Analysis of design tool attributes with regards to sustainability benefits

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Abstract. The trend of global manufacturing competitiveness has shown a significant shift from profit and customer driven business to a more harmonious sustainability paradigm. This new direction, which emphasises the interests of three pillars of sustainability, i.e., social, economic and environment dimensions, has changed the ways products are designed. As a result, the roles of design tools in the product development stage of manufacturing in adapting to the new strategy are vital and increasingly challenging. The aim of this paper is to review the literature on the attributes of design tools with regards to the sustainability perspective. Four well-established design tools are selected, namely Quality Function Deployment (QFD), Failure Mode and Element Analysis (FMEA), Design for Six Sigma (DFSS) and Design for Environment (DfE). By analysing previous 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. From this study, it is learnt that each of the design tools contributes to the three pillars of sustainability either directly or indirectly, but they are unbalanced and not holistic. Therefore, the prospective of improving and optimising the design tools is projected, and the possibility of collaboration between the different tools is discussed.

1. Introduction
The traditional practice of manufacturing is obviously biased towards the economic dimension [1]. The stimulus behind product development and production is how to retain market share and become more competitive. 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, four well established design tools in industry are analysed, namely Quality Function Deployment (QFD), Failure Mode and Element Analysis (FMEA), Design For Six Sigma (DFSS) and Design for Environment (DfE). The justification behind the selection is due to their unique attributes with regards to their powerful customer-driven and market oriented method [2], effective analysis and solution of potential failure modes tool [3], comprehensive tool created under the Six Sigma umbrella to design products and processes to achieve greater variations [4] and systematic approach to improve the environmental performance of products [5], respectively.

Firstly, the background and approach of each design tool are studied. Next, by studying their attributes, their contribution to the three dimensions of sustainability, namely, social, economic and environment throughout the product lifecycle are analysed. There are four phases of the product lifecycle, starting with engineering, where the product is designed, followed by production, use and finally end of life. 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.

2. Attributes of Design Tools in response to the sustainability call

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), cost (e.g. materials, waste) and time (e.g. time to market). However, according to Gmelin [6], the previous work on product development is not well-covered with respect to all dimensions of sustainability. 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 1.

2.1 Quality Function Deployment (QFD)

Originally developed in Japan in the 1970s [7], 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. 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) [2], using a series of matrices called House of Quality (HoQ), throughout the product development and production stages. The matrices 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) [2]. After being successfully implemented in Japanese companies, in 1983, QFD then was introduced in the USA and Europe [7] and since then has become increasingly popular in various sectors globally [2].

Previous studies show that QFD dominantly contributes to both social and economic dimensions, especially in engineering, production and usage phases. Throughout its four stages, QFD promotes active communication [8] between management and cross-functional units in the firm, as well as customers, which consequently leading the firm to achieve the expected results. 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. 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 [9] as well as improving documentation and operational procedures [10]. Bicknell & Bicknell [10] 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.
### Table 1.
(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.

| Phase 1: Engineering | Phase 2: Production |
|----------------------|----------------------|
| **Social** | **Economic** | **Environment** | **Social** | **Economic** | **Environment** |
| Manufacturers: | | | Manufacturers: | | |
| • Development of experts (e.g., design team) | • Product Development cost | • Selection of Materials (e.g., environmentally friendly/renewable materials) | • Development of experts and skilled workers | • Production cost | • Consumption of raw materials |
| • Communication, integration and collaboration between inter functional units | • Utilisation of facilities and technology | • Waste reduction (functionality, materials, etc.) | • Safety & Health (employees) | • Effectiveness and efficiency of manufacturing processes, assembly and testing | • Efficiency of operation (electricity, machines, water, etc.) |
| Users: | • Design cycle | • Design optimisation (functionality, materials etc.) | • Comfort and satisfaction (employees) | • Operation cost (electricity, water, etc.) | • Minimising wastages and pollution (air, water, sound) |
| • Communication with manufacturer | • Time to market | | • Communication, integration and collaboration between inter functional units | • Utilisation of facilities and technology | • Utilisation of green energy and technology |

| Phase 3: Use | Phase 4: End of Life |
|---------------|----------------------|
| **Social** | **Economic** | **Environment** | **Social** | **Economic** | **Environment** |
| Manufacturers: | | | Manufacturers: | | |
| • Competent staff for service after sales (e.g., repair) | | | • Develop expertise in disposal science (e.g., adverse effect of plastic materials on animals, plants) | | |
| Users: | | | Users: | | |
| • Safety & Health | • Warranty | • Efficiency of operation (electricity, water, fuel, etc.) | • Conservate by reuse products/parts | • Remanufacture & reuse products/parts | • Reusable, recyclable & remanufacturable products/parts |
| • Ergonomic & Comfort | • Maintenance (spare parts, service, etc.) | • Minimising wastages (e.g., spoiled parts) | Users: | | Efficient waste management |
| • Aesthetic & Perceived Quality | • Value for money | • Minimising pollution (air, water, sound) | • Conserve by reusing products/parts | | Minimising pollution (air, water, sound) |
| • Satisfaction | • Operation cost | • Utilisation of green energy and technology | | | Efficient and environment friendly disposal |
| | • Maintenance cost | | | | |
| | • Protection of product (from theft, corrosion, dirt, flood, etc.) | | | | |
| | • Resale value (if applicable) | | | | |

- (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.
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 [9], [10]. Manufacturers can benefit from this financial gain due to fewer warranty claims [10], 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 [8], which can be translated into an increase in loyal and new customers, and most importantly, increase in revenue and market share. As for the environment, the attributes of QFD to minimise environmental impact throughout the entire product lifecycle is hardly found in the literature.

