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ORIGINAL ARTICLE

A systematic review of design for X techniques from 1980 to 2018: concepts, applications, and perspectives

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Abstract

Managing the new product development (NPD) is a challenging mission, and most researches would argue that design is fundamentally linked to intentional action and it cannot emerge out of complexity. In fact, its complexity is generated by a large number of entities and actors which cooperate simultaneously with an unpredictable way to understand what customers want and then design product with diverse objectives in mind. A slight change in one activity may cause tremors everywhere. Within a dynamic environment and in order to meet concurrently these challenges, several researchers have implemented design for X (DFX) techniques. Regarding the availability of numerous DFX, the decision as to which one to apply remains absent. Hence, the purpose of this paper is to present a comprehensive overview of the most prominent DFX techniques with respect to sustainability dimension as well as the cost ownership and product differentiation strategies. In addition to that, complex product necessitates the consideration of integrated DFX to optimize product life cycle from a more holistic perspective. In this respect, the paper addresses a systematic review from 1980 to 2018 by investigating and discussing the past and current research of each DFX techniques as well as for integrated ones. The key problems and issues that future DFX research should address have been identified and discussed in this paper.

Keywords New product development · Design for X · Sustainability · Cost ownership strategy · Product differentiation strategy

1 Introduction

Today, globally operating companies face additional challenges due to the turbulent fluctuations in market demand, the increasing variability of products, and the complexity of processes [1]. Designing a composite product for minimal weight, minimum cost, high quality, reliability, and recyclability has become crucial in the composite industry. In order to meet most of these requirements, many enterprises face a critical need for system engineering tools and methods. One solution to improve the competitiveness, compress cycle times, and increase customer satisfaction is to change from a traditional design to a concurrent design process.

As a business strategy used for the first time in the USA in 1989, concurrent engineering (CE) includes the consideration of a number of factors such as manufacturing, assembly, quality, logistics, service, environment, sustainability, and so on. The means of achieving these objectives is through cooperative multi-disciplinary teams that consider all interacting issues in designing product, process, and system earlier in the design phase of the NPD process. However, one of the most effective approaches to implement and to address these challenges for different factors Xs is by implementing DFX. It describes the proactive, methodical approach for coordinating and communicating requirements emerging from both internal and external NPD. The benefits of using DFX can be related to [2]

- The competitiveness measures.
- Improvement and rationalization decisions in designing products, process, and resources.
- Quality improvements, lead time reduction, product risk reduction, and product material cost reduction.

Therefore, these benefits can be reached either for a specific stage in product life cycle (design for manufacture, design for supply chain, etc.) or for a specific virtue (design for

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environment, design for cost, design for quality, etc.) [3]. Over the years, there were over 75 different DFX techniques found in the literature which have extended beyond manufacture and assembly (DFMA) to the entire supply chain (DFSC) and have taken into account the impact of the environment (DFE), the quality (DFQ), the serviceability (DFSv), and safety (DFS) in the product development. This complexity makes it difficult for researchers and practitioners to keep up with its development. There are DFX techniques that have the same idea with different names, while others have the same names but have different meaning, approaches, and guidelines. Furthermore, due to their specific focus on a particular stage or virtue, a holistic product design considering all aspects of the product life cycle is highly complex.

The decisions regarding which DFX criteria to apply are directly influenced by the appropriate strategy that firms undertake [4]. To do so, this paper presents first a comprehensive overview of the prominent DFX techniques with respect to the three dimensions of sustainability that are economy, ecology, and equity. Second, it seeks to select DFX techniques that should be considered in designing complex product while considering cost ownership and product differentiation strategies for quality and customer satisfaction. Therefore, the paper attempts to present an exhaustive literature review on each selected DFX as well as for integrated ones. This last issue is important when dealing with complex product such as automotive. It necessitates the consideration of different virtues such as safety, reliability, maintainability, and sustainability which can be difficult to address with only one DFX technique. Compared to the existing studies, the major contribution of this paper can be summarized in five aspects:

- An overview of the most used DFX techniques from 1980 to 2018.
- A classification of different DFX with respect to the strategy considered by companies.
- An analysis and categorization of the selected DFX techniques.
- A presentation of the existing integrated DFX that optimize the product life cycle.
- An investigation of the major challenges and future prospects.

The remaining part of this paper is organized as follows: Section 2 describes the framework of this review study. Section 3 presents an extensive overview of the different DFX found in the literature using the presented methodology, which allows us to select the most prominent ones. Section 4 thoroughly investigates the past and current research of each DFX as well as for integrated ones. Section 5 presents the DFX technique applications as well as their repartition by industry sector. Section 6 provides a discussion, research perspectives, and research gaps for both individuals selected DFX and integrated ones. The conclusions and future works are drawn in the final section.

2 Literature review methodology

For more than 50 years, research studies have enriched our understanding and improved decision-making processes of various design issues. Hundreds of DFX techniques covering many topics across several disciplines have been developed. Almost among all of the research contributions and advancement developed, there is no paper that deals purely with the connection between DFX techniques and strategies in the automotive sector. Even more, the link between customer's quality perceptions to choose the suitable DFX techniques to use in automotive product is still lacking. Some researches review different DFX techniques without considering the application sector [5–7]. In other researches, authors consider a specific DFX technique such as design for remanufacture [8–10], design for safety [11–16], and design for sustainability [17–19]. In a further research, authors linked sustainability with the automotive sector through life cycle assessment (LCA) method [20, 21] rather than with DFX method. Whereas Stylidis et al. [22] overcome boundaries between manufacturing and perceived quality in the automotive industry by using just DFQ.

Parallel to the investigation of complicated issues that continue to be examined, research initiatives need to consider multiple DFX in a holistic method. Therefore, before discussing past, current, and future researches that consider the last issue, an overview that facilitates the selection of each DFX techniques according to the design strategies is first presented. Second, a classification of each DFX technique with respect to the strategy considered by companies allows us the selection of the most prominent ones. Third, an analysis of the literature review that covered more than 30 years (1980–2018) is conducted for each selected DFX techniques and also for integrated ones. Figure 1 presents the architecture of the review.

According to the above architecture, the systematic review is conducted through three main section:

1. Which DFX for which strategy?

The goal is to find the most prominent DFX with respect to the appropriate strategy that the company undertakes. To do so, this level is decomposed into two steps:

- Literature search was conducted through two databases ScienceDirect and Taylor & Francis using a combination of the following keywords: "design for," "sustainable product," "DFX," and specific types of techniques such as ("Environment (DFE)," "Quality (DFQ)," "Safety (DFS)," "Manufacturing (DFM)," "Assembly (DFA)," "Service (DFSv)," "Supply Chain (DFSC)," etc.). With

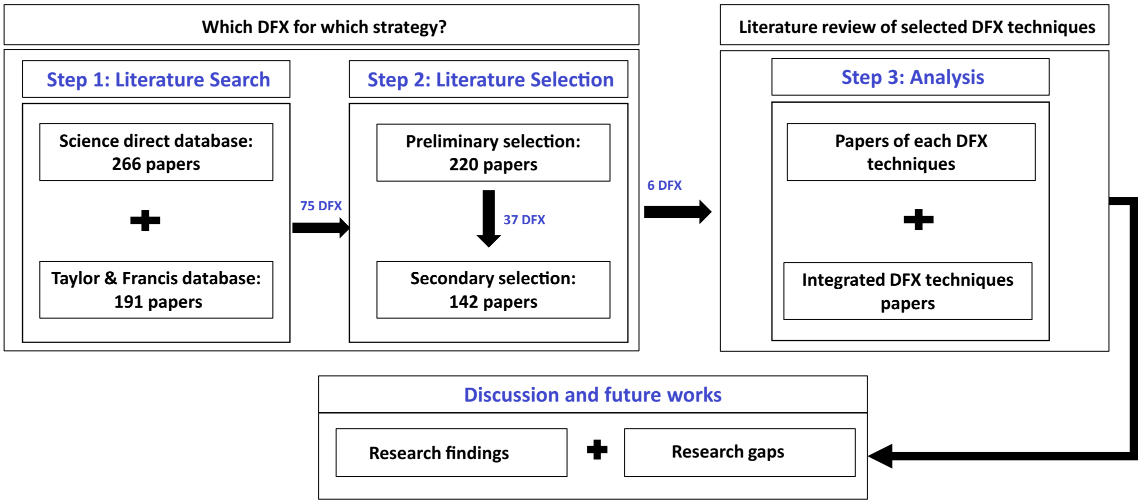


Fig. 1 Architecture of the systematic review

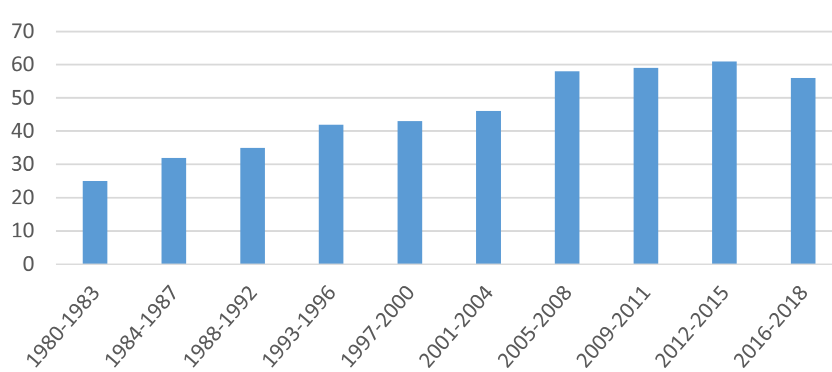
no constraint placed on journals or disciplines, the first screening in "ScienceDirect" database gives 266 papers and in "Taylor & Francis" gives 191 papers. Hence, the preliminary search identified a total of 457 papers. Their distribution over 39-year period is shown in Fig. 2. An analysis based on keywords shows that there are more than 75 DFX techniques found in this step. This multiplicity makes it difficult for practitioners to keep up with DFX development and to take profit from their use. To reduce this complexity and facilitate the selection of DFX techniques, the literature selection step is considered.

- Literature selection was conducted following Newbert methodology [23]. Among 457 papers selected in the previous step, just 220 are considered. We select first the papers based on two criteria: (1) was the work appropriate to the DFX literature? and (2) was the published work more significant than other work in the same area? From these papers, some of them did not match the subject or are not appropriate to the DFX literature. For this reason, it was essential to make further efforts to screen and filter the 220 papers for in-depth review. To do so, two others filter criteria were used (1) how many times the paper had been cited? and (2) has the paper provide a useful applicability for many industries? By reading abstracts and keywords of the papers with the two criteria in mind, the process is repeated until useful new references were exhausted. As a consequence, the review was comprehensive, resulting in the analysis of over 142 papers used for this paper with the selection of six prominent DFX techniques to use in designing mechanical and more specifically automotive product. The earliest paper included was from 1980, with the final papers included being published in 2018.

2. Literature review of selected DFX techniques

The goal is to deeply analyze the 142 research paper selected for each DFX technique. In other words, we offer a systematic review on past, current, and future researches of the six DFX techniques selected from the previous step. In addition to analyzing the 142 papers selected for content, we also classified the papers in terms of their methodology. Moreover, the need to coordinate and evaluate trade-offs when using multiple DFX techniques in product design has been the subject of several studies that are thoroughly discussed and analyzed in this section.

