Design for manufacturing and assembly methods in the product development process of mechanical products: a systematic literature review

Design for Manufacturing and Assembly methods in the product development process of mechanical products: a systematic literature review

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Abstract

The DFMA is a family of methods belonging to the Design for X (DfX) category which goal is to optimize the manufacturing and assembly phase of products. DFMA methods have been developed at the beginning of the ‘80s and widely used both in academia and industries since then. However, to the best of the authors' knowledge, no systematic literature reviews or mapping have been proposed yet in the field of mechanical design. The goal of this paper is to provide a systematic review of DFMA methods applied to mechanical and electro-mechanical products with the aim to collect, analyse and summarize the knowledge acquired until today and identify future research areas. The paper provides an overview of the DFMA topic in the last four decades (i.e., from 1980 to 2021) emphasizing operational perspectives such as the design phase in which methods are used, the type of products analysed, the adoption of quantitative or qualitative metrics, the tool adopted for the assessment, and the technologies involved. As a result, the paper addresses several aspects associated with the DFMA and different outcomes retrieved by the literature review have been highlighted. The first one concerns the fact that most of the DFMA methods have been used to analyse simple products made of few components (i.e., easy to manage with a short lead-time). Another important result is the lack of valuable DFMA methods applicable at early design phases (i.e., conceptual design) when information is not detailed and more qualitative than quantitative. Both results lead to the evidence that the definition of a general DFMA method and metric adaptable for every type of product and/or design phase is a challenging goal that presents several issues. Finally, a bibliographic map was developed as a suitable tool to visualize results and identify future research trends on this topic. From the bibliometric analysis, it has been shown that the overall interest in DFMA methodologies decreased in the last decade.

Keywords:

Design for Manufacturing; Design for Assembly; Design for Manufacturing and Assembly; DFA; DFM; DFMA; engineering design; product development; systematic review;

1 Introduction 5
2 Materials & Methods 6
2.1. Definition of research questions 6
2.2. Definition of search process 6
2.3. Definition of criteria for article sorting 7
2.4. Execution of data extraction and classification 8
2.5. Execution of analysis 9
2.6. Bibliometric Analysis 9
3 Results of the literature review 10
3.1. Results related to the general questions 11
3.1.1. Field of application and products analysed by DFMA methods 11
3.1.2. Product design phase challenged by DFMA methods 13
3.1.3. Future challenges to address by using DFMA methods 14
3.2. Results related to the focused question 15
3.2.1. Qualitative vs. quantitative DFMA methods 15
3.2.2. Tools used to support DFMA methods 18
3.2.3. Industry 4.0 enabling technologies challenging DFMA methods 19
4 Limitations 31
5 Discussion 31
6 Conclusion 33
References 36

B&D
Boothroyd & Dewhurst; 5; 9; 13; 14; 15
DFA
Design for Assembly; 5; 7; 14
DFM
Design for Manufacturing; 5; 7; 14
DFMA
Design for Manufacturing and Assembly; 2; 5; 6; 7; 8; 9; 11; 13; 14; 15; 17; 18; 19; 20; 31; 32; 33; 34
DfX
Design for X; 2; 5
KPI
Key Performance Indicator; 15
nPDP
new Product Development Process; 5
PCB
Printed Circuit Board; 7
PDP
Product Development Process; 13

1 Introduction

The DFMA is a family of methods belonging to the *Design for X* (DfX) category which goal is to optimize the manufacturing and assembly phase of a product. DfX methodologies are used to improve specific aspects of the product under development. The *X* is generally substituted with the optimization goal, and these methodologies are used to support the product development process (PDP). DFA is a systematic procedure aiming at the reduction of assembly time through the following actions: (i) reduction of the overall number of components in a given assembly, and (ii) elimination of critical assembly tasks (Boothroyd, 1987). DFM is an engineering practice that seeks the simplification of the manufacturing process for cost reduction of a given component through the following actions: (i) selection of raw material type, (ii) selection of raw material geometry, (iii) definition of dimensional and geometrical tolerances, (iv) definition of roughness, (v) characterization of specific shape constraints based on the manufacturing process, and (vi) selection of secondary processing such as finishing (Favi et al., 2016b).

DFMA methods have been around for many years. The first DFMA method is dated back to the ‘80s since it was noticed that a positive impact is obtainable on the overall costs if the manufacturing and assembly phases were challenged. Among the several methods developed on this aim, three approaches have been mainly used both in academia and industry: (i) Boothroyd & Dewhurst (B&D) (Boothroyd & Dewhurst, 1987), (ii) Hitachi (Leaney & Wittenberg, 1992), and (iii) Lucas method (Lucas Engineering Systems Ltd., 1993). Despite the quite long history of this subject, only a few papers present a literature review about DFMA methods. For instance, Gao et al., (2020), Ginting et al., (2020), and Wasim et al., (2020) proposed a review of DFMA methods in the building sector which shows different features compared with the mechanical products considered in this review. Regarding mechanical products, four reviews were focused on DFM methods (Kuo & Zhang, 1995; Youssef, 1994; Stoll, 1986; Carlsson & Egan, 1994), six on DFA methods (Sackett & Holbrook, 1988; Kuo et al., 2001; Bogue, 2012; Booker et al., 2005; Xia et al.,a.2013; Xia et al.,b.2013), and four on DFMA methods (Boothroyd, 1994; Agyapong-Kodua et al., 2013; Battaïa et al., 2018; Naiju, 2021). By the analysis of these works, three main limitations have been identified. The first one concerns the fact that the majority of reviews are dated (conducted more than 15 years ago), and missing information about current DFMA methods and trends is noticed. The second one deals with the fact that some reviews have been published in conference proceedings and only limited outcomes are provided. Finally, the third limitation concerns the review methodology. The available reviews lack a systematic approach, not allowing the reproducibility and replicability of the review process. Although DFMA methods are widely used both in industrial and academic fields, there are no recent reviews on this topic for mechanical applications.