2.2 Failure Mode and Element Analysis (FMEA)
Initially introduced in the early 1950s in the US [11], 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 [25,26]. By doing so, this will significantly improve the safety, quality and reliability characteristics of the product [14]. Although initially used in the aerospace and automobile industry [3], nowadays, FMEA is widely applied in various industries such as the military, nuclear, healthcare, electronics and electro-technical industry [13], [14].

Similar to QFD, previous studies show that the benefits of FMEA are mostly associated with social and economic dimensions in engineering, production and usage phases. 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 the customers [3], [14], [15] 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 [3] and ultimately, their loyalty. It seems that the economical dimension enjoys most of the benefits of FMEA, both for manufacturers and customers. The comprehensive technique of the FMEA increases the efficiency of product development and production in terms of implementation time and cost [3]. Besides that, Huang, Shi and Mak [15] 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 [13]. Furthermore, when the product reaches the end users, due to increased quality and reliability attributes [15], 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 [3], [14], 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 [3]. Nevertheless, the benefits of FMEA application in the disposal phase are scarcely found in the literature.

2.3 Design for Six Sigma (DFSS)
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 minimise process variability and unpredictability [16] without compromising the product’s quality [4]. 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[17]. 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) [18]. Since its establishment at Motorola in the 1980s [19], Six Sigma has been applied widely in various sectors, nevertheless, DFSS application is still growing, especially in automotive, manufacturing, energy, medical and aerospace industries [4].

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. [4,30,32]. 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 [16], [18] and development time [4,30] 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 [4], time to market can be shortened [19] and overall production costs can be reduced greatly as a result of reduction in defects [18] and waste [19]. Furthermore, when the products reach end users, the number of claims and costs can be diminished significantly [17], [19].

In term of social benefits to the manufacturers, the execution of DFSS encourages involvement and extensive teamwork from cross-functional units [4] as well as substantial support from the management [18]. Moreover, most of the personnel especially those from the management and technical team needs to undergo extensive training such as Black Belt and Green Belt [4], hence 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 [4]. These social and economic benefits consequently spur an increase in productivity and sales [18], hence leading to improved market share [16]. 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 [20]. In the end of life phase, however, the attributes of DFSS with regards to social and economic benefits are less discussed in the literature. The discussion of the specific attributes of DFSS that contribute to the environmental domain in the literature, however, is very limited.

2.4 Design for Environment (DfE)

DfE was introduced in the early 1990s [21] as an initiative in the manufacturing industry in response to the global concern for the environment, as a result of environmental neglect for decades [22]. DfE is a systematic guideline that encompasses any design activity which aims to enhance the environmental performance of a product [5] and to minimise the impact of manufacturing on the environment across the entire life cycle of the product [23]. DfE covers several related environmental issues in design such as human health and safety, hazardous material management, recycling, disassembly and disposal [24]. 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 [5], [24] such as Guidelines and Checklist Document, Product Design Matrix, Environmental Effect Analysis (EEA), etc. DfE has been applied in various industries such as automotive, medical and electronics [5] and the interest is growing globally.

Through the implementation of DfE, environment 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 [22], [24]. 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 because 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 [5]. This, as a result, may prolong the life of the products/parts and reducing the volume of waste and harmful materials going to landfills.

The aforementioned environmental advantage can be translated into social and economic benefits. DfE is an interdisciplinary approach that encourages interaction and collaboration of multi-disciplinary teams [23]. In the production stage, employees can benefit from better and safer working conditions [22], 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 [5]. 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 [22] caused by the manufacturing industry, and hence contributes greatly to the sustainability of the planet.

3. Discussion
From the above analysis, it is discovered that all of the selected design tools contribute to each of the sustainability dimensions throughout the entire product lifecycle, either directly or indirectly, as summarised as in Table 2. The three pillars of sustainability, although they are disparate, they are closely interrelated and interplayed. 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.

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

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

The above study also shows that each design tool has its own advantages and disadvantages with regard to its contribution to the sustainability demand. By employing QFD, products that accurately fulfil customer requirements in term of functionalities, performance, features etc. can be produced, as a result, the customers’ satisfaction and their loyalty to the products and firms would be increased. Moreover, 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. 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. 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.

Nevertheless, QFD, FMEA and DFSS share similar disadvantages when it comes into environmental performance, where none of the tools possesses specific attributes that directly contribute to the environmental sustainability. Furthermore, in the end of life phase, product recovery efforts seem to be obviously ignored by all of the design tools. Consequently, the contribution of these three design tools to the three pillars of sustainability at this phase is expectedly minor. These weaknesses, however, could be addressed by employing DfE. Even though these characteristics are not necessarily what the customers require and do not promise better quality and a cheaper product, this would contribute greatly to the social and economic sustainability in the long run, whether directly and indirectly. 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.

4. Conclusion

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, four design tools, namely QFD, FMEA, 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. 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.

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