Fig. 2 Chronology of 457 DFX papers



Discussions and future works carefully investigate the major challenges and future prospects in DFX theory.

3 Which DFX for which strategy?

Design for X was first appeared in 1983, in the Handbook of parts, forms, processes, and materials in design engineering [24], in designing for manufacturing [25], and concurrent engineering's roots in the World War II era [26]. Until that time, DFX was not a known term in the industry and was implicitly considered. The original "design for" was created first to make the production aspects more efficient and to reduce time, cost, and errors. Afterward, DFX techniques expanded beyond production to the entire supply chain and enabled consideration of the impact that design has on the economy, ecology, social, and the health of the company. Hence, a multitude of different DFX technique has been developed over time with a focus on several topics such as manufacturing, supply chain, environment, and so on. However, the forward overview will focus on widely and broadly applicable techniques found in the literature. To adopt a simple model of use, several researchers and practitioners proposed to categorize DFX techniques into several categories, with different perspectives:

- Chiu et al. categorize DFX techniques using three ranges of perceptions: product scope, system scope, and ecosystem scope [5].
- Arnette et al. split them into the three dimensions of sustainability: economy (economic growth), ecology (environmental protection), and equity (social equity) [19].
- Radzwill et al. classify DFX techniques in terms of their scope (where the DFX is applied at the product level, system level, or the ecosystem level) and focus (the degree to which DFX must incorporate the requirements of stakeholders, it can be internal or external or both) [7].

Looking through the preliminary step (literature search), there were over 75 different DFX techniques found which can be overwhelming and difficult to navigate. Hence, in order to provide a most informative, yet concise overview of these techniques, we focus first on influential and well-cited papers that contribute to the development of particular DFX techniques (literature selection step). Table 1 classifies the 37 selected DFX techniques in terms of their (1) sustainable dimension, (2) scope, (3) abbreviations, and (4) design considerations. With deep analysis of Table 1, several points emerge

- First, there are some techniques, which are difficult to classify as exclusively in the economic or ecological dimensions such as DFD, DFRL, and DFPk. These techniques can be used for both, as a technique with economy focus but no consideration for environmental impact or vice versa.
- Second, the equity dimension contains just one DFX due to the lack of considering social dimension into the design process.
- Third, there are several techniques, which have the same design considerations with different names such as DFE and DFSt, DFSS and DFQ, DFTest and DFMEA, and so on.
- Fourth, many of the traditional engineering-based DFX techniques are related to the economic dimension of sustainability and have several connections between them. For example, DFMA technique that incorporates both DFA and DFM was created to cover the production phase. Other subcategories of DFMA can be related to DFF and DFRb, which, in turn, contains DFMac and DFMod. Hence, by considering DFMA for manufacturing stage, we consider DFA, DFM, DFF, DFRb, DFMac, and DFMod. However, manufacture is just one stage in the NPD process. In fact, there exist several DFX, which cover the whole supply chain process such as DFSC, which includes DFL, DFRL, DFP, and DFSp.

In addition, to relate DFX techniques to sustainable dimensions, there is a need to link them with the appropriate strategies that the company undertakes. Generally, a strategy is defined as the business-level decision mechanism that should guide competitive decisions with respect to one product or a family of products [4]. In the literature, there are two main strategies [4, 19]: (1) *cost leadership* attempts to reduce cost in their value chain to be cost competitive and (2) *product differentiation* attempts to meet customer requirements based on service or features [4]. Nonetheless, in order to more understand the strategy concerns and enhance their efficiency, we decompose them further into several subcategories. The cost leadership strategy is decomposed into three subcategories that contain (1) the reduction of production costs, (2) the reduction of supply chain costs, and (3) the reduction of cost ownership. Whereas, product differentiation strategy can be divided into two categories related to (1) the reduction of variation and defects and (2) the reduction of environmental impact.

Figure 3a, b presents a categorization of different DFX techniques with respect to the considered strategy. The percentage of each DFX refers to the number of relevant papers published in this field from 1980 to 2018. According to them, we can argue that the number of publications varies from techniques to another and from strategy to another. To select the most relevant design for X based just on a distribution of papers is not sufficient. Certainly, the designer is a key user of method or tool, but the selection of DFX techniques cannot be left to his preferences. It is

Table 1 Overview of design for X techniques

	Scope	Design for	Design considerations
Economy	Product	Assembly (DFA)	Design to reduce the number of parts, tasks, and motions; design to reduce the difficulty of processes.
		Manufacture (DFM)	Design to eliminate expensive manufacturing processes and materials.
		Manufacture and assembly (DFMA)	Design to address both DFM and DFA.
		Variety (DFV)	Design to reduce design effort and time to market and to reduce the impact of variations in life cycle costs.
		Six sigma (DFSS)	Design to reduce variation and defects; design to meet customers' requirements.
		Safety (DFS)	Design to reduce risks of injury and to integrate hazard and risks of humans, materials, etc.
		Testability (DFTest)	Design to reduce failure modes.
		Maintainability (DFMt)	Design to simplify repairs process: design to reduce repair time and to improve fault isolation.
		Robustness (DFRb)	Design to decrease production costs.
		Failure modes (DFMEA)	Design to reduce failure rate.
		Supportability (DFSp)	Design to improve installation, user training, maintenance, customer support, and product upgrades.
		Flexibility (DFF)	Design to consider changes in customer need/want; design to enable product reconfiguration.
		Modularity (DFMod)	Design to have loosely coupled interfaces enabling module variation in products.
		Miniaturization (DFMin)	Design to reduce production costs and to reduce barriers to innovation.
		Serviceability (DFSv)	Design for compatibility with service and for streamlined service process, component, and storage.
	System	Supply chain (DFSC)	Design to address the performance of both logistics and reverse logistics benefits.
		Logistics (DFL)	Design to decrease packaging and to reduce product size for storage and transportation.
		Mass customization (DFMac)	Design to enable commonality and reusability between product parts and process.
		Procurement (DFP)	Design to enable parts commonality and to leverage existing supplier relationships.
	Both	Quality (DFQ)	Design to eliminate defects in production processes and to meet customers' requirements.
		Life cycle (DFLC)	Design to reduce life cycle cost.
		Cost (DFC)	Design to reduce life cycle cost.
Ecology	Product	Recycle (DFR)	Design to increase recyclable material inputs and outputs and to minimize material variety.
		Reuse (DFRu)	Design to standardize components and to enhance the durability of reuse targeted components.
		End of life (DFEOL)	Design to ensure easy access to fasteners and joints and to lower destructiveness and selectiveness of disassembly process.
		Remanufacture (DFRem)	Design to enable disassembly, assembly, cleaning, testing, repair, and replacement.
		Reliability (DFRL)	Design to use proven components and to identify and eliminate critical failure modes.
		Sustainability (DFSt)	Design to consider the three dimensions of sustainability: economy, ecology, and equity.
		Environment (DFE)	Systematic consideration of environmental safety and health.
		Chronic risk reduction (DFCRR)	Design to reduce hazardous materials and emissions or waste.
		Energy conservation (DFEC)	Design to reduce energy consumption and to ensure rapid warm up and power down.
		Material conservation (DFMC)	Design to reduce product dimensions and to utilize renewable, abundant, and recyclable resources.
		Waste minimization and recovery (DFWMR)	Design to reduce waste; design to increase use of biodegradable materials.
Ecology and economy		Reverse logistics (DFRL)	Design to enable customers to support preventing returns.
		Disassembly (DFD)	Design to reduce environmental impact, to simplify repair time, and to improve fault isolation.
		Packaging (DFPk)	Design to reduce production costs; design to reduce environmental impact.
Equity	Product	Social responsibility (DFSR)	Design to enable linkages with society; design to consider non-traditional markets; design to eliminate social problems.

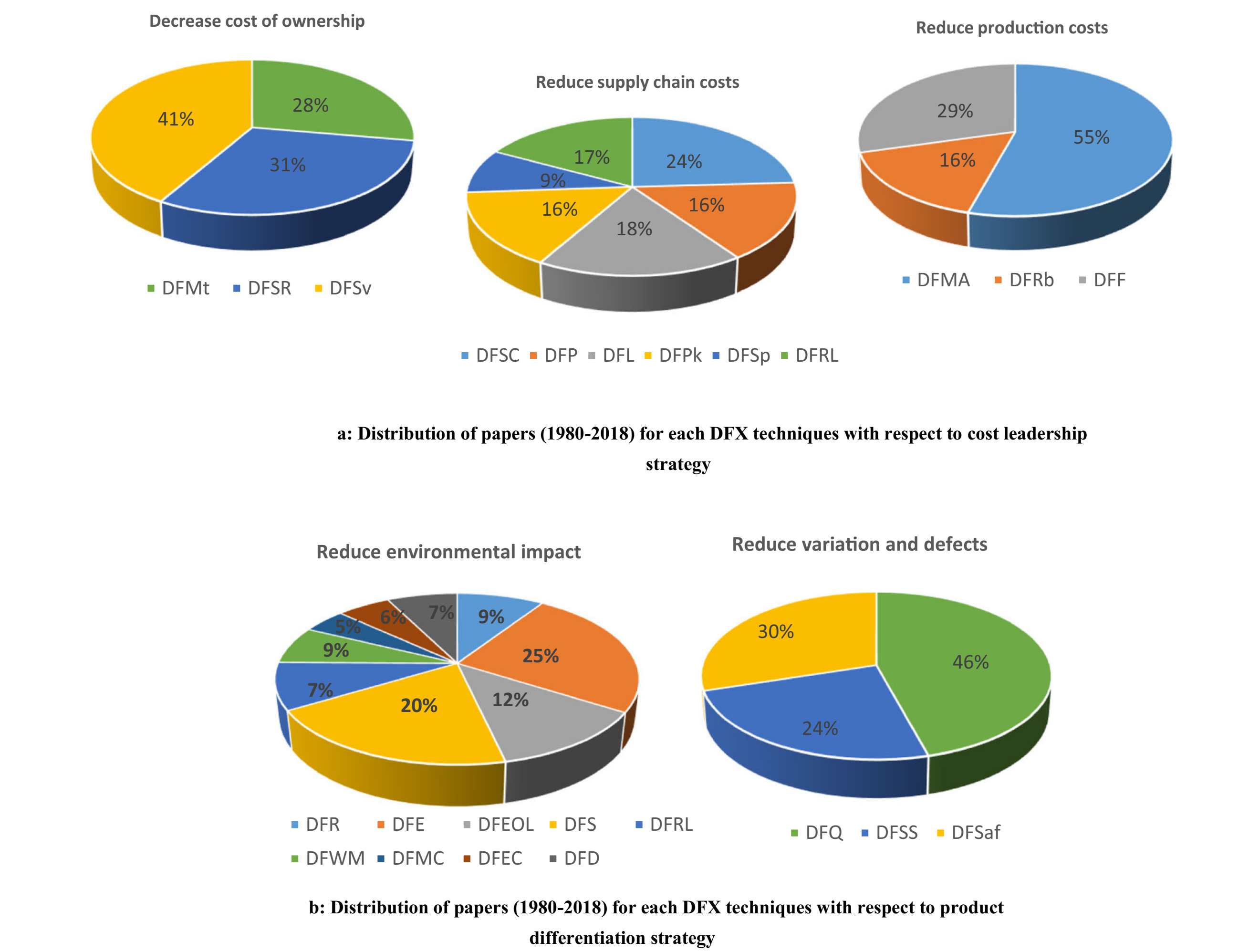


Fig. 3 **a** Distribution of papers (1980–2018) for each DFX techniques with respect to cost leadership strategy. **b** Distribution of papers (1980–2018) for each DFX techniques with respect to product differentiation strategy

the responsibility of the quality manager to ensure the appropriate training for the best use of the methods or tools. How can we choose the appropriate DFX from the 37 techniques presented in Table 1? One possible response is that the DFX method should fulfill the customer's requirements. This leads finding answers to questions as what are the requirements that designer should respect and which DFX techniques to consider? Using the analytical hierarchy process (AHP) method, authors in [27] rank and prioritize the DFX techniques that must be used with respect to different quality attributes extracted from the IATF/ISO 16949 automotive standard. Regarding this work, the most prominent DFXs that fulfill the customer's non-functional requirements are design for manufacture and assembly (DFMA), design for quality (DFQ), design for service (DFSv), design for safety (DFS); design for supply chain (DFSC) and design for environment (DFE). The six DFX selected is called design for relevance [27].