The goal of this paper is to provide a systematic review of DFMA methods applied to mechanical products. The systematic review was conducted to collect, analyse, and summarize the knowledge acquired until today, as well as to identify future research areas, following the results of relevant researches on this subject to answer specific research questions. Two clusters of research questions were identified by the authors: general questions (GQs), and focused questions (FQs). Each cluster presents a list of questions that are used to drive the review and to identify specific topics associated with the DFMA subject. The following topics were covered by this review: (i) the industrial fields and the type of products covered by DFMA methods, (ii) the mapping of the DFMA methods in relation to the product development phases, (iii) the identification of trends and challenges for DFMA methods, (iv) the metrics used to analyse the results of DFMA methods, (v) the design tools implemented in compliance with DFMA methods, and (vi) the use of Industry 4.0 enabling technologies in the development of DFMA methods.

In the following section (Materials & Methods) the method proposed to perform the systematic mapping is described in detail along with the chosen research questions. Then in the section Results of the literature review, the outcome of the performed review is reported showing data used to answer the research questions. A section (Limitations) explaining the limitations of the proposed review is presented, followed by a discussion of the obtained results (Discussion). Finally, the last section (Conclusion) summarizes the outcome of the review and highlights future research trends for DFMA methods.

2 Materials & Methods

The method used to conduct the study is composed of five phases: (i) definition of the research questions, (i) definition of the search process, (iii) definition of criteria for article selection, (iv) execution of data extraction and classification, and (v) execution of the analysis The following part of this section describes each phase in detail, including how the literature review was performed.

2.1. Definition of research questions

For the development of this review, the following questions were obtained with a top-down approach. Research questions concerning DFMA methods were divided into two clusters GQs and FQs. The first cluster gives an overview of the research field, providing specific application fields and design phases in which DFMA methods have been applied the most, including future challenges of the studies that employ DFMA methods. The second cluster analyses technical aspects of DFMA methods, such as the method type, the tool used for computational reasons, and if Industry 4.0 enabling technologies were implemented. Table 1 reports the research questions defined for this review.

Table 1 - Research questions

General Questions		***Area***
GQ1	In which mechanical field industry DFMA methods are mainly used?	Application field
GQ2	In which design phase are DFMA method used?	Design phase
GQ3	What are the future challenges for DFMA methods?	Future challenges
Focused Questions		***Technical aspects***
FQ1	Is the DFMA method used quantitative or qualitative?	Method type
FQ2	Which tools are used to implement DFMA methods?	Computational Tool
FQ3	How DFMA and Industry 4.0 enabling technologies are consolidated (i.e., Artificial Intelligent, Virtual Reality, etc.)?	Technological advancements

2.2. Definition of search process

Since the first research activities and applications about DFMA methods are dated back to the early ‘80s, this review was conducted considering all papers published between 1980 and 2021. The research process was performed on four databases: (i) Scopus, (ii) Elsevier, (iii) Taylor & Francis, and (iv) Emerald, which were considered the most coherent publishers in the engineering sciences by the authors. The queries were filtered by authors, abstract, and keywords, when possible. Table 2 summarises the filtering items used for each database.

Table 2 - Databases filters (N/A – Not applicable)

Database	***Filters***			
	Type	*Language*	*Subject*	*Years*
Scopus	Journal; Proceedings	English	Engineering	1980-2021

Elsevier	Journal; Proceedings	English	Engineering	1980-2021
Taylor & Francis	N/A	English	Engineering & Technology	1980-2021
Emerald	Journal; Proceedings	English	N/A	1980-2021

The definition of keywords was performed iteratively due to the high number of papers resulting from the first database querying. To obtain a manageable number of articles, three filtering steps were performed as reported in Figure 1. Initially, general keywords such as "*Design*", "*Manufacturing*", "*Assembly*", "*for*" were collected with the operator "AND". Moreover, to broaden the research and mitigate possible errors, synonyms were considered (i.e., *"Manufacturability", "Production", "Manufacture", "Assemblability"*, and *"Installation"*). The second step was performed to narrow results and the two keywords "*Assembly*" and "*Manufacturing*" were combined using the operator "AND" (e.g., "*Assembly AND Production", "Assembly AND Manufacture"*, etc.). Finally, the last filtering step consisted in the introduction of new keywords to reduce the overall number of results trying to target only mechanical-related articles. The acronyms *"DFA", "DFM"* and *"DFMA"* were added to the previous keywords with the operator "AND".

2.3. Definition of criteria for article sorting

After the initial search process, articles were skimmed with a three-step process: (i) identification and elimination of duplicated articles, (ii) use of global exclusion criteria to select articles related to the field of interest, and (iii) use of specific criteria (SC) to select only the most representative articles. Both criteria (GC and SC) used for the exclusion process are reported in Table 3.

Table 3 - Criteria for article exclusion

	Global Exclusion Criteria	
GC1	No keywords in the title	An article which title does not contain at least two of the following keywords DFA, DFMA, Assembly, Design.
GC2	Not related to Engineer and Design field	Article not related to engineer and design field (e.g., biology, biomedical, etc.)
GC3	Not related to mechanical engineer	Article not related to mechanical engineering (e.g., constructions, buildings, management engineer, etc.)
GC4	Not related to mechanical products	Article not related to mechanical products (e.g., printed circuit board - PCB, etc.) or not related to the product itself (e.g., assembly line, production site, etc.)
	Specific Exclusion Criteria	
SC1	Not available for download	Article not available for download
SC2	Out of scope	Article not related to DFMA methods or clearly misleading about the aim of the review

A quality assessment process was not performed, and all the retrieved papers were kept for the review process. At the end of the article selection, 141 articles were kept and analysed. The overall selection process is represented in Figure 1.

