation, and (III) data fitting and application (Raja, 2008; Sokovic & Kopac, 2006). The first two steps involve a 3D-scan of the existing product by using contact (e.g., probe) or non-contact (e.g., laser) scanners. Subsequently, the data are cleaned, merged and set in the most convenient format. The outcome is then transformed into CAD format in order to perform other product development activities (Raja, 2008).

The most significant benefit of applying the RE approach is the tremendous shortening of the product development cycle (Raja, 2008) and a promising reduction in manufacturing time (Sokovic & Kopac, 2006). As a result, this will greatly reduce the time needed to bring the product to the market (Raja, 2008). The availability of computer aided design packages such as CAD/CAM software, Computer Tomography, Coordinate Measuring Machine (CMM) and Rapid Prototyping, have greatly contributed to the success and efficiency of RE applications (Marinsek & Paolasini, 1999). Although the improvement in the total lead time does not guarantee the reduction of product development and manufacturing costs, this may financially benefit the manufacturers in the long run. In addition to the shorter time to market, benchmarking and product optimisation will improve the product quality, hence collectively increase the competitiveness of the manufacturers (Sokovic & Kopac, 2006). The customers may enjoy the social and economic benefits of having numerous competitive products available in the market as a result of healthy competition. Nevertheless, there is the possibility that certain quality characteristics in the existing product, for instance, those associated with the manufacturing process, which may not be captured in the RE process, thus affecting the reliability of the new product (Curtis, Harston, & Mattson, 2011). If this is not addressed, it will affect the customers' safety and loyalty, as well as the manufacturers' reputation and sales. In terms of environmental dimension, there is noticeably less attention on the RE approach in all phases of the product life cycle. In the disposal phase, specifically, there is no direct consideration of RE with respect to the three sustainable dimensions.

Design for Six Sigma (DFSS)

Six Sigma is a business strategy (Taghizadegan, 2006) that employs a structured continuous improvement technique to address process variability in the production phase (Bañuelas & Antony, 2003). In technical terms, sigma denotes "the variation about the average of any process" in the form of standard deviation, whereas Six Sigma statistically means 3.4 defects per million opportunities (Bañuelas & Antony, 2003). According to Allen (Allen, 2010), most of the quality problems are due to the process variation in the quality characteristics values of produced products. Therefore, the aim of Six Sigma is to reduce variation in existing processes (Gremyr & Fouquet, 2012) by eliminating its sources and improving the robustness of the processes (Allen, 2010). Design for Six Sigma (DFSS) is the complementary tool to Six Sigma. It is a proactive design tool that leads to the design or redesign of the products, services or processes to objectively achieve a Six Sigma quality level as well as to avoid further associated problems (Bañuelas & Antony, 2003). Therefore, the DFSS focus is on minimising process variability and unpredictability (Allen, 2010) as early as at the design phase, without changing the product's quality (Gremyr & Fouquet, 2012). In contrast to Six Sigma, which focuses on improving the consistency of the processes, the DFSS approach is focused more on improving the effectiveness of the processes; hence, it is capable of proposing better options for the processes, as an alternative to the existing processes (Bañuelas & Antony, 2003). The commonly used approach in DFSS is DMADV, which is the process of Define, Measure, Analyse, Design and Verify. The first three steps are associated with process characterisation (existing process), while the Design and Verify steps are associated with process optimisation (new process) (Taghizadegan, 2006). Since its establishment at Motorola in the 1980s (Antony, 2002), Six Sigma has been applied widely in various sectors; nevertheless, DFSS application is still growing, especially in certain industries such as automotive, manufacturing, energy, medical, aerospace, etc. (Gremyr & Fouquet, 2012).

Most design tools work individually to achieve a specific objective; however, DFSS employs other widely used tools such as QFD, FMEA, Design of Experiments (DOE), Robust Design etc. (Allen, 2010; Gremyr & Fouquet, 2012; Taghizadegan, 2006). This, as a result, makes DFSS more comprehensive and hence understandably offers more benefits. In term of sustainability benefits, economic performance is the winner by far, followed by social impact. In the design stage, both the product development cost (Allen, 2010; Taghizadegan, 2006) and development time (Gremyr & Fouquet, 2012; Taghizadegan, 2006) could be reduced as a result of the application of DFSS. The production phase is where DFSS greatly contributes economically. This is because the preventive action performed by DFSS at the design stage is substituted with the application of Six Sigma in this manufacturing phase. Consequently, the quality, reliability and robustness of the products can be increased (Gremyr & Fouquet, 2012), time to market can be shortened (Antony, 2002) and overall production costs can be reduced greatly as a result of reduction in defects (Taghizadegan, 2006) and waste (Antony, 2002). Furthermore, when the products reach end users, the number of claims and costs can be diminished significantly (Antony, 2002; Bañuelas & Antony, 2003).