Furthermore, in the context of linking DFX techniques with their corresponding strategy, we can argue that

- To decrease the cost of ownership, we need to consider DFSv.
- To reduce variation and defects, we need DFQ and DFS.
- To reduce environmental impact, we need DFE.
- To reduce supply chain costs, we need DFSC.
- To reduce production costs, we need DFMA.

For practitioners, this simplification provides a framework for selecting appropriate DFX techniques to achieve improved performance based on strategy. Finally, in order to provide an analysis of the six prominent DFX techniques, the next section allows us an exhaustive overview of each of the selected DFX technique as well as for integrated ones.

4 Literature review of selected DFX techniques

DFX publications are increasing year by year, which proves that researchers are paying more and more attention to this issue. The DFX techniques have extended beyond manufacture and assembly (DFMA) to the entire supply chain (DFSC) and have taken into account the impact of environment (DFE), quality (DFQ), serviceability (DFSv), and safety (DFS) in the product development. In the following literature review, the search was conducted by using the same methodology presented before based on the following keywords: design for "Environment," "Quality," "Safety," "Manufacturing," "Assembly," "Service," "Logistics." Of the 142 sources used, 14 are books, while 22 are from conference proceedings. This left 106 journal articles, which are derived from different journals that focus on manufacturing/production, engineering, environment, computer science, and design. Figure 4 demonstrates the number of publications selected in this literature review over the past 24 years in each DFX technique.

In addition to analyzing the 142 papers selected for content, we also classified the papers in term of methodology types. In general, there are four main categories which encompasses several other types:

- Review papers are expected to provide insightful and expert reviews of previous research.
- Research papers are expected to present innovative solutions, novel concepts that can help to address existing or emerging technical challenges in the field. The solution can be analytical with quantitative focus or simulation with an imitation of a real-world focus.
- Theoretical papers are expected to present original concepts or hypotheses for the techniques.
- Empirical papers are concerned with case study or surveys based on practice.

Figure 5 shows that theoretical works make up the largest portion of research utilized in this review. Whereas the weak portion is concerned with empirical research. This categorization makes sense since the basis of each analytical or empirical research is a theoretical one. The description of each paper for each DFX technique is given in Appendix. In the following, the analysis of each paper for each DFX technique is detailed.

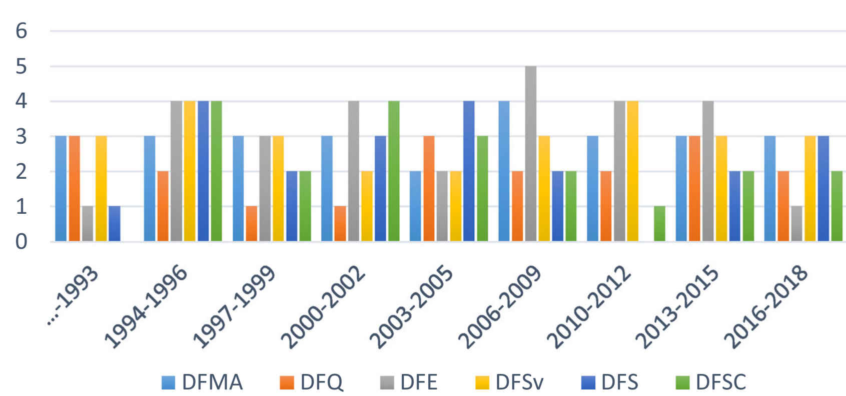
4.1 Design for manufacture and assembly

Design for manufacture and assembly (DFMA) has been used by many companies around the world to develop product designs that use optimal manufacturing and assembly processes. It has been reported that Polaroid Corporation has saved $16,000–$20,000 on the cost of tooling for an injection-molded part [28]. Ford Motor Company saved over $1000M annually as a result of applying DFMA to the Taurus line of cars [29]. McDonnell Douglas Corporation applying DFMA reduced part count by 37% and fastener count by 46% on average [30]. In spite of all the previous case study, it is clear that the use of the DFMA software has a tremendous impact when properly applied in a concurrent engineering environment.

The development of DFMA started in the 1990s with research into automatic assembly (DFA). Several researchers have extensively design product and part for a specific operation: (1) modularity [3, 31, 32], (2) while others provide methods to obtain cost estimation for specific parts of manufacturing processes for machined parts [33], (3) injection-molded parts [2], (4) die-cast parts [34], (5) sheet-metal stampings [35], and (6) powder-metal parts [36]. The main goal from all these papers is to minimize part count and reorientation of parts, standardize parts, encourage modular design, emphasize top-down assemblies, design for component symmetry, design parts with self-aligning and fastening features, and design parts for retrieval, handling, and insertion. In other research, authors present frameworks for creating, analyzing, improving, and representing manufacturing systems during the design process [37–39]. In further research, authors develop methods to decrease the complexity of the assembly process using assembly sequence analysis [40], using semi-autonomous teams with well-defined responsibilities [41], or using contact relation matrix [42] or even investigating how DFA affects the material and manufacturing costs [43].

Later, Boothoroyd and his colleague [56] believed that they could make a significant contribution to the broader subject of product design for ease of manufacture (DFM). During this process, the best materials and processes to be used for the

Fig. 4 Chronology of design for relevance publications in this literature review



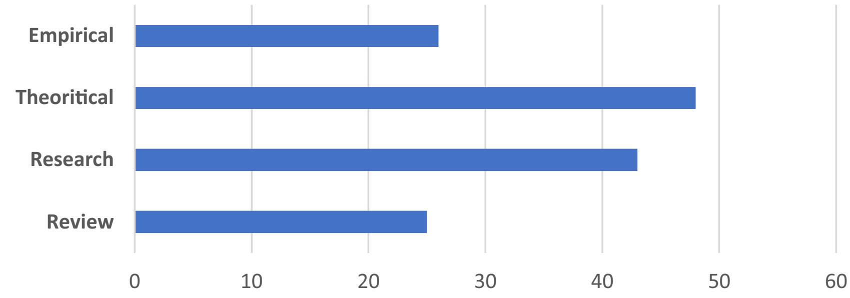


Fig. 5 Methodology classification of 142 papers

various parts are considered. Some authors provide guidelines [44, 45] and surveys [46, 47] to ensure the good design practices. While others combined guidelines with techniques such as axiomatic design [48, 49], decision analysis [50–54], and even with optimization consideration [55].

DFA and DFM were born, later to become DFMA [56, 57]. The general idea of DFMA is to design products for the ease of assembly and to design their component parts for the ease of manufacture. It provides also to designers the capability to minimize the number of components; to simplify and reduce the number of manufacturing operations; to use standard parts and materials; to design for efficient joining, for ease of part fabrication, for ease of packaging, and for ease of assembly; to use common parts across product lines, flexible components, and modular design; and to eliminate or reduce adjustment required.

As a summary, to remain competitive in the future, almost every manufacturing organization has to adopt the DFMA philosophy and apply cost quantification tools at the early stages of product design. However, to be effective in product design, to increase product complexity, and to address globalization and rapid technological development, manufacturing companies need to innovate their offers to consumers by creating more complete solutions that combine maximizing the use of component (DFA) and maximizing the use of manufacturing processes (DFM).

4.2 Design for service

Under traditional manufacturing modes, manufacturers usually spare no effort to promote product sales in order to earn more money and increase their market share. They seldom pay attention to the products' end of life, which usually results in a waste of limited resources and environmental problems. With the economic globalization, more and more manufacturers realize that the possibility of making a profit by selling products is rather limited and it is hard to maintain a competitive advantage. To overcome this, companies must consider serviceability into the design process. When dealing with it, many scholars have responded with two complementary perspectives:

- Product Service System (PSS) is a strategy for innovation that shifts the business model from selling products to offering both products and services. This combination is jointly capable of fulfilling specific customer needs and delivering value in use [58].
- Design for service (DFSv) is an activity of planning and organizing people, infrastructure, communication, and material components of service. It improves the quality and the interaction between service provider and customers. The main purpose is to design the product according to the needs of customers or participants. It encompasses the consideration of maintainability and reliability as the most critical issues that affect product serviceability. Unfortunately, these two techniques are not held a prominent role in DFX literature with few exceptions [56, 59–61].

In order to take a view of all the related actors [62], their interactions [63], and supporting materials and infrastructures [64], we use the DFSv. It provides visualization tools that support participation and collaboration among different stakeholders [65, 66]. More clearly, the basic principles underlying DFSv are (1) user-centered (understanding the user), (2) co-creative (involving all relevant stakeholders), (3) sequencing (separate complex service system into several processes), (4) evidencing (visualizing service experiences that make them tangible), and (5) holistic (considering network of users interactions). Regarding the advantages, Boothoroyd [56] reports that DFSv can decrease the time and cost of service to increase service efficiency. In fact, the time-based efficiency of printed circuit board (PCB) replacement in the pressure recorder was about 3.8% before using DFSv, while it increases to 54.5% after using DFSv.

Over the years, researchers have proposed many design methodologies to support serviceability by different ideas from a different perspective. Several authors discuss the serviceability with customer perspective [67–73]. Other authors present set of frameworks by integrating social, legal, and political considerations into the service design [74, 75]; integrating the network interactions between actors [76, 77]; or even by integrating the PSS design issues into a real case study [73, 78]. In other research, authors use system dynamics perspective to integrate service into design product [79–81]. In further research, authors deal with serviceability by investigating the knowledge management perspective [82–84] or even by matching service to sustainable perspective [85–87].

With deep analysis, we can say that taking a service design approach can disrupt traditional channels to market, lead to innovation, increase customer satisfaction, improve firm effectiveness, and offer a means for differentiation to ultimately boost competitiveness [74]. Moreover, service design can open up opportunities for systemic innovation, in the absence of a specific service offering [88].

4.3 Design for supply chain

In today's highly competitive and globalized market, manufacturing companies are placing an emphasis on efficiency and cost-effectiveness. It has been shown that one method for cutting costs and improving efficiency that is gaining popularity is a concept known as design for supply chain (DFSC). At Digital Equipment Corporation, 4 years after implementing DFSC, they realized saving of approximately $1 billion through simpler, streamlined supply chain and product designs, effective techniques, and cooperative planning between their 12 plants [89]. DFSC can be viewed in broad terms as being "concerned with designing the product while taking into account the impact on the performance and success of the supply chain to satisfy customers demand" [90]. The underlying theme is to design a product in terms of quality, transportation, cost, inventory, packaging, pricing, routing, and forecasting by considering both (Fig. 6):

- Forward logistics (DFL) which includes a series of activities in the process of converting raw materials to finished products.
- Reverse logistics (DFRL) refers to all procedures associated with product returns, repairs, maintenance, recycling, and dismantling for products and materials. It incorporates running products in reverse through the supply chain to gain maximum value.