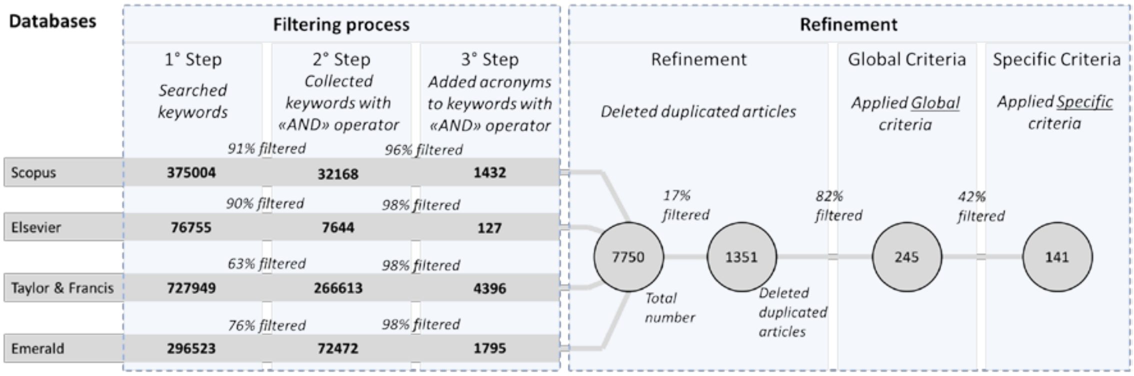

Figure 1 - Filtering process and refinement steps

2.4. Execution of data extraction and classification

Data extraction and classification allowed for retrieving key information from the articles selected for the analysis by the use of a structured framework. The data extraction framework (Table 4) is composed of items according to the type of research question they are answering.

Table 4 - Data extraction framework (N/A – Not applicable)

Metadata	***Type***	***Question Category***
Title	String	N/A
Corresponding author	String	N/A
Other authors	String	N/A
Objective	String	N/A
Comments	String	N/A
General questions		
DFMA Product Complexity	String	GQ1 - GQ3
DFMA Case Study	String	GQ1 - GQ3
DFMA Field - General	String	GQ1 - GQ3
DFMA Field - Specific	String	GQ1 - GQ3
DFMA Phase	String	GQ2 - GQ3 - FQ1
Focused questions		
DFMA Quantitative/Qualitative	String	FQ1
DFMA Automatic/Manual	String	FQ2
DFMA Tool	Boolean	FQ2
DFMA CAD Linked	Boolean	FQ2
DFMA Method	Boolean	FQ2
DFMA I4.0 Enabling Technology	String	FQ3

2.5. Execution of analysis

The execution of analysis was performed with the help of the framework provided in the previous step (Table 4). In relation to the general questions, the first topic concerns the identification of the specific field in which DFMA methods have been applied for years. Fields were divided into general (i.e., electronic, and mechanical) and specific (i.e., sensors, automotive aerospace, industrial). To further support this classification, the product complexity was identified. In this paper, a product is considered complex if it has a medium-long lead time and it is difficult to handle (i.e., due to weight, dimensions, or a high number of components), while a simple product has a short lead time and is made by few components (i.e., less than sixty). The second topic concerns the identification of the design phase in which DFMA is applied (i.e., conceptual design, embodiment design, and detail design). The detail design phase presents the most accurate and complete information regarding the product, while the conceptual design phase presents most generic data (e.g., functional information, product architecture, etc.). The third topic concerns the identification of future trends and challenges of DFMA methods in relation to the application field, product complexity, and design phase previously investigated.

On the other hand, in relation to the focused questions, the first topic refers to the DFMA method type, which can be quantitative or qualitative. A method is considered quantitative when it provides a numerical evaluation (e.g., the B&D DFMA method), while a method is qualitative when it provides suggestions and guidelines, not directly linked to numbers or mathematical equations (e.g., heuristics, guidelines, etc.). The second topic tackles the computational tool used to perform DFMA analysis. Three different types of tools were identified for this purpose: spreadsheets, software, and graph. The third topic analyses the application of advanced technologies with DFMA methods (i.e., the ones that currently characterize the enabling technologies of Industry 4.0).

2.6. Bibliometric Analysis

A bibliometric analysis was performed to understand when and where papers regarding DFMA methods have been published. The analysis was performed considering four decades and the overall result is shown in Figure 2. An exception was made for the last decade (i.e., D4) which considers a time span ranging from 2010 to 2021 to include all the latest publications. The first decade includes only four papers and it appears to be the lowest in terms of publications, while the second decade presents a high number of papers (48). The third decade presents 30 papers published for the DFMA field, and finally, the latest decade presents the highest number of papers, which is 59. Although the graph shows a scattered distribution of papers, ranging from 0 to 8 for each year, the mean value for the last three decades is approximately 4,3. This result highlights a homogeneous distribution of paper over time about DFMA.