In term of social benefits to the manufacturers, the execution of DFSS encourages involvement and extensive teamwork from cross-functional units (Gremyr & Fouquet, 2012) as well as substantial support from the management (Taghizadegan, 2006) throughout the design and production phases. Moreover, in order to ensure the success of DFSS, most of the personnel, especially those from the management and technical teams, needs to undergo extensive training such as Black Belt and Green Belt (Gremyr & Fouquet, 2012), as this will offer added value to their career development. Customers, meanwhile, are also involved and contribute to voice their demands and feedbacks during the design stage. As a result, they may enjoy the benefits when they use the products thanks to the great work done by DFSS and Six Sigma to produce quality and robust products that can be translated into great value for money and eventually customer satisfaction (Gremyr & Fouquet, 2012).

These social and economic benefits consequently spur an increase in productivity and sales (Taghizadegan, 2006), hence leading to improved market share (Allen, 2010). These claims have been proved by Samsung when they implemented DFSS in 2000; they managed to increase Samsung's R&D projects, reaching 80 percent of commercialization in 2014 as compared to 61 percent in 2002. Meanwhile the total sales of the Samsung Group and its 63 affiliates reached $122 billion in 2004, up from $102 billion in 2003, which led Samsung to be a global leader in the electronic business (Park & Gil, 2006). In the end of life phase, however, the attributes of DFSS with regards to social and economic benefits are less discussed in the literature.

Similar to the abovementioned quality tools, environmental sustainability is the area that DFSS as well as Six Sigma are lacking in attention in terms of all product life cycle phases. The discussion of the specific attributes of DFSS that contribute to the environmental domain in the literature is very limited. Nonetheless, some benefits such as large reductions in defects indirectly contribute to the reduction in pollution and waste in the production, usage and end of life phases.

Design for Environment (DfE)

DfE was introduced in the early 1990s (US Environmental Protection Agency, 2016) as an initiative in the manufacturing industry in response to the global concern for the environment, as a result of environmental neglect for decades (DeMendonça & Baxter, 2001). DfE is a systematic guideline that encompasses any design activity which aims to enhance the environmental performance of a product (Hauschild et al., 2004) and to minimise the impact of manufacturing on the environment across the entire life cycle of the product (Billatos & Basaly, 1997). While the quality of the functions of the product are continuously improved (Santos-Reyes & Lawlor-Wright, 2001), DfE covers several related environmental issues in design such as human health and safety, hazardous material management, recycling, disassembly and disposal (Fitzgerald, Herrmann, Sandborn, Schmidt, & Gogoll, 2007). DfE has been applied in various industries such as automotive, medical and electronics (Hauschild et al., 2004), and the interest is growing globally.

There is no exclusive approach in DfE. A variety of methods have been developed which range from general to specific to support the design team in making the optimal decision (Hauschild et al., 2004). According to Fitzgerald et al. (2007), there are several general DfE tools that are often integrated into the product development process. For instance, the Guidelines and Checklist Document is a simple tool that guides the design team to make the right actions and decisions to fulfil specific environmental requirements. The Product Design Matrix, meanwhile, consists of series of questions outlined in a matrix of Product Life Cycle versus Environmental Concern (e.g., Materials, Energy Use, Solid Residue, and Liquid Residue). The matrix aims to support the design team in making design improvements based on their review on the largest environmental concern and the most detrimental phase computed in the matrix. Environmental Effect Analysis (EEA) is another DfE tool developed by adopting the FMEA concept. By applying this approach, the design team needs to identify the key activities and environmental aspects as well as the impact in every phase of a product's life cycle. The environmental impacts, subsequently, are evaluated by defining the Environmental Priority Number (EPN) to determine the significance of the impact. Finally, the data are transferred to an evaluation matrix. Recommendations for design changes and actual design change decisions are made based on this matrix.

Before the introduction of Ecodesign tools including the DfE, a product's eco-performance as well as the impact of manufacturing activities on the environment was not given much attention. Through the implementation of DfE, therefore, the environmental dimension is arguably the dominant dimension that benefits throughout the four phases of the product's life cycle. In the product development, production and usage stages, DfE contributes significantly to the environmental sustainability through the reduction of the consumption of material extraction and processing, conservation of input materials, selection of materials and processes that are less harmful, increase in energy and resource efficiency, reduction of waste and toxin containment and enhancement of product durability and maintainability (DeMendonça & Baxter, 2001; Fitzgerald et al., 2007). The product's end of life phase, meanwhile, is where DfE prominently offers a range of solutions to address environmental problems neglected by most design tools as discussed previously. At the disposal stage, the main issue is the treatment of huge volume of waste generated as a consequence of our consumption. In order to minimise the end of life impacts, DfE increases the environmental performance of products in terms of their remanufacturability, reusability and recyclability (Hauschild et al., 2004). This, as a result, will prolong the life of the products/parts, hence reducing the volume of waste and harmful materials going to landfills.