Researchers and practitioners began to recognize the benefits of an integrated DFSC approach in the early 1990s. They are researchers that focused on the contributions of external parties in the supply chain, without exploring the internal procurement role [92–94]. Others have looked at the impact of design on manufacturability, cost, lead time, and the ability to satisfy customer demand [95, 96]. In other research, authors implement DFSC in different companies to determine the optimal product differentiation and to prove the benefits from using DFSC [89, 97–99]. In further research, authors use a stochastic or hybrid model to deal with uncertainties and risk related to supplier reliability and market demand [100, 101]. Furthermore, to support remanufacturing, recycling, and disposal, researchers have responded with reverse logistics or closed-loop supply chain for handling product service and support, returns, and product recovery at the end-of-life stage of the product. Most of the literature related to this field is related to (1) location allocation of collection center [102–105], (2) inspected and sorted products after collection [106, 107], and (3) product recovery [91, 108–113].

An in-depth analysis shows that DFSC is the process of optimizing the fit between supply chain capabilities and product designs. It creates product configurations that address infrastructure limitations and use supply chain capabilities as they evolve throughout the life of the product. It uses a series of supply chain management processes and techniques that increase customer satisfaction, minimize total costs, and maximize the flexibility to address unplanned events. It can be the answer to the question, "How do we stay competitive in an increasingly commoditized market?" As a consequence, companies can choose to formally reflect supply chain requirements on their product design or suffer the consequences of ignoring them!

4.4 Design for quality

Nowadays, an organization will survive only if it creates satisfied customers. This will only be achieved if it requires products of a given quality to be delivered by a given time and to be of a price that reflects the value of money. While price is a function of cost, profit margin, and market forces, and delivery is a function of the organizational efficiency and effectiveness, quality is determined by the degree to which product or service successfully serves the purposes of the user. Quality has different meanings and is generally defined in the

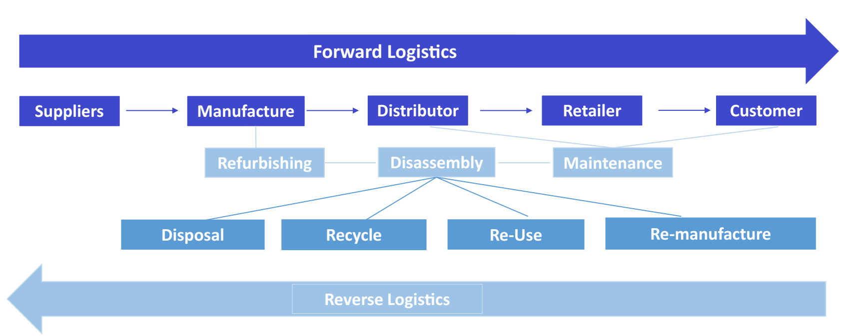


Fig. 6 Closed-loop supply chain adapted from Jindal and Sangwan [91]

literature as "compliance with requirements," "degree of excellence," "fitness for use," "freedom from defects," "imperfections or contamination," and "delighting customers." More specifically, Crow [114] defines quality as a systematic process that provides guidance to facilitate the design of products and process by maximizing the production efficiency and safety while enhancing the product manufacturability and control. However, before the 1960s, companies that consider quality into their manufacturing process used the development of quality function deployment (QFD) approach. Nowadays, this approach is replaced by a more popular technique, called design for quality (DFQ).

The objectives of DFQ are to meet customer requirements and to design a robust product by minimizing the effects of potential variation in manufacture and product's environment. It improves also product reliability, performance, and technology to exceed customer expectations and offer supervisor value [114]. In other words, DFQ is all about providing a product by taking into account the reliability, safety, and toxicity of the product. In fact, if the product or service is unreliable, it is clearly unfit for use and hence of poor quality. If a product is reliable but emits toxic fumes, is too heavy, or not transportable when required to be, it is of poor quality. If a product is unsafe, it is of poor quality even though it may meet its specification in other ways and so ones. The concept of DFQ exists for a long time, but it was not implemented until the Taguchi method [115] was introduced. DFQ can, therefore, be described more accurately as a design for six-sigma (DFSS).

Several researchers discuss the importance of DFSS as an important concept in DFQ [116–118]. In other research, authors present a statistical model to implement quality virtues to determine robust working conditions as well as the evaluation of virtual prototype [119]. In a further research, authors provide a benchmarking tool in DFQ [115, 120–125]. Quality has also been applied to DFM literature for several papers [31, 126–131].

As a conclusion, quality is the combination of processes, resources, and organization that will deliver quality products. It means that quality concerns both products and system. Regarding the product, quality meets customer needs and expectations. While regarding the system, quality is the mean by which organizations produce products that meet customer needs and expectations. As has already been said, quality does not happen by chance, quality must be designed into the product not inspected into it [114]. To get quality you had to pay for inspectors to detect the errors! In fact, there is the cost of doing the right things in the right first time and the cost of not doing the right things in the right first time.

4.5 Design for safety

In safety critical domains, such as automotive domain, failure or malfunction of a safety critical system may result in death or serious injuries to people and to equipment [132]. Even more, hundreds of millions of consumer products are recalled every year for safety risk reasons, and the financial risks to individual firms are significant too [133]. Toyota announced that the company could face losses around US$2 billion from lost sales worldwide [134]. General Motors recalled 28 million cars worldwide due to faulty ignition switches in 2014 at a cost estimated in the billions of dollars [135].

Nowadays, manufacturers are expected to deliver continuous safety for both products and humans. Product safety addresses the quality of a product and its utilization without risk. It can be related to the non-functioning of a system or parts of a system under given time [136]. Whereas human safety concerns accident prevention in work situations and can be related to the risk of human entanglement with a rotating element [137]. This leads to finding answers to questions such as how can we take into consideration the variability of main components, human beings, equipment, and their environment? How can we measure the variability of possible interactions between these components? One possible answer that deals with this complexity and integrates knowledge of both human safety and product safety in the design process is by implementing DFS technique. Hence, in order to ensure safety, you should understand what risk is? The authors in Sadeghi et al [137] and Ghemraoui et al [138] consider that there are three types of risks (accident risks, ergonomics risks, and residual risks) related, respectively, to the three design phases (conceptual phase, embodiment phase, and detailed phase) proposed by Pahl et al. [140].

Several researchers have considered safety performance indicator or risk analysis techniques to monitor the level of safety in a system, to motivate action, and to provide the necessary information for decision-makers about where and how to act [141–144]. Whereas other safety practitioners have suggested that the issue of product safety should be addressed in parallel with the design process especially in the organizational culture [141, 143, 145, 146]. Other researchers supported the importance of improving human safety during design. We can distinguish from the literature six main groups of DFHS research surfaced:

- The utilization of the theory of inventive problem solving (TRIZ) that helps the designer to find solutions based on the analysis of the design problem and knowledge bases to solve design problems [147, 148].
- Axiomatic design theory to establish a scientific basis to improve design activities by providing the designer with a theoretical foundation based on logical and rational thought processes and tools [137–139].
- Failure mode and effect analysis (FMEA) to address concurrently and for the same failure the consequence of using DFS on product quality and humans safety [149].
- Function behavior structure (FBS) to model design as a process and capture the nature of the concepts

manipulated during it using a knowledge representation diagram [150].
- Functional analysis (FA) methodology that fully describes the functions and their relationships, which are systematically characterized, classified, and evaluated [147, 151].
- QFD method for introducing quality in design to satisfy the customer and to transform customer requirements into design objectives in design for human safety [152].

As a summary, we can say that one of the main sources of risk is linked to the variety of work situations. To take into account this variety, the aim in design is to consider human behaviors demonstrated in work situations in parallel with the product, so as not to focus only on product design or only on designing human activities. However, in this new organization, in spite of the differences of culture among the various actors, the human factors and safety dimensions have federated all the points of view not only around the product technical performance but around the man as an agent of safety and reliability of the system productivity and sustainability.

4.6 Design for environment

All human-induced environmental impacts are related to products and the use of them [131]. In this sense, several researchers and practitioners argued that the environmental impacts could be lessened through improved product design, leading to new DFXs (design for recyclability [153–155], design for remanufacture [156–159], design for life cycle [160–162], and design for environment [5, 51, 163, 164]). Due to its capacity to fully address the environmental issues (depletion, pollution, and disturbance) and to cover a wide range of product development activities, we have chosen in this paper to consider design for environment.

DFE was introduced by Allenby and Fullerton [163] and was expanded upon by Fiksel and Wapman [165] wherein DFE is defined as the "systematic consideration during new product and process development of design issues associated with environmental safety and health over the full product life-cycle." DFE technique improves decisions made in product development related to products, processes, and plants and has the greatest potential when used as early as feasible. It strives to achieve products that have the lowest possible environmental impact with cost-effective and high-quality life cycle management [166]. In this respect, DFE as an integral component of the DFX paradigm should be a component of the product definition and creation cycle [167].

In order to help product designers make environmentally friendly design choices, a number of methodologies, guidelines, and checklist have been developed. Some researchers used techniques such as quality function deployment (QFD), life cycle analysis (LCA), analytical hierarchical process (AHP), and TRIZ-based DFE methodologies for the simultaneous consideration of environmental criteria and customer requirements [168–181]. In other studies, authors use fuzzy logic (FL) to handle imprecise and vague information in the early design stage [182, 183]. Further researchers have developed a number of tools for the evaluation of product designs with respect to environmental criteria [184–196].

As a summary, designers should now be readying themselves to deal with environmental issues by developing the ability to thoroughly research the environmentally relevant issues and access environmental knowledge about materials, processes, technologies, and legislation. By employing a holistic approach and developing DFE by adapting current design methods to take environmental considerations into account, it may become a common feature in future product development process. The greatest improvement of DFE is the systematic consideration of design performance with respect to the environment, health, and safety objectives over the full product and process life cycle [193].

4.7 Integrated DFX approaches

The need to coordinate and evaluate trade-offs when using multiple DFX techniques in product design has been the subject of previous studies. Compared to the number of papers that are focused on a single DFX, few researchers have explored using multiple DFX to optimize product life cycle from a more holistic perspective to easily develop new methods. One of the earliest attempts at DFX integration was the work of Tichem and Storm [197] when the authors discuss the role that a computer-based support tool for coordinating DFX could play alongside other design programs like for example CAD. They develop a model of the design process that includes DFA, DFM, and DFD which serves as a basis for developing supporting tools which contains three main elements: execution of design activities, results of design activities, and coordination of design activities. Huang and Mak [3] proposed a framework called DFX shell to identify where consumption takes place and specify how resources are consumed by activities. It includes requirement analysis, product modeling using bill of materials (BOM), process modeling, selecting performance measures, compiling DFX manuals, and verification of the method. Ridker [198] proposed a hierarchical structure for the relationships between all DFX, categorized according to whether they pertained to the planning, concept design, or development phases. He proposed three classes of DFX: design for profit (immediate or future), design for resources (materials, environment, sustainability), and design for staff (encompass any human aspects of a design problem). Meerkamm [199] suggested that each DFX could similarly be decomposed into a hierarchy to more effectively communicate the intention of the guidance within the DFX technique. Lindemann [200] recognized that the application of DFX techniques was mostly "chaotic" and recommended that teams apply network analysis, design for structure matrices (DSM), and domain mapping matrices (DMM) to clarify the use of DFX at various stages.