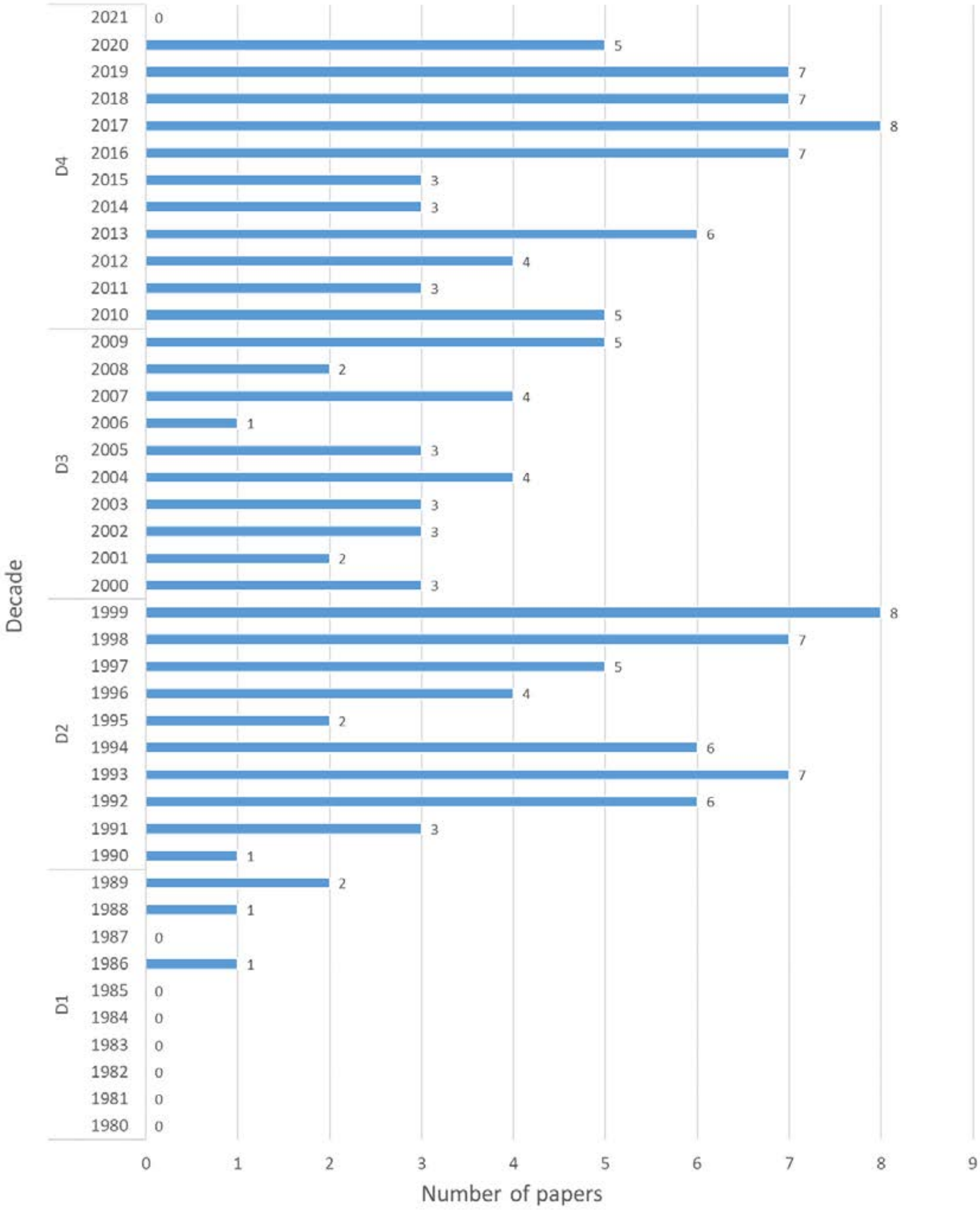

Figure 2 – Number of papers vs. years

Both paper types published in journals and conference proceedings have been considered. Journals guarantee a stricter review process than proceedings following the time given to reviewers and the accessibility to scientific databases. Moreover, journals present more structured and mature research than conference proceedings. Additionally, a higher number of publications on conference proceedings indicates a considerable interest, since they present ongoing activities from different practitioners.

3 Results of the literature review

In this section, results of the literature review are presented following the two main groups of research questions previously identified.

3.1. Results related to the general questions

To answer the first general question only papers in which a case study is presented have been analysed. The aim is to identify the industry’s field in which DFMA methods have been applied and the type of product analysed as a case study. On the other hand, to answer the second and the third general questions all papers except reviews were considered. The aim is to understand in which phase DFMA methods are mainly applied, to identify the advantages/disadvantages of each design phase and to derive future research opportunities in the DFMA field.

3.1.1. Field of application and products analysed by DFMA methods

At the beginning of DFMA methods development (early ‘80s), articles were focusing on the conceptualization and description of DFMA methods, providing academic and exemplary case studies. During the ‘90s, the application of DFMA methods in industries increased exponentially, particularly in the mechanical field. Starting from the second decade (D2) several case studies were provided to demonstrate the applicability of DFMA in mechanical and electro-mechanical products, and the same trend was confirmed in the following decades (D3 and D4). It is worth noting that most of the publications giving case studies have been implemented in the industrial field. The reason lies in the fact that several DFMA methods available in the literature are tested on generic products made of few components (i.e., dust filters, stapler, boiler, etc.) to validate the methods and their reliability. The number of papers presenting case studies in the automotive and aerospace fields is well balanced. Products analysed with DFMA methods are varying from sub-assemblies of a car (i.e., the suspension system, brake and clutch, etc.) to aircraft systems (i.e., pilot instrument panel, contactor assembly, etc.). Only a few articles tried to tackle the assemblability of a whole product; among them Thompson et al., (2018) tried to point out the relation between DFMA rules and late design changes in high-speed product development (i.e., circulator pumps for the commercial building services market). Gerding et al., (1998) tackles the problem of implementing DFMA rules in long-lead-time products (i.e., aircraft) while Barbosa & Carvalho, (2013, 2014) proposed DFMA rules to optimize the assembly phase of an aircraft through re-design actions. Figure 3 shows the distribution of papers according to the type of product, the general field, and the specific field of application.

Figure 3 - GQ1 data distribution

To understand the interest of the topic over time, the publications' year was analysed together with the type of publication (i.e., journal or conference proceeding). Results of this analysis is summarised in Figure 4. Papers describing DFMA applications on both complex and simple products have increased over the years. It is interesting to notice that most of the articles proposing DFMA methods for complex products have been published in the last two decades (D3 and D4). This trend may be justified by several reasons. The first one concerns the fact that more and more industries are focusing on reaching a global improvement of their product, making the application of traditional DFMA challenging since the whole system must be considered. Another major factor in the development of DFMA methods for complex products concerns the increment of processing power that allows designers and engineers to process a high number of data in a limited timeframe, enlarging the boundary of their optimization problem from sub-parts to the whole system. The study of DFMA methods applied to simple products in the last three decades has increased as well. However, for the last decade (D4) most of the papers are published in conference proceedings and they present an application of already well-known DFMA techniques on different systems. Despite these works being useful to increase the number of case studies where DFMA methods are applied, they cannot be considered as research advancement in the DFMA methods. Besides, the other works published in conference proceedings are trying to extend DFMA principles in several ways. For example, Kamath, (2010) attempted to apply DFMA to the improvement of assembly lines, Wood, (2014) and Nyemba, (2017) provided new design rules to cope with constraint production of the developing countries, and finally Favi, (2016), Hein, (2018), and Gupta, (2019) included new principles and criteria for multi-objective analysis (i.e., cost, sustainability, etc.).