The environmental advantage can be translated into social and economic benefits. DfE is an interdisciplinary approach that encourages interaction and collaboration of multi-disciplinary teams (Soylu & Dumville, 2011). In the production stage, employees can benefit from better and safer working conditions (DeMendonça & Baxter, 2001), whilst end users may enjoy greener and eco-efficient products that can lead to an increase in their levels of satisfaction. The efficiency of materials management and resource operation as well as the improvement of the eco-performance of products can be translated into a major reduction in operational cost and a foreseeable increase in sales and profits. After the end of the products' life, the ability of the used products/parts to be remanufactured, reused and recycled will turn them into new products (Hauschild et al., 2004). This, in turn, can generate new opportunities for business and employment in recycling, green technology, waste management and related industries. Overall, DfE is a very effective tool in reducing pollution and the long-term impact on the environment (DeMendonça & Baxter, 2001) caused by the manufacturing industry, and hence contributes greatly to the sustainability of the planet.

Discussion

From the above analysis, it is clearly stated that the main purpose of the creation of the design tools is to facilitate the efforts to improve the product design effectively with regards to quality, time and cost. The approaches, as a result, contribute to each of the sustainability dimensions throughout the product life cycle, either directly or indirectly as summarised as in Table 3. The three pillars of sustainability, although they are disparate, they are closely interrelated and interplayed. For example, by reducing the volume of product defects and waste, the production cost can be reduced greatly. As a result, a more competitive product price can be offered in the market. This consequently would not only benefit the customers economically but also socially, as this might increase their satisfaction and loyalty. Another example is, by neglecting the environmental aspect after the product's end of life, the volume of waste and pollution would increase, the result of which, from a social perspective, might threaten people's safety and health. Meanwhile, economically, a considerable amount of money is required to overcome the problems. In this regard, the analysis shows that economy, noticeably, is the sustainability dimension that benefits the most. This is expected because economic profitability is the main reason behind the establishment of the manufacturing players. Moreover, the economy is the aspect that is often given attention by both the government and customers.

Table 3. Summary of the contribution of design tools with regards to sustainability benefits.

No.	Design Tools	Engineering			Production			Use			End of Life		
		S	E	Env.	S	E	Env.	S	E	Env.	S	E	Env.
1	QFD	M:X U:X	M:X	O	M:X	M:X	O	M:O U:X	M:X U:X	O	M:O U:O	M:O U:O	O
2	FMEA	M:X U:X	M:X	O	M:X	M:X	O	M:O U:X	M:X U:X	O	M:O U:O	M:O U:O	O
3	RE	M:X U:O	M:X	O	M:X	M:X	O	M:O U:X	M:O U:X	O	M:O U:O	M:O U:O	O
4	DFSS	M:X U:X	M:X	O	M:X	M:X	O	M:O U:X	M:X U:X	O	M:O U:O	M:O U:O	O
5	DfE	M:X U:O	M:X	X	M:X	M:X	X	M:O U:X	M:X U:X	X	M:X U:X	M:X U:X	X

Note: S—Social, E—Economic, Env.—Environment, M—Manufacturers, U—Users, X—Contribute directly, O—Contribute indirectly.

The study also shows that each design tool has its own advantages and disadvantages with regard to its contribution to the sustainability demand. QFD and FMEA are among evergreen methods which have been employed widely in the industry since their introduction more than half century ago. The uniqueness of QFD is that it allows effective communication between the customers and the design team to facilitate the design process to be executed thoroughly based on the voice of customers. The main objective is to produce products that accurately fulfil customer requirements in term of functionalities, performance, features etc., and as a result, socially, which would improve their satisfaction and loyalty to the products and firms. By employing this method, economically, huge savings can be made across the product lifecycle as most of the unnecessary requirements are designed out as early as during the design stage. Otherwise, the needless characteristics would be useless and eventually turned into waste in various forms and contribute substantially to pollution. FMEA, meanwhile, has a special capability in improving the reliability of a product which is crucial when it is utilised by the end users. The approaches applied in FMEA include identifying potential failure modes in the critical parts, functions and components in the product design and in the end, addressing them systematically in order to eliminate or minimise the risks. This would be translated into mutual benefits, socially (e.g., high safety, decent performance) and economically (e.g., fewer defects and maintenance) to the users. Both QFD and FMEA are among the tools normally employed in DFSS including other tools such as Robust Design. The advantage of DFSS, however, is its ability to reduce the process variability and unpredictability in the production phase through design, which is crucial in order to achieve the Six Sigma quality level. As a result, DFSS collectively is not only able to fulfil the customer demand but is also capable of improving the accuracy and precision of the manufactured products, which contribute extensive benefits to both manufacturers and customers. The focus of RE, meanwhile, is to accelerate the redesign process by capturing digital data of targeted existing products via the use of computer aided design software and equipment and successively modify the design to improve its quality and value. By doing so, the development time and time to market can be reduced significantly. As a result, the products could enter the market earlier, ahead of the competitors. Economically, this advantage has an enormous contribution in increasing sales, retaining the products longer in the market and improving the competitiveness of the products.