Other researchers have looked at the numerous DFX techniques available to determine which are the most pertinent to use and how to decide when to use these techniques. Chiu and Okudan [5] developed a framework that consisted of 14 DFX divided into two high-level categories, design for efficiency and the product scope. Based on these classifications, a matrix was developed with these 14 DFX related to four phases of product design to specify the point in the design process that each DFX should be considered.

In other research, authors linked human factors and ergonomics, a discipline that enables the design of products, services, tasks, and environment to serve the physical and cognitive requirements of users, to design for sustainability. By raising awareness of the diversity of human needs and the extent of human variability, especially in multi-national contexts, Nadadur and Parkinson [201] suggest that ergonomic considerations should be integrated into other DFX rather than standing alone. Arnette [19] developed a framework and placed the DFX under the heading of sustainability in the dimensions of economics, ecology, and social equity. A DFS taxonomy is presented to order and consolidate current techniques within these categories. A new DFX concept is developed that incorporates remanufacture, reuse, and recycling as one environmentally friendly approach for end of life. Moreover, this framework only recognized the influences of the three dimensions of sustainability. There is a need to further develop and recognize the role that these influences play with respect to product design and trade-offs between decisions in the design process.

In a further research, the authors dealt with integrating DFX with the non-functional requirement of the designer by using the multi-criteria approach. Keil and Lash [202] apply analytic network process (ANP), based on the AHP for multi-criteria decision making (MCDM), to illustrate the utility of applying the family of DFX to process design and improvement. They suggest that the next generation of DFX should instead focus on the use of information and multi-criteria decision making that must support the design, that is, a new family of "decision model for X" techniques. To confirm that, Radzwill and Benton [7] examined the utility of DFX in the emerging IoT system. Using AHP methods, the authors identify DFX that are applicable to IoT-related design in order to support actionable strategies for quality and customer satisfaction. The author concludes the need to leverage Big Data to solve problems considered unsolvable and to better address the potential's position of human variability. However, after this exhaustive overview and in order to be aware of the impact of implementing each technique, the next section presents the main DFX applications found in the analyzed papers.

5 DFX applications

Searching for early works on DFX with applications is like mining for gold. In fact, thinking about assembly, manufacturing, quality, safety, serviceability, and environment aspects when designing a product has always been laudable, although not practiced enough or often omitted. In addition, even if designers are aware of the importance of implementing such techniques, they cannot adopt it if they do not have a real-life example. In the following, we present the applications found in the literature for each DFX techniques discussed above.

Design for manufacture and assembly provides some criteria and guidelines to reduce the number of parts, ensures the ease of assembly, and increases the modularity of design [203, 204] [2]. The first application developed was about the redesign of the motor drive while using DFMA technique which reduces the number of items into four instead on 19, reduces the time of assembly from 121 to 64 s, and realizes a total saving of \$15.95. By using the DFMA technique, it was found that the total possible saving in an assembly cost is about 95 cents and the design efficiency is about $4 \times 3\ /\ 121 = 9.9\%$ [2]. Another case study was developed by the same author and Magma Seating group concerning the redesign of a pickup car seat. The car seat initially consists of 105 separate parts made from four different material types and uses several different manufacturing techniques (welding, riveting, screwing, snapping, etc.) The total assembly time is 24 min. After applying the DFMA, the part count is reduced from 105 to 19 and assembly time is reduced from 24 to 1.5 min [205]. A further example shows the importance of DFMA on the design of digital mouse on which the cycle and assembly time is reduced to 15 s instead of 130 s, and the part is reduced from 83 items to 54 items [206]. The last example that shows the benefits of using DFMA is the redesign of Motorola vehicular adaptor which increases the assembly and manufacture efficiency from 4 to 36%. The assembly time was reduced from 2742 to 354 s, while the cost and fasteners are, respectively, reduced from \$217 to \$47 and from 72 to 0 fasteners [3].

Design for service covers the range of disassembly and reassembly operations commonly carried out in service work [56]. However, one important aspect which has a positive influence on serviceability is the DFA. In fact, in the case studies presented above, most of the new part redesigned are not necessarily easier to service. For example, in the redesign of the replacement of a headlamp bulb, after using DFS technique, 32 items are removed and then reassembled in order to replace a relatively inexpensive item which has a high likelihood of failure. The assembly time has been reduced from 8.6 detected in applying DFMA to 2.5 by adding DFS [207]. Another example illustrates the benefits of using DFS on PCB replacement in the pressure recorder. The time base efficiency was about 3.8% when using just DFMA and was about 54.5% when adding DFS, and the average reduction in the number of parts to be assembled is 56% whereas the average reduction in the number of separate fasteners is 72% [3]. A further example of the I-BRE respiration wearable mask shows how DFS can be applied to the product to enhance its efficiency and to achieve customer satisfaction with less environmental impact using SCP platform generated in data-driven manner [78]. The last example applied integrative DFS approach in order to design a new smart lab product service system solution in a mid-sized Portuguese company. The DFS enabled a more customer-centric approach with a focus on solutions within the customer value constellation and enabled also a shift from a product-centric to a holistic system view, both in terms of the organizational network and the customer network [208].

Design for supply chain optimizes the fit between supply chain capabilities and product design. The first application when DFSC was developed is about defining the type of order picking used to deliver the product. The order picking needed to deliver 1000 units per day is quite different from the type of order picking needed to deliver 100,000 units per day. To deal which such differences, the authors used the STORE software with its components PALLET and SIMPICK to deduce the appropriate order picking type needed to store and distribute product [3]. Another example which uses DFSC on various beer can's collages that have been carried out in virtual setting, deploying eye-tracking methodology with package colleges to assure a reasonably realistic product category context [209]. The authors provide some important managerial implications by providing identification of the most conspicuous designs among competing alternatives and reveal what package features affect customer attention. With the same perspective, DFSC and especially design for packaging was used on the BA50 process at IKEA to elucidate how packaging and logistic consideration can have a greater impact in the product development process [210]. Other examples have been carried out on different anonym companies that show the benefits of using DFSC and the impact of product design changes on the scale of process and supply chain [211]. This analysis leads to several propositions: (1) Product design changes that are more substantial and complex will generate more substantial and complex changes in the process and supply chain systems associated with them; (2) the more competitive product design competence a firm seeks, the more flexible, advanced process technologies it will acquire; (3) the more competitive product design competence a firm seeks, the more likely a firm will be to implement collaborative and time-focused supplier practices; and (4) the more competitive product design competence a firm seeks, the more likely a firm will be to achieve product design customization capability [211]. The final example uses ontology of a mechanical industry to show the modeling of the system by adopting DFSC technique. The examined system is composed of a mini-load for case picking and storage operating within a factory warehouse [212].

Design for quality concerns both products and system; it meets customer needs and expectations and even the system by which organizations produce products that meet customer needs and expectations. The first case study that shows the application of DFQ deals with the concept design of a new model of classic Neapolitan coffee maker. From 200 coffee maker prototypes developed from 1987 to 1979, Giromino et al. have proposed two new prototypes that follow DFQ guidelines and meet customers' requirements [213]. By computing several indices, the authors conclude that the "Sofia" prototype is the best prototype concept for that machine. The second use case was about the concept design of the dashboard of a new minicar conceived to make few kilometers, principally in a city and whose users are about 15–22 years old [213]. By following DFQ guidelines, the authors generate the optimal concept with regard to all the quality indices presented in the paper. A confirmation test was also carried out by an expert team in order to verify the efficiency and effectiveness of the new proposal. Further case study concerns the selection of the best architect that follows quality requirements for the design of the new town hall and library for the historical city center of Deventer. The aim of this case study was to investigate by following DFQ principles which aspects of architectural value feature in the judgments made when selecting an architect in the context of a European tendering procedure [214]. The final example is an application of commercial software that organizes files of mechanical solutions by following DFQ principles [3]. The evaluation of the solution obtained by the software is made by an expert system.

Design for safety detects the main sources of humans and process risks linked to the variety of work situation. Sandberg et al. have applied DFS and have presented a list of essential criteria to consider in mechanical equipment, pipes and valves, plumbing, refrigerants, rooftop air conditioners, fan drivers and motors, air distribution, ventilation control, batteries, electrical equipment locations, electric utility commissioning, contractor qualifications, miscellaneous, fire precautions, etc. Another example is related to the power take-off (PTO) drive shaft [215]. The reasons behind choosing this example are the serious problems that they have on human safety [137]. To overcome these problems, the authors propose new safety indicators to compare design solutions from a safety point of view when the risks related to these solutions are identified. By doing so, the level of importance hazard was reduced and the risks factors related to human and environment are limited. DFS was also applied to the re-design of the molded plug cover and cord insulation [216]. In the first design, the placement of the power cord was at the appliance handle which represents a risk for the user and can lead to damage to the insulation and possible electric shock. Whereas in the redesign which applied DFS, the cord attachment is separated from the handle. A further case study has been performed in the context of the FP7 project OPENCOSS in the automotive sector [217]. The goal of choosing this example was to establish a common certification framework for different safety domain to implement DFS principles. The last example was about the Harmony Block of the HKHA public housing project [218]. The simulated framework is used to test the capability of the DFS to capture safety knowledge and has led important implications such as the capacity to represent the virtually real project and the capacity to detect hazard.

Design for environment considers design performance with respect to the environment, health, and safety objectives over the full product and process life cycle. In order to illustrate the DFE principles, Huang presents the selection of materials for the manufacture of bottles [3]. Several hypotheses were assumed such as the bottles are of equal capacity and 1 l will be used to contain soft drinks. These hypotheses have placed additional constraints on the choice of materials in terms of permeability and strength. The analysis results show that the glass used in bottle manufacture is assumed to be 100% recycled whereas the polymers are assumed to be virgin. Another case study related to resin transfer molding (RTM) products is considered. The RTM is a process which involves the transfer of resin into an enclosed mold containing previously positioned reinforcement performs [219]. An analysis with DFE shows that various environmental considerations such as exposure to water, water vapor, or other corrosive environments like low and high temperature, and long-term physical and chemical stabilities can be analyzed and considered when designing such a product. Further case study related to the improvement of an automobile door illustrates the advantages of using DFE [220]. Three doors were compared: Chrysler door at $430, a Buick door at $338, and a Saturn door at $143. Using DFE, several parts were redesigned such as door skin, window frame plastic trim, corner window with moldings, outer window molding, and window regulator mechanism. Through this investigation, the authors illustrate how DFE can improve the design of automobile door with respect to environment virtue.