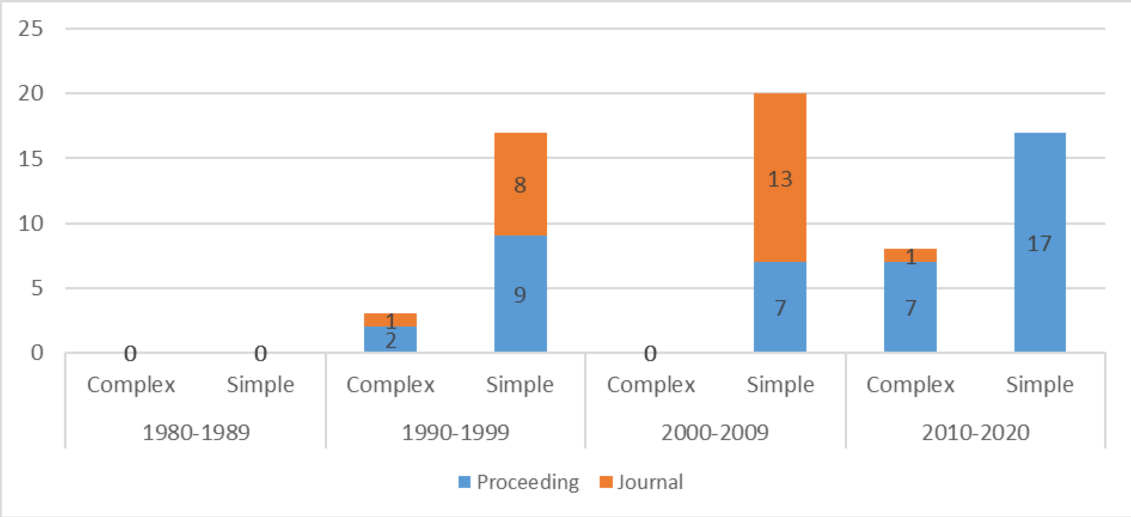

Figure 4 - Distribution of papers per decade in relation to simple and complex products

The overall data collected about this topic are summarized in Table 6. From the performed analysis, DFMA methods have been mainly applied on simple products or sub-assemblies, in which all parts are made with traditional production technologies (i.e., fusion, sheet metal stamping and bending, forging, etc.). DFMA analysis evaluates assembly solutions adopted in the analysed products. Assembly solutions are generally bolted joints, more rarely welded or riveted joints. The main goal of these analyses is to understand if it is possible to reduce the number of components which, typically, leads to a reduction of assembly time (Boothroyd, 1994). As an outcome, the typical product analysed using DFMA techniques is a simple product assembled manually with bolted joints made of less than 60 parts. Another interesting result concerns the fact that sub-assemblies are considered rather than the whole product. This result leads to the application of DFMA methodologies in a limited context (i.e., the companies which are designing and manufacturing sub-assemblies) making effective the benefits of DFMA for suppliers. In this scenario, each module (sub-assembly) is assembled with a specific assembly technology, making the overall analysis easier to manage. For instance, a car engine is assembled with bolted joints, chassis are assembled with welding technologies, etc. If the assembly technology varies, then the DFMA analysis becomes more challenging and, consequently, the overall final improvement might not have an elevated positive impact as the sub-systems improvements might have.

3.1.2. Product design phase challenged by DFMA methods

According to (Pahl et al., 2007), the PDP process can be divided into conceptual design, embodiment design, and detail design. For each phase, different information and tools are available to support designers in the definition of the product. The conceptual design phase represents the initial phase of the product development process, in which only general information (e.g., product functions, product architecture, etc.) is available. The embodiment phase represents a more mature phase of a project in which a preliminary product layout is available. Generally, this design phase is linked with the use of 3D CAD drawings. Finally, the detail design phase represents the step with a higher level of detail. Specific information is available at this phase, such as the number and type of screws, assembly procedures, assembly sequence, takt time, etc. In this phase, detailed drawings are made to fully describe the product for the manufacturing process. Together with the information granularity, also the cost of changes varies according to the design phase in which modifications are introduced. With the aim to analyse this topic all papers except reviews have been considered. The analysis of the literature shows that DFMA methods are mainly used during detail and embodiment design phases (Table 6). Indeed, considering the most spread DFMA methods (i.e., B&D and Lucas method), the analysis is performed starting with detailed design information. Among the analysed papers, a large part of them tried to use DFMA methods at the embodiment phase by reducing the need for specific information. For instance, Sanders et al., (2009) proposed a knowledge-based system to optimize products without detailed information, while Samadhi et al., (2018) tried to develop a fully automated DFMA method, linked to a 3D CAD modeller, enabling to extract data related to the product under development. The application of DFMA methods at the late design phase is in line with the idea of DFMA since most of the methodologies have been developed as a systematic approach, whose aim is to optimize the product through different design iterations (incremental improvement through product re-design). However, several problems arise working at the late design phases such as the high cost of change. Since the beginning of the advent of DFMA methods, some studies tried to move the analysis from the detail design phase to the conceptual design phase. Among these, the paper proposed by Rampersad, (1996) was one of the first to investigate DFMA methods from a relational point of view, to understand how design variables affect product assembly. A more recent attempt was performed by Emmatty & Sarmah, (2012) that tried to merge DFA and DFM techniques with product architectures analysis. Across the collected works, only two works proposed to integrate the TRIZ methodology and the DFMA to widen the solution space, which is a typical task of conceptual design (Bariani et al., 2004; Cakir & Cilsal, 2008). The typical output of DFMA methods in the conceptual design phase is a product architecture with optimized performance in terms of assembly. Functional modules, interconnections and related parameters are considered in the DFMA analyses to identify installation and assembly issues. For instance, the position, the attachment points, the overall number of the functional modules, and/or the interface route among modules are some of the parameters considered in the developed DFMA methods conceived for the conceptual design phase. Hence, DFMA analysis performed at the conceptual design phase focuses on the module rather than the physical components and provides product optimization through module arrangement and layout inside the product (i.e., product architecture). When DFMA analyses are conducted at the detail or embodiment design phase, the typical output is again a product with optimized assembly performances, but the focus concerns the components/parts. DFMA tools aim at improving the product assemblability by reducing the overall number of components, minimizing the number of fixations (i.e., screws, rivets, etc.), standardizing the type of fixations, reducing the part re-orientation during the manual operations, and choosing the most appropriated manufacturing technology among others. Hence, DFMA analysis performed at the embodiment/detail design phases focuses on the physical component providing a product optimization through the improvement of component shape, features geometries, and manufacturing aspects. It is interesting to notice that in the last decade, the efforts to propose DFMA methods applicable at the conceptual design phase have been increased for both simple and complex products.