Nevertheless, QFD, FMEA, DFSS and RE share similar disadvantages when it comes into environmental performance, where none of the tools possess specific attributes that directly contribute to environmental sustainability throughout all four phases of the product lifecycle. Furthermore, in the end of life phase, product recovery efforts seem to be obviously ignored by all of the design tools. Therefore, the contribution of these four design tools to the three pillars of sustainability at this stage is expectedly minor. These weaknesses, however, could be addressed by employing DfE. The speciality of DfE is its thorough attention in addressing environmental issues throughout the entire lifecycle of a product. This approach emphasises the efficiency and optimisation of the product's environmental performance involving the consumption of materials, energy and natural resources, reduction of waste and pollution, and improvement in product recovery, etc. Even though these characteristics are not necessarily what the customers require and do not promise better quality and a cheaper product, whether directly and indirectly, this would contribute greatly to the social and economic sustainability in the long run. For instance, if the degree of pollution can be reduced comprehensively, this would provide a better atmosphere for social life. Furthermore, taxes associated with environmental recovery can be reduced, and new business opportunities with regards to recycling, remanufacturing and waste management activities, etc., can be created.

As a summary, we can conclude here that even though all the design tools are well established and have been proven to be effective in overcoming certain design problems in the industry, it is noticed that there is no individual design tool that can fulfil the demands from the sustainability dimension comprehensively. This is in line with the findings of Gmelin & Seuring (2014), i.e., that the previous work in product development did not adequately cover all dimensions of sustainability.

The Way Forward

In order to produce better product designs that meet the sustainability performance as expected in the sustainable manufacturing paradigm, therefore, collaborative and integration of a number of design tools may offer a promising solution. Collaborative approach involves the arrangement of several design tools in an effective sequence in the design process such as in DFSS. From the analysis above, DfE can be employed together with any of the other four tools, whether in the middle or final stage of the design process, in order to address the ignored environmental performance. Out of the four tools, it is predictable that by adding DfE to DFSS, the finest product design from a sustainable perspective could be yielded. The integration approach, meanwhile, involves the incorporation of two or more design tools as a single tool. A good example is Eco-QFD, where DfE attributes are integrated into QFD (Kianpour, Jusoh, & Asghari, 2014). In this tool, the customer requirements and engineering characteristics with regards to environmental performance are embedded and given special attention. In practical, modification of a design tool through an integration approach seems more difficult and challenging. This is because each design tool has different design objectives and methods, resulting in complexity of the integration process. In other words, a collaborative approach perhaps is the more practical solution as each design tool can be employed separately in sequence. In terms of application, selection of integrated or collaborative tools may depend on the size of the project and type of the product. In this regard, compared to the integrated tool, the disadvantage of collaborative tools is that their application may take longer and require more resources.

Furthermore, in order to ensure the design objectives are more tangible, all criteria in each sustainability dimension should be defined specifically and arranged based on priority. For instance, in the social dimension, user’s safety (life) should be placed as the top priority; meanwhile, other aspects such as aesthetics features have lower priority. These tangible criteria, further, could be converted as sustainable indicators for the purpose of performance measurement, analysis and benchmarking. Besides that, the potential to develop new design tools that can fulfil the sustainability demands in a more comprehensive manner should also be explored.

Conclusions

Considering the limits of resources to accommodate an increasing global population and development activities, sustainability has become an urgent action to ensure the survival of existing communities and the future generation. In the manufacturing sector, design tools have been employed widely in order to systematically increase the competitive merits of the products as well as the manufacturers. Therefore, it is crucial to study the attributes of these design tools and their contribution to sustainability. In this study, five design tools, namely QFD, FMEA, RE, DFSS and DfE and their unique attributes have been analysed in terms of their contribution to the sustainability benefits. From the analysis, it is discovered that each design tool contributes directly and indirectly to certain dimensions of sustainability, but they are unbalanced and not comprehensive. In other words, it is safe to conclude that from a sustainability perspective, there is no design tool that can work individually to fulfil the sustainability demand comprehensively. Therefore, it is necessary to enhance the capability, flexibility and attributes of the existing design tools. Besides that, the effort required to improve the collaboration among the design tools must be explored and integrated to the product development process. In addition, development of a new design tool to specifically address the sustainability imbalance can be discovered as a potential alternative. Finally, the aforementioned efforts would not be successful without an effective strategy, commitment and collective collaboration from the manufacturing players, regulators, suppliers, customers as well as society.

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