With a presentation of all these different DFX applications, we provide first for practitioners and especially designers some useful advantages for implementing DFX techniques to achieve improved performance. Second, we present the repartition of applications by sectors (Fig. 7). The figure

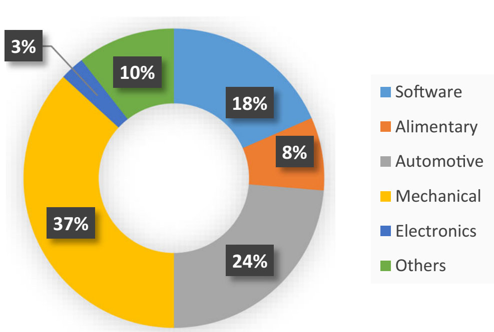


Fig. 7 Repartition of empirical research by industry sector

shows that the majority of applications are related to mechanical products (37%) followed by automotive product (24%) and by software product (18%). The distribution also reveals that the number of applications published on other sectors such as alimentary (8%), electronics (3%), and other different sectors (10%) were minimal. The dominance of the mechanical product could potentially be explained by the fact that DFX was started in this sector. Notwithstanding, this analysis revealed the need for continuous improvements in the vital role of integrated DFX techniques in the product development process especially when there is no application that considers holistically all the DFX techniques presented. The next section highlights gaps in the existing literature as a basis for developing a research agenda.

6 Discussion and future works

DFX is a very complex subject characterized by several factors including systemic, economic, human, social, and environmental ones that have to be considered from a holistic perspective. However, regarding the multiplicity of techniques found in the literature, the volume of papers dedicated to designing the product with integrated factors is still relatively small. In addition, the literature shows that the conditions of use are not or are hardly taken into account during the design phase, which means that there is always a gap between what is imagined in the design and what is experienced when using the product. The previous analysis also revealed the need for continuous improvement in the vital role of knowledge on the product development process. On careful examination, we note that regardless of how a new theory is created, several future direction researches need to be discussed.

First, the majority of DFX studies have revolved around design methods and tools. However, most of the current DFX techniques are insufficient, and cannot be adopted by companies simply because they are too complex, too time-consuming, or may be related to other issues. In other words, the methods do not meet the needs of the users, i.e., the designers. Hence, the methods or tools can be effectively used if the user's requirements are fully considered which means that customers' requirements should be taken into account. In this respect, an important consideration for future research would be trying to better understand the relationships between DFX-based approaches to enable the development and improvement of existing methods by considering both the users and customers' requirements.

Second, several researchers and practitioners have written about the benefits that can be gained from designing products for a specific virtue of life phase. Every paper dedicated to the subject begins with some kind of justification for the research. However, there is a lack of empirical evidence presented in the literature that demonstrates these benefits in practice. The ability of DFX techniques to deliver desired performance results is still lacking too. The case studies and examples such as motor drive [56] do not represent the whole spectrum of the design process. If the designers do not have a real-life example that is relevant to their own work, they will not adopt the model. Consequently, providing more varied and representative case studies will not only enhance the robustness of any DFX investigation but will also provide greater inspiration to a wider variety of industry sector. Thus, there is a need to analyze exactly how and on what DFX technique has an impact in the design process and the various stakeholders involved.

Third, few papers have discussed the advantages of considering life cycle thinking in product design with different DFXs. For example, the authors in Arnette et al [19] have discussed the relationships between different DFX techniques with respect to the life cycle phases and the strategy used by companies. But, they do not present guidelines or methodology that really considers the elements of life cycle thinking. Therefore, one clear direction for future work is the need to incorporate life cycle thinking into the design for X principles.

Fourth, it is apparent from this literature that the methodologies followed by previous researchers have involved the study of the concerned DFX techniques only. This means that the general understanding of the technique has been developed based only on the concerned perspective. For example, in the DFMA, the developed models aimed at solving the problem related just to the manufacture and assembly virtues. They have not considered how these models may fit with the complex design process.

Fifth, the government must support the creation of sustainable information database which can be shared among inventory, environmental impact assessment, safety preventions, human risks, quality assessment, customer's perceptions, and other relevant databases.

Sixth, in a concurrent project, when designing a new product with respect to different virtues, the way that knowledge is used and stored is very important. To have an overview of a project or to remember the collaborative work of past projects is difficult. Only experiment teams can define the fundamental knowledge to store. Thus, designers are lacking knowledge and understanding. Regarding the papers that deal with knowledge management in DFX techniques, the methods are facing many challenges: (1) The global information needed by a centralized system to make decisions is not always available, it cannot provide accurate and timely data to make decisions; (2) the taxonomies existing in the scientific community and in the industry are not shared and structured; (3) the history of the product in major DFX techniques is not capitalized and reused; (4) the vocabulary between disparate people within the same domain is not standardized; and (5) the integrated strategies adopted for market pressure and changing requirements of the industry is not effective. Therefore, one clear direction for future works is the need to incorporate the principles that the fourth industrial revolution (Industry 4.0) gives us such as interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity [221, 222]. In fact, it is recognized by several researchers that Industry 4.0 which is closely related with the Internet of Things (IoT), cyber-physical system (CPS), information and communication technology (ICT), enterprise architecture (EA), enterprise integration (EI), and advancements in other digital technologies such as Big Data and additive manufacturing had a disruptive impact on engineering design [223–229].

Seventh, an important concern is regarding the efficiency and effectiveness of translating experience and information to knowledge that can be deployed within the DFX framework. Benefits from the development of information technology, knowledge sharing, and the information exchange can have a clear impact on product/process design and can be used in support of DfX applications. In fact,

- With the Internet of Things, data can be used to optimize manufacturing processes, often through engineering adjustments. It is able to (1) offer advanced connectivity of physical objects, systems, and services, enabling object-to-object communication and data sharing [230]; (2) improve the quality of human life by enabling ambient intelligence, ubiquitous communication, and increased processing capabilities [231]; (3) support stakeholder's actions by improving its productivity as well as improving collaborative work [232]; and (4) design a real-time information in integration service in order to reduce traffic congestion and improved energy efficiency [233, 234].
- Cloud computing refers to delivering computational services through visualized and scalable resources over the internet [235, 236]. It can provide opportunities for designers to test, learn, experiment, and innovate [237]. It can also model manufacturing resources and capabilities as well as service configuration [238, 239]. Besides, the significant benefits of cloud computing and critical challenges affect the reliability of these concepts such as privacy and security [240, 241], the scalability and availability [242], data management [243, 244], load balancing [245], interoperability, and communication between cloud [246].
- Another important issue is to embrace Big Data analytics for optimizing performance at every stage of development, from design through recycle or/and disposal [247]. It is also needed to identify and analyze consumer trends, which can directly impact what engineers make and how they make them. For example, an automobile company can launch a "facelift car" that will satisfy customers more than before, by mining history orders and user feedback [248]. By processing Big Data, a manufacturer can

discover critical parameters that have the greatest impact on quality or yield variation [249] such as reducing process flows [249], assessing and prediction number of returns in the future [250], minimizing product escapes, driving quality and reducing cost in development process [248], and eliminating yield variation [249].

Eighth, the use of intelligent DFX systems can play a significant role in DFX research and development. In fact, the emerging field of artificial intelligence (AI) and the knowledge that engineering offers will allow designers to produce symbolic reasoning on computers. These techniques allow designers to model intuitive knowledge, judgment and experiences that expert designers use, and to integrate them into available quantitative tools [251, 252]. However, the research on intelligent DFX systems is still in its infancy [203]. Researchers should explore the use of different algorithms in machine learning and pattern recognition techniques, such as fuzzy logic, neural networks, genetic algorithms, and case-based reasoning in DFX. The use of these techniques could hold the key to transforming factories of the near future and will allow the design process to become more reliable, more flexible, will reduce labor costs, and improve productivity. Hence, not only engineers need to redesign processes and operations to accommodate these new advances, Industry 4.0 impacts how they design products for increasingly smart manufacturing facilities.

As a summary, DFX implementation should not be based on voluntary action but rather on a mandatory action. The application of DFX should be explored simultaneously for an improved understanding of product design and need to integrate the key concept drivers of the Industry 4.0 revolution. This endeavor can potentially illuminate several critical issues within DFX that are currently rare in design literature. Thus, it enables companies to cope with the challenges of producing increasingly individualized products with a short lead time, higher quality, and sustainable consideration. More precisely, the implementation of integrated DFX techniques needs the consideration of the following points:

- A systematic identification of user's and customers' requirements.
- The life cycle thinking must be incorporated into the design for X principles. After that, the method should present a comprehensive measure of goodness of a design such as estimating life cycle cost or time.
- Each method needs several case studies and examples to analyze exactly how and to what DFX technique has an impact in the design process.
- Product development process requires more sensors, actors, and autonomous systems in order to respond to the quick development of technologies that arise with Industry 4.0 revolution.
- Product design needs a holistic perspective that integrates different DFX techniques with different Industry 4.0 technologies to allow human beings to communicate with products.
- Design in data collection systems would allow the part to gather information from each machine and record each process that it goes through. It could be then reviewed as a part of the quality control process and enable actors to point any issues within the system or help identify areas that could be improved.
- The consideration of intelligent manufacturing products allows to achieve a flexible, smart, and reconfigurable development process to address a dynamic and global market. This can enable direct communication with product development actors, thereby allowing problems to be solved and adaptive decisions to be made in time, as well as by allowing the system to learn from experiences to realize a connected, intelligent, and ubiquitous industrial practices.
- A knowledge-based method that encompasses knowledge associated with not only our understanding of the product features but also with its life cycle issues is very useful to designers. The emerging field of artificial intelligence and the knowledge that engineering offers will allow designers to produce symbolic reasoning on computers. These techniques allow designers to model intuitive knowledge, judgment, and experiences and to integrate them into available quantitative tools.

7 Conclusion

This research on the current state of the DFX literature revealed a number of trends and deficiencies. Using journals, books, and conference papers published from the past 38 years, the "current understanding" of what DFX means, what it involves, and who it involves has been discussed. In fact, the fourth step was conducted. The first step aims to collect enough appropriate publications related to DFX techniques linked to sustainable dimensions. The DFX techniques are also discussed with respect to the strategy that companies pursue. This makes a contribution by giving practitioners a framework to decide which DFX techniques are applicable to a given product design with a given strategy. Afterward, considering the Newbert methodology which is based on four criteria, the literature selection was comprehensive, and as a result the analysis of over 142 papers. DFX techniques are thoroughly analyzed by investigating the past and current researches of each DFX as well as for integrated ones.

Following this presentation of the state of the art, future investigations that would enhance our understanding of DFX are identified. One among them is the need to develop a new design tool that provides an exact answer of customer's requirements and facilitates internal communication of data and results within the product development project. However, the most significant finding is the need to address the question of how designers can share, capitalize, and re-use knowledge in an effective and reliable way by considering integrated DFX techniques into the overall product life cycle and how designers become context-aware and provide added-value information to improve the monitoring of operations and their performance. In this respect, knowledge management (KM) practices provide a conceptual and methodological framework that enables considering these issues. This requires ontology which is considered as a relevant method for representing knowledge in a machine interpretable way. As an emerged strategy associated with AI and natural language processing (NLP), it is concerned with the representation, organization, acquisition, creation, and evolution of knowledge in its many forms. Besides, its modular architecture allows describing different design virtue capabilities of DFX resources in different levels of modularity. In addition and in order to support the interoperability between different domain ontologies and actors, to increase communication and collaboration within and across DFX disciplines, the alignment of the context of ontologies with high level ontologies will be crucial. As the automotive sector is regarded as one of the most challenging, important, and strategic industries in the manufacturing sector, we are going to present in a future paper a conceptual framework that supports knowledge capitalization and enables the consideration of the six DFX techniques discussed in this paper. The consideration of the integrated DFX techniques will be applied to the redesign of a specific mechanical product used in the automotive sector while considering assembly, safety, service, supply chain, quality, and environment virtues. This case study will be developed in order to apply and test the proposed solution in a concrete scenario.