3.1.3. Future challenges to address by using DFMA methods

From the extracted data, most of the papers are dealing with the improvement of simple products at the detail design phase. The analysis shows also how the DFMA evolved integrating new objectives (e.g., ergonomic and environmental aspects) and multi-attribute analysis. On the other hand, the research activity related to DFMA methods shifted towards the analysis of complex products, and an increased interest in the conceptual design phase was noticed. To cite a few, Remirez et al., (2019) tried to adapt the B&D DFMA methodology to tackle the assembly issues of a solar tracker, while Mora et al., (2020) adapted the Design Structure Matrix method to work with large size products (i.e., elevators, wind turbines, solar plants, pilot plants or petrochemical facilities). With the same aim Formentini et al., (2020) provided a method to collect design guidelines to optimize the aircraft architecture at the conceptual design phases. The transition of DFMA analysis towards the early design phases emerged as a trend to be investigated in future years. This trend emphasizes the need to shift the DFMA paradigm by establishing a systematic optimization method that may be used at the conceptual stage, when degrees of freedom are larger, to achieve the Right First Time design (Boothroyd, 1994), before moving on to the later design phases. Another aspect that characterizes DFMA studies of products with a certain complexity is the high number of data required for the analysis and computational time needed to perform the analysis. To summarize the outcome of the literature analysis, an increasing interest in the development of DFMA methods for complex products is raising in the scientific community. However, there is no evidence stating that DFMA methods provide better benefits to complex rather than simple products. Based on the revised papers, a high number of manuscripts presented applications of DFMA methods on simple products. This trend may be justified by the fact that on simple products DFMA results can be validated and tested through product prototypes. Moreover, the application of DFMA analysis on simple products is in line with the concept of incremental innovation. In this respect, DFMA techniques were applied to product sub-systems (or sub-assemblies), which indirectly provides an overall optimization of the product. The application of DFMA analysis on the entire product, especially when it is complex, may generate different outputs and might lead to radical innovation in terms of assembly performances. To date, there is no evidence about a direct comparison (e.g., DFMA index assessment) between a complex product developed with DFMA criteria and the same product in which the DFMA principles were applied to sub-assemblies. This lack lies in the needs of industry where usually sub-systems are provided by different suppliers, thus there is no interest in investigating the product assemblability as a whole system. This perspective is currently not addressed within the literature and represents an opportunity for further research. Another upcoming challenge for DFMA is the need to integrate DFMA analysis with other design aspects (multi-objective analysis), creating engineering design methodologies that consider multiple aspects. For instance, ergonomic analysis is important to guarantee the assembly optimization of the product. Boothroyd, (1994) already considered the ergonomic aspect in his approach; however, it was considered in relation to the operator in the assembly line, where small products are handled. Moving towards bigger and complex products, the assembly process requires the operator to actively adapt to the working space and environment, and different ergonomic parameters need to be considered, such as working position, the access to the place where activities are performed, and ergonomic operator posture among others (Judt et al., 2020).

3.2. Results related to the focused question

To answer the focused questions only a proper subset of papers was analysed for each topic with the aim to explore specific aspects related to the type of DFMA methods. These specific topics concern the type of tools used for the analysis, as well as the enabling technologies used to implement DFMA in modern industries.

3.2.1. Qualitative vs. quantitative DFMA methods

DFMA methods can be clustered into different categories: qualitative and quantitative. A method is considered quantitative when it provides numbers and indicators (i.e., metrics) to evaluate the goodness of a product from the assembly and manufacturing point of view. According to this definition, quantitative methods have been widely used as engineering design tools (Stool, 1986). An example of the DFMA quantitative method is the B&D method. On the other hand, a method is considered qualitative when it provides an evaluation of the product manufacturability and assemblability using design practice derived from experience. Qualitative methods are usually providing design suggestions, rules, guidelines without the adoption of numerical metrics. Dealing with the study of qualitative vs. quantitative DFMA methods, the analysis was performed looking at all papers except the reviews and papers oriented to the plant management. Results show that three quarters of the papers are proposing quantitative approaches, while only a one quarter studied qualitative approaches. Among all, only two papers tried to provide a method that can be considered both qualitative and quantitative (Sik Oh et al., 1995; Gupta & Okudan, 2008). Table 5 reports the main types of information required to perform DFMA analysis, in relation to quantitative and qualitative methods. Despite some inputs being shared among quantitative and qualitative methods (e.g., number of parts, etc.), the main outputs are different.

Table 5 - Inputs & Outputs of qualitative and quantitative methods (DN - dimensionless; [#] - Quantity; NA - Not available)

Method type	***Input data***	***DFMA Index***
Quantitative	Material cost [*$*] Volume [$m^3$] Manufacturing process cost [*$*] Number of parts [*#*] Number of fasteners [*#*] Assembly time [*s*] Weight [*kg*] Orientation [°] Access [*DN*] Mating features [*DN*] Insertion difficulties [*DN*] Finish factor [*DN*] Waste coefficient [*DN*]	Manufacturing cost index [$] DFA Index (Design Efficiency) [*DN*] Fitting ratio [*DN*] Efficiency index [*DN*] Feeding ratio [*DN*] Theoretical minimum parts [#] Total Grade of the part [*DN*] Total Grade of the assembly [*DN*]
Qualitative	Part handling *[DN]* Part relations *[DN]* Weight *[kg]* Number of Parts *[#]*	Design Structure Matrix [*NA*] Performance Index [*DN*]

From the performed analysis, the most-used inputs for DFMA indices are Assembly Time [s], Material Cost [$] and Number of Parts [#]. DFMA indices for quantitative methods have all the same root, which is providing a score based on the identified product parameters (input data). According to the type of parameters and the developed method, the DFMA index can assume a different meaning. For instance, the most popular DFA index from the B&D approach (also known as Design Efficiency) is computed by the following equation (Boothroyd, 1994):

$$DFA\ Index = 3 * NM / TM$$

where:

- *NM = theoretical number of parts*, is an estimation concerning the number of essential parts of the product derived by the optimization process proposed by the method, and
- *TM = total assembly time*, is the overall assembly time of the product measured with experimental tests.

The DFA index gives an overall assessment of the product assemblability performance (dimensionless index). The DFA index can be applied to different products, and it is based on values derived from standardized tables. Differently from DFA index, the total grade indices allow considering both DFA (total grade of the assembly) and DFM (total grade of the part) (Harik and Sahmrani, 2010). The method identified a list of product parameters for the manufacturing assessment (billet, work material, features, machine accessibility, etc.) and for the assembly assessment (i.e., billet dimension, part handling, assembly fixtures, tolerance and clearance, etc.) providing a weight for each parameter (from 0 to 10). According to a value engineering approach, a score of 0 is assigned if the parameter is not critical for the manufacturing/assembly, while 1 is assigned if the parameter affects the manufacturing/assembly process. Total grade indices are obtained by multiplying the weight of each parameter with the score associated with the considered parameter and finally making an overall sum. The lower the total grade of the part and the assembly is, the more efficient the product is from the manufacturing and assembly perspectives. Both DFA index and total grade of the assembly/part are quantitative.

Regarding qualitative DFMA methods, the general outcome is a list of item (i.e., rules, graph, guidelines, etc.) in which design suggestions to improve product manufacturability and assemblability are collected. For instance, the Design Structure Matrix (DSM) is a well-known tool to represent product architectures. DSM representation helps designers to create products with enhanced manufacturing and assembly properties. Qualitative DFMA methods can also provide a Performance Index, which provides a sort of scale to assess the improvement obtained by the implemented design actions. According to the method used, the Performance Index is derived using different inputs (e.g., the initial number of components/final number of components, initial cost/final cost, etc.) and it provides a rough estimation of the benefits introduced by the implementation of the design guidelines.

Regardless the fact that a DFMA index is quantitative or qualitative, the analysis showed that DFMA indices can be divided into two groups: time-based and feature based. Time-based DFMA indices rely on tables to convert time-related assembly parameters into scores. Tables are derived through extensive experiments. The main drawback of these indices is the complexity to personalize these tables on a specific product (e.g., complex products). On the other hand, feature-based DFMA indices rely on tables to convert assembly-related features into scores. Tables are derived through knowledge formalization techniques. These type of indices allow personalising tables on the product analysed, but require a great effort to be set up and they may be subjected to bias. As an outcome of the literature review, the definition of a general DFMA index which can be adopted for every type of product or system can present several issues. A trade-off among analysis accuracy, available time, and availability of data must be reached and the proper DFMA index selected accordingly.

Another interesting area of investigation regards the type of DFMA method versus the design phase at which it is used. Figure 5 presents the data collected from the analysis of the qualitative/quantitative DFMA methods versus the design phase.

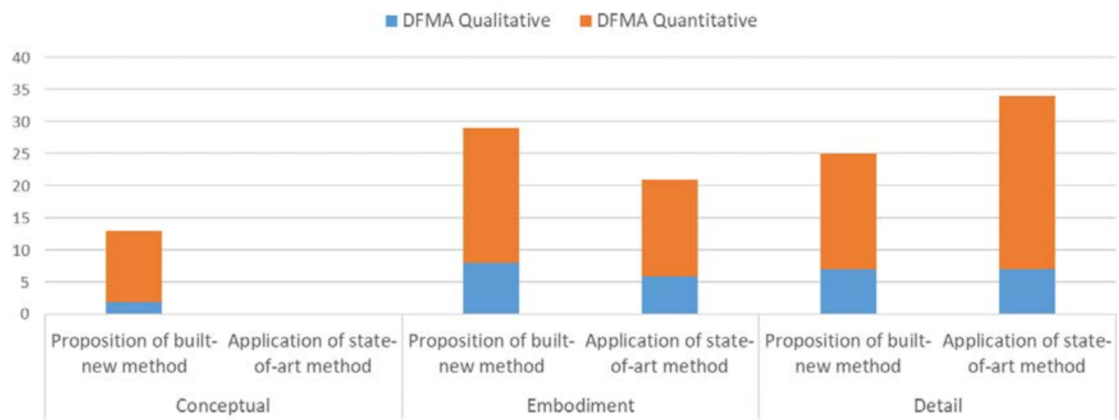

Figure 5 – Distribution of quantitative and qualitative methods in relation to the design phase

Quantitative methods appear to be widely used at the late design phase. This result is in line with the available information, which is mainly numerical. Moving towards the early design phase (i.e., conceptual design), a great effort was done to develop new methods to study manufacturing and assembly aspects with less information. Among the DFMA methods focusing on the early stage of the design process, the majority of them are quantitative. This is an interesting outcome since no quantitative information is available in this design phase. For instance, Jung & Billatos, (1993) examined some elements of intelligent design systems to assess manufacturability of a product through the development of a knowledge based expert system for assembly. The knowledge base has been acquired from design for assembly along with axiomatic design concepts with emphasis on the conceptual design stage where the structure of the product as a whole is considered. Dagman & Soderberg, (2012) proposed to use axiomatic design principles as a way to analyse and improve product architecture by the assessment of manufacturing, assembly, and disassembly parameters during the early design phase. Both methodologies, which are based on axiomatic design, are quantitative and use matrices to link functional requirements with design parameters. Favi et al, (2016a) proposed a method to perform a multi-objective optimization in terms of assembly, materials, processes, costs, and times at the conceptual design phase. The analysis was performed at the product architecture level, using product modules and design solutions derived with the help of the morphological matrix. In the mentioned work, all parameters required for performing the DFMA analysis were supposed from an already existing product. A similar approach was proposed by Formentini et al., (2020), Favi et al., (2019), and Bouissiere et al., (2019) for the study of product architectures assembly performances for systems installation of a commercial aircraft.