Given the challenges facing product engineering, which are increasing complexity in breadth and depth, manufacturing companies need not only to adopt flexible solutions but they must also innovate constantly and manage different challenges with different factors Xs by managing the massive and intensive data that appears with Industry 4.0. Thus, Big Data management which considers data mining, data classification, and data storage becomes a large challenge. However, in order to make the product better suited in all the life phases and increase the general product virtues with respect to cost, functionality, manufacturability, assembly, security, reliability, quality, serviceability, and environmental issues, there is the need to embrace the benefits of Industry 4.0 technologies. In fact, cloud architecture can be used for analyzing data depending on the security and safety structures, artificial intelligence can be used for deriving responses that approximate human experience and know-how, and machine learning algorithms to predict data to be acquired in the future. Machine learning for data mining associated with artificial intelligence and cloud services is a direction for future research.

Appendix

Table 2 Description of papers used the section literature review of selected DFX techniques

	References (DFMA)	Description
Design for manufacture and assembly	Stool et al. [44]	Guidelines to ensure good design practices are presented. This framework facilitates the manufacturing process and provides cost estimates early in design phases.
	Knight et al. [36]	A spreadsheet approach to rating design based on their ease of automatic assembly
	Boothoroyd and Dewhurst [2]	The lowest assembly cost can be achieved by designing a product in such a way that it can be economically assembled by the most appropriate assembly system.
	Dewhurst and Blum [34]	An economic model of the die-casting process is established to consider the optimum number of cavities, appropriate machine sizes, etc.
	Suh [31]	Decoupling the independence of functional requirement to have a controllable effect and a minimal negative impact on specific functional requirements in design.
	Boothoroyd and Dewhurst [56]	Combining manufacture issues with assembly issues in one method in order to reduce at the same time cost, errors, and time to market.
	Fabricus and Lautitzen [45]	A set of guidelines to enhance the linkage between design and manufacturing using a model with three dimensions.
	Huang [3]	A matrix approach to represent various types of modules (component swapping, component sharing, and bus modularity, etc.) is presented.

Table 2 (continued)

	References (DFMA)	Description
	Tsai and Wang [32]	Modular design in the conceptual stage using fuzzy cluster identification. It supports concurrent engineering based on the fact that the functions are classified into different types of modules according to the correlation in design.
	Fazio and Schwen [40]	An assembly sequence analysis (ASA) method, which tackles complex assemblies in two steps is presented.
	Asar and Day [121]	A knowledge-based design methodology (KBDM) for automated assembly lines is presented. The method can be applied to single, multi-, and mixed product assembly lines with either deterministic operation times or stochastic operation times.
	Becker et al. [53]	Surveys of the generalized assembly line balancing problem (GALBP).
	Zhao et al. [57]	A rule-based expert system, which concurrently considers product design and process planning by including six functions in the system: knowledge: conceptual design (CD), computer-aided design (CAD), design for manufacture (DFM; design for assembly (DfA), assembly system design (ASD, and assembly planning (AP).
	Bukchin and Masin [41]	Design methodology for assembly systems based on teams, where each team is semi-autonomous with well-defined responsibilities.
	Lin et al. [42]	Contact relation matrix (CRM) approach to generate an assembly sequence for product design.
	Xiao et al. [50]	A collaborative multi-disciplinary decision-making (CMDM) methodology for design for manufacturing (DFM) by considering the three design challenges: exchange of information, accommodating interactions between activities, and maintaining feasible and satisfactory overall designs.
	Möttönen et al. [6]	The role that management plays in facilitating DFM practices through a case study of an international communications technology firm
	Holt and Barnes [51]	A numerical model of the dye-sensitized solar cell (DSSC) is used to explore factors influencing device performance.
	Nee et al. [46]	Review the research and development of augmented reality (AR) applications in design and manufacturing.
	Salonitis [37]	A framework for the simultaneous modular product design and the design of an automated manufacturing system using design structure matrix and modular function deployment.
	Benkanoun et al. [38]	An architecture framework that establishes a common practice for creating, analyzing, and representing manufacturing systems during design and re-design processes.
	Holzner et al. [49]	A systematic design approach focusing on SME requirements, which were carried out by a questionnaire survey of a sample of several manufacturing SMEs in Italy.
	Thorsten et al. [52]	State of the art in gathering and evaluating product usage and life cycle data, additive manufacturing and sensor integration, automated design, and cloud-based services in manufacturing.
	Favi et al. [43]	An approach investigating how the application of DFA affects the material and manufacturing costs. A complex product which is "tool-holder carousel of a CNC machine" is used as a case study.
	Uglert et al. [53]	A design model of RCMS that allows automated design and analysis of system configurations based on computational design synthesis (CDS).
	Erwin Rauch et al. [54]	A framework of possible network models for distributed manufacturing networks of smart and agile mini-factories is provided and enforced by examples from industrial practice.
	Oh and Behdad [47]	A review of the literature on re-designing an original model into assemblies produced in additive manufacturing (AM), named Par decomposition (PD)
	Thompson et al. [39]	An industrial case study of late engineering changes (EC) in high-speed product development. It proposes a framework with a set of key performance indicators (KPI) to measure and improve producibility and product quality throughout the product development process.

Table 2 (continued)

	References (DFMA)	Description
Design for service	Kimura [70]	An approach for designers to estimate customer satisfaction and compare design options at the conceptual stage.
	Song and Fields [68]	"Industrial customer activity cycle" is presented by using the subjectivity and vagueness in a fuzzy context.
	Alexander et al. [81]	The lack of continuous simulation methods, especially system dynamics, in the computer simulation of manufacturing systems.
	Berkovich et al. [67]	Describe and classify various requirements and their interrelationships according to the design process in a requirement data model (RDMod) for PSS.
	Lee and Brown [85]	A system dynamics (SD) to deal with the dynamics and triple bottom line (TBL) to encompass the multi-dimensionality of PSS sustainability.
	Zhang et al. [170]	Framework for knowledge management and reuse in construction machinery industry with four layers: application, process task, representation, and shared layers, and the proposed framework was validated through an expert interview and a case study.
	Hu and Bentler [86]	A framework to evaluate the sustainable performance of PSS with fuzzy Delphi method to identify criteria consistency and fuzzy analytic hierarchy process to determine weights of the selected criteria.
	Bianchi [79]	A qualitative system dynamics (including profits over the whole life cycle, low environmental impact, and localization of services) to improve the product-oriented market mode.
	Baxter [83]	A method for knowledge reuse in PSS design context, aiming to collect, represent, and reuse knowledge to support product development.
	Autich and Fuchs [74]	A service design process based on three main strategies for combining the product with related service.
	Michelini and Razzoli [75]	Sets of technology-driven developments are considered based on four independent factors while setting aside economic, social, legal, and political considerations.
	Xing et al. [87]	A sustainability-oriented value assessment model based on life cycle thinking, in which the fitness for extended utilization indicators, the net present value (NPV) approach, and life cycle assessment (LCA) were applied as the measures for value assessment.
	Rexfelt and Hiort af Ornäs [72]	The conditions for users to accept a PSS and proposed a PSS developing approach
	Afshar and Wang [80]	An SD approach for sustainable product-service system to solve the complicated structure in PSS design
	Johansson et al. [82]	Analyzed the concept of knowledge maturity as a means to provide decision support and increase decision makers' understanding of the knowledge base.
	Hoogen et al. [73]	A method of combining the net present value (NPV) approach and the real options approach (ROA) to determine the quantified value of the IPS2 framework to meet the needs of both users and markets.
	Carreira et al. [69]	Combined customers' experience requirements in the design of PSS with the extension of Kansei Engineering by an in-depth study of the customer experience and active participation of inter-company experts.
	Schotman and Ludden [71]	Users and manufacturers need to change their habits to put forward the successful implementation of PSS.
	Carvalho et al. [76]	How contemporary ideas on individual, group, and network-wide learning can benefit research on services and service innovation
	Baek et al. [77]	A framework for developing service design goals and strategies to faster collaboration within a community, starting from an understanding of its collaboration network.
	Zheng et al. [78]	A systematic design framework for its service innovation with an elaborated case study of a personalized smart wearable. The paper presents a novel definition of smart PSS.

Table 2 (continued)

	References (DFMA)	Description
Design for supply chain	Arntzen et al. [89]	A DFSC analysis at Digital Equipment Corporation to minimize cost and time. This model was used in the design of 20 new products and helped achieve a reported savings of $1 billion in 4 years with approximate unit production improvements around 500%.
	Lee and Sasser [97]	A DFSC model, which HP used during the development of a new product to determine the optimal product differentiation point and to avoid high inventory stock out and long lead times.
	Bloemhof et al. [106]	A generic facility location model to analyze the impact of product return flows on logistics networks.
	Spengler et al. [102]	The development of sophisticated operations research models for two selected planning problems: recycling of industrial by-products and dismantling and recycling of products at the end of their lifetime is presented.
	Handfield et al. [92]	A detailed survey to determine whether particular quality management, supply base management, and customer relations practices can impact corporate performance.
	Dowlatshahi [108]	A holistic view of reverse logistics from the existing literature and published case studies are presented and analyzed.
	Guide [111]	A survey of production planning and control activities at remanufacturing firms in the USA is presented.
	Ferguson and Browne [110]	A review of the literature on the end-of-life product recovery and inventory management issues in reverse supply chains and to outline some future directions for research on these issues.
	Jayaraman et al. [103]	A background to better understand the trends of environmental management and operations. The authors argued that it is moved from local optimization of environmental factors to consideration of the entire supply chain during the production, consumption, customer service, and post-disposal disposition of products.
	Graves and Willems [98]	A supply chain design model for a product that has already been designed. They created a large designed experiment to test for several different factors that can be considered as risks. The experiment included 810 different supply chain configurations with varying cost-accrual profiles, time accrual profiles, demand values, standard deviations of demand, and holding cost rates.
	Sharifi et al. [90]	A theoretical framework for operating in a DFSC environment. They also provided a case study, which proved that it is more effective to operate in a DFSC manner as opposed to designing the new product and supply chain separately.
	Gokhan [95]	Model which included manufacturing costs, customer satisfaction, demand generation, inbound supply chain operation, and maximized profitability over the entire life cycle of the product.
	Wojanowski et al. [102]	A continuous modeling framework for designing a drop-off facility network and determining the sales price that maximizes the firm's profit under a given deposit–refund is presented.
	Aras and Aksen [104]	A mixed-integer non-linear facility location-allocation model to determine both the optimal locations of the collection centers and the optimal incentive values for each return type is presented.
	Sasikumar and Kannan [107]	Authors analyze the interaction of criteria that is used to select the green suppliers who address the environmental performance using interpretive structural modeling (ISM) and analytic hierarchy process (AHP).
	Kumar et al. [105]	Include the plant location and capacity decision, shipping channels, and product pricing. Their DFSC problem is solved using a genetic algorithm
	Droge et al. [94]	This study investigates the role of supply chain integration in mediating the effects of product and process modularity strategies on service performance.