3.2.2. Tools used to support DFMA methods

Concerning the development of engineering tools able to support the DFMA analysis of mechanical products, only a subset (74) of papers addressed this topic. Three different types of tool were identified by the analysis of the literature: graph, software, and spreadsheets. Each tool was further classified according to the aim of the analysis: (i) redesign suggestions, (ii) guidelines collection, (iii) metrics computations, and (iv) method integration. Redesign suggestions tool allows at the identification of redesign actions to improve the assemblability and manufacturability of the product under analysis. Guideline's collection tool aims at transforming implicit knowledge into explicit one. Metrics computations tool consists of the automatization of the computation of assembly and manufacturing parameters, and method integration tool describes the link with other engineering methods (i.e., FEM analysis). From the performed review, a dedicated software system is the main used tool, followed by spreadsheets and graphs (see Figure 6). By the analysis of the type of software, research works presenting case studies are more willing to use commercial DFMA software (e.g., B&D commercial software) than an ad-hoc developed software tool. Among commercial software tools, most of them were developed for metrics computations (i.e., assembly time, required assembly steps, etc.). The same trend is noticed for the spreadsheets. Only two papers are making use of graphs as tool for DFMA analysis. For example, Wu & O'Grady, (1999) suggested to use Petri-Nets to model CE aspects and make the application of DFMA techniques leaner, while Hsu & Lin, (1998) used graphs to integrate DFA, assembly functional presentation, and problem recommendation driven mechanism. According to the performed analysis, spreadsheets and ad-hoc software appear to be the most used tools. The use of spreadsheets lies in the accessibility and straightness in their use. They are the best choice when a method is not consolidated and only a few analyses were performed. Additionally, the software has been widely used to implement the DFMA method. Two types of software have been identified in the analysis: (i) ad-hoc developed software, and (ii) commercially available software. Generally, the development of software implies a greater effort in terms of time than commercial software or spreadsheets. The commercial software tools identified during the review concern both design tools and simulations tools (i.e., DFMA® Boothroyd Dewhurst Software, Tecnomatix Dynamo, and Flexible Line Balancing Software). In other cases, the analysis was performed retrieving information from CAD tool but no information was provided regarding the DFMA software used (Azevedo et al., 2015; Robinson et al., 2017). Moreover, it is interesting to analyse the use of tools versus the type of publication. Figure 6 shows that the use of spreadsheets is higher in the conference proceeding publications than the journal ones. Spreadsheets are mainly used to perform isolated analyses while ad-hoc software tools were developed to include methodological aspects within the novel DFMA framework which are more suitable for journal publications. Table 6 reports a summary of the outcomes related to this topic.

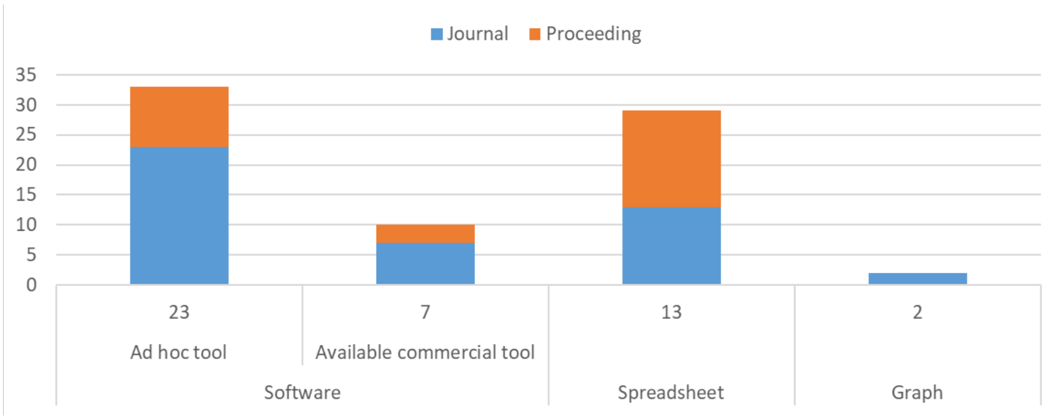

Figure 6 - Tool vs. number and type of publication

3.2.3. *Industry 4.0 enabling technologies challenging DFMA methods*

The advances in Industry 4.0 provide both challenges and opportunities for digital manufacturing and assembly systems. Industry 4.0 aims at the development of a new generation of smart factories grounded on the manufacturing and assembly process digitalization. Most of the Industry 4.0 enabling technologies are related to digitization, data management, and connectivity and they are dependent on solid data acquisition technologies. For the purpose of this review, not all the enabling technologies have been considered (Figure 7) due to different reasons.

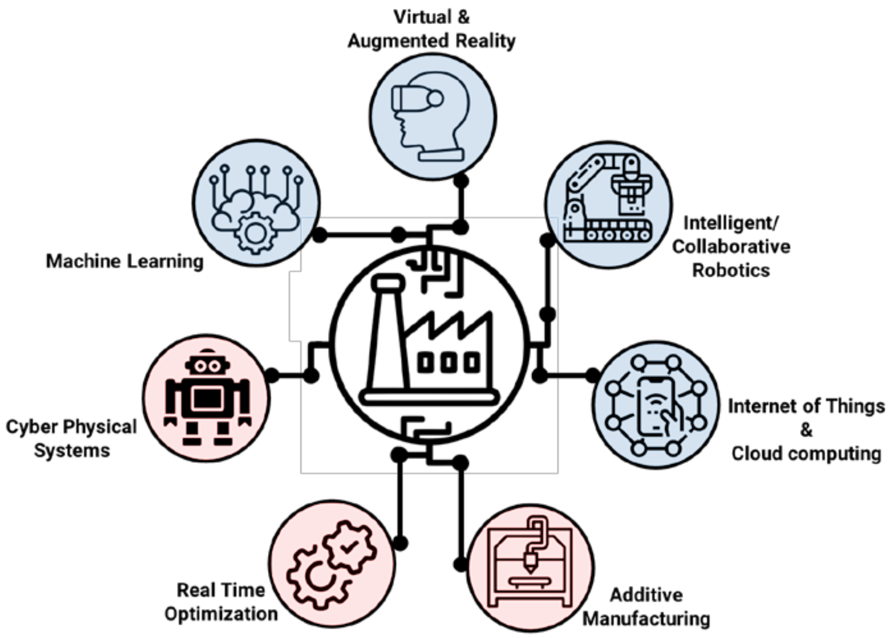

Figure 7 - Enabling technology for Industry 4.0 (blue included in the review; red excluded)

The “Additive manufacturing” technology was not studied since design methods called “Design for Additive Manufacturing” have been specifically developed to consider this technology and they are not the goal of this review. The interested reader can find further information regarding DFAM methods in the review proposed by Wiberg et al., (2019). “Real-time optimization” and “Cyber-physical Systems” were not considered since they are mainly focusing on plant management rather than product design. For the aim of this review only “Machine Learning & AI”, “Virtual & Augmented Reality”, “Intelligent/Collaborative Robotics” and “Internet of Things & Cloud Computing” were examined. In addition, a more detailed list of tools was identified for the technology “Machine Learning & AI”