Table 2 (continued)

	References (DFMA)	Description
	Erin Claypool [100]	A hybrid approach which was a combination of extensions to the framework and a new simulation model. The MIP obtains the optimal product design and supply chain while simultaneously analyzing TTM risks, supplier reliability, and strategic exposure risk.
	Chen et al. [101]	A two-stage stochastic closed-loop supply chain design model that incorporates the uncertainties in the market size, the return volume, as well as the quality of the returns.
	Zhang and Mao [55]	A new design methodology for HES green cellular networks with the help of Lyapunov optimization techniques is presented.
	Jindal and Sangwan [91]	A fuzzy-based multi-criteria decision-making framework has been proposed for the evaluation of alternate product recovery processes.
	Zhu and He [112]	How supply chains' decisions on the "greenness" of products are affected by factors such as supply chain structures (centralized and decentralized), the green product types (development-intensive product or marginal cost intensive product), and the types of competition (price competition and greenness competition).
	Brewer [96]	The tie of design initiatives in the areas of lead time reduction, standardization, core competence–focused sourcing, ESI, maintaining existing supply bases, and environmental sourcing to product performance.
	Kanchan Das [113]	The antecedents, enablers, and ingredients of sustainable supply chain based on the literature. It also identifies practices and outcomes of lean-based systems that may be applied to supply chain functions in the perspectives of established sustainability criteria
Design for quality	Koch et al. [116]	A mathematical model to improve the structural reliability and robust design of the product.
	Zairi [124]	Consider three types of benchmarking: internal, external, and generic.
	Taguchi [115]	Three stages in a product development: system design, parameter design, and tolerance design.
	Suh [31]	The role that plays quality on the product success and the fact that quality needs to be designed into the product
	Savage [117]	Probability constrained optimization (PCO) function as a tool for design for six sigma (DfSS) with three stages.
	Hlatky et al. [131]	Software of DFQ that follows four major steps: (1) determine functions, (2) determine archives, (3) determine characteristics, and (4) evaluate solutions.
	Das et al. [126]	Reduction on defects in the production process in DFQ.
	Swink and Calantone [127]	A structural equation modeling is used to test the potential of design-manufacturing integration (DMI) as a mediator of the effects of project organization complexity and technology novelty on product design quality.
	Kaymaz and McMahon [118]	Response surface method (RSM), which replaced probabilistic constraints with response functions to save time in structural reliability analysis.
	Omayma and ElMaraghy [128]	A hierarchical fuzzy inference system was developed for modeling the relationship between manufacturing system design parameters and the resulting product quality level.
	Mukhopadhyay and Setaputra [120]	A dynamic profit maximization model to jointly obtain optimal policies for the product quality level, price, and the return policy over time.
	Khan et al. [121]	An integrated single class–based metric called weighted class complexity (WCC) for object-oriented design. The proposed metric could be used to provide an overall quality assessment of object-oriented software system in the early stage of development life cycle.
	Johannes Freisleben [129]	An approach that provides a rationale for investments in design quality improvement, a complement to the economic analysis of production quality, and inspiration for future empirical studies.
	Ovaska et al. [122]	An approach with supporting tools enables the systematic development of high-quality software by merging the benefits of knowledge modeling and management, and model-driven architecture design enhanced with domain-specific quality attributes.

Table 2 (continued)

	References (DFMA)	Description
	Strug [123]	A kernels graph approach that assists the designer in dealing with evaluating the quality of a design. Especially, spatial relationships and arrangements of components within a design dealt with.
	Hubert et al. [119]	Using polynomial regression response modeling as well as Monte Carlo simulations for error propagation, design space (DS) was computed in order to determine robust working conditions for the developed stability-indicating method.
	Gu et al. [130]	The environmental consequences of designing for remanufacturability by defining a measure of environmental impact and applying it to assess the environmental impact associated with the firm's optimal strategy relative to the environmental impact associated with the firm's otherwise optimal strategy if a non-remanufacturable product were designed and produced.
	Neumann et al. [125]	A systematic review of studies providing evidence of the linkage between human factors (HF) in the design and management of operations to production quality performance was conducted.
Design for safety	Tarrants [142]	Explain that the term "indicator" in the safety field is rather new: Although safety measures were undertaken in the 1980s and before, these attempts used terms such as "index," "rate," and "measurements."
	Harms-Ringdahl [143]	An analysis process with seven steps to ensure safety during process (safety policy, obtain information required for hazard analysis, identify hazard using one or more safety analysis methods, evaluate the hazard identified, etc.)
	Stoop [141]	Safety becomes explicit in the design process at three decision points: (1) the selection of relevant use scenarios, (2) the selection of a technological principle and energy source, and (3) the third decision is that of which hazards must be dealt with and thus which hazard patterns.
	Schein [147]	Defined organizational structure culture as a set of observed behavioral regularities, group norms, espoused values, formal philosophy, and rules of the game, climate, embedded skills, and habits of thinking, shared meanings, and root metaphors.
	Begg et al. [151]	A distributed design approach that combines an ergonomic approach with an FA, and which places the emphasis on hazard identification and analysis in man/machine systems.
	Marsot and Claudon [147]	An approach based on TRIZ, FA, and QFD to integrate ergonomics in design. They believe that FA allows ergonomists to take part in drafting specifications for the product to be designed and to formalize ergonomics-related expectations.
	Harms-Ringdahl [143]	Technical safety features, nature, and characteristics of the hazards, formal safety organization systems, and ergonomic consequences is highlighted.
	Ghemraoui et al. Tricot [138]	Innovative risk assessment design (IRAD) methods that consist of a general suggestion for systematic risk identification and human safety integration in the early design phase. It considers design as an iterative activity between a design process and a risk process.
	Huang et al. [144]	An overview of research on safety indicators. They believe the research on indicators started with the need to measure safety or risk.
	Village et al. [149]	An approach based on FMEA tools to address, concurrently and for the same failure, its consequences on product quality and on operator safety.
	Houssin and Coulibaly [148]	An innovative approach aimed at eliminating these contradictions in order to improve product performance. Base on four steps, they demonstrated the possibility of using the features and the inventive principles of contradiction to solve the safety problem.
	Sun and Gardoni [150]	Global view of the behavioral design approach (BDA) to help designers to analyze the interaction between user tasks and technical tasks, to evaluate system performance, and to find potential hazards.
	Cicardi et al. [152]	An analysis of four acquired types of hereditary angioedema data is conducted to classify angioedema.

Table 2 (continued)

	References (DFMA)	Description
	Sadeghi et al. [16]	The objective of the study was to measure human safety when using a system during its design process. The proposed safety indicator depends on two values indicating the presence or absence of danger and the level of importance of hazardous conditions.
	Jin et al. [146]	The authors identify hNPCs as a direct ZIKV target. In addition, we establish a tractable experimental model system to investigate the impact and mechanism of ZIKV on human brain development and provide a platform to screen therapeutic compounds.
Design for environment	Cristofari et al. [169]	A methodology called green QFD which considers quality requirements, environmental impact, and production costs at the design phase.
	Zhang et al. [147]	Improve the green QFD by developing a new methodology called green QFD II which combines life cycle analysis (LCA) and life cycle costing (LCC) into QFD matrices and provides a mechanism to deploy customer, environmental, and costing requirements throughout the entire product development process.
	Veerakamolmal and Gupta [178]	A review of techniques used to design for disassembly, reuse and recycling (DfDRR) is explored. It guides product designers toward a specific design goal.
	Blanchini and Miani [184]	The problem of controlling the molten metal level in continuous casting processes with particular reference to high-speed slab casters with large-sized mold is presented. The main objectives are to achieve robust stability and good disturbance rejection.
	Mehta and Wang [171]	Green QFD III simplifies the detailed LCA and complex product comparison algorithm of Green QFD II
	Santos-Reyes and Lawlor [173]	Develop a four-phase methodology. In phase 1 and phase 2, eco-profile strategies are defined and prioritized using analytic hierarchy process (AHP). In phase 3 and phase 4, eco-performance strategies are identified and associated with eco-profile strategies using QFD.
	Madu et al. [172]	A step-by-step approach for environmentally conscious design. First, AHP is used to prioritize customer requirements. Then, QFD is used to match design requirements for customer requirements. A cost-effective design plan is finally developed by applying Taguchi experimental design and Taguchi loss function.
	Lye et al. [177]	Develop a computer-based design evaluation tool, called ECoDE, to assess the environmental impact of components in a product. ECoDE employs AHP for the comparison and ranking of each criterion.
	Knight and Curtis [185]	Describe a software tool which quantifies the economic and environmental effects of the disassembly by simulating the disassembly process.
	Kuo and Wu [174]	Apply QFD to translate customer needs into the six categories of environmentally technical measures. Then gray relational analysis (GRA) is employed in this QFD matrix to determine the best design alternative based on the product's life cycle.
	Kuo et al. [182]	A hierarchical structure of the environmentally conscious design indices by using AHP. Then, fuzzy multi-attribute decision-making model is used to select the best design alternative.
	Hopkinson et al. [186]	Present the application of a DFE software in a rapid manufacturing environment.
	Boks and Stevels [193]	Emphasize the fact that dissemination of DFE information requires the consideration of the intended audience and relevant contexts.
	Johansson et al. [192]	Investigate the different mechanisms for their potential to support integration between product designers and environmental specialists.
	Bevilacqua et al. [180]	A methodology for integrating DFE and life cycle assessment LCA techniques both into the new product development and into the process of redesigning existing products.
	Sakao [175]	Extends the Masui et al. (2003) by integrating LCA and TRIZ (theory of inventive problem solving) into QFD.

Table 2 (continued)

	References (DFMA)	Description
	Bovea and Wang [176]	DFE methodology which integrates QFD, LCA, LCC, and contingent valuation techniques for the evaluation of the customer, environmental, cost criteria, and customer willingness to pay, respectively.
	Mathieux et al. [189]	Develop a recovery-conscious design method for the multi-criteria and quantitative analysis of the recoverability of complex products.
	Park and Tahara [190]	Consider the quality, environmental, and customer satisfaction–related aspects of products by using producer-based eco-efficiency (PBEE) and consumer-based eco-efficiency (CBEE).
	Mascle and Zhao [191]	Use FL and feature modeling to evaluate parts together with the disassembly efficiency and liability.
	Platcheck et al. [194]	Define a new product development methodology comprising of four phases: briefing phase, development phase, projection phase, and communication phase. They insert environmental criteria into the different phases of the methodology.
	Li et al. [183]	Using the fuzzy graph, a graph-based clustering algorithm recommends a modular design based on minimization of the difficulty involved in disassembly and recycling of the EOL products.
	Qian and Zhang [179]	Develop a methodology for environmentally conscious modularity assessment of electromechanical products by using fuzzy AHP.
	Haschim and Denan [187]	The importance of preserving the natural environment of design schools, based on the analysis of observation and questionnaire surveys are investigated.
	Ghazilla et al. [188]	A practitioner's perspective to investigate the current state of DFE and DFD among manufacturers in the local Malaysian industry.
	Younesi and Roghanian [181]	An integrated QFDE fuzzy Decision Making Trial and Evaluation Laboratory (DEMATEL) and fuzzy analytic network process (FANP) is proposed for sustainable product design to help companies identify the best design criteria for a specific product.
	Liu et al. [195]	A number of backward and forward methods for inverse design are investigated. Backward methods, such as the quasireversibility method, pseudoreversibility method, and regularized inverse matrix method, can be used to identify contaminant sources in an enclosed environment
	Rio et al. [196]	Parameter network model is used to follow the emergence of environmental parameter linkage with product designer expertise's parameters. An industrial cooker hood design process case study explores the co-creation of local environmentally aware knowledge between product designers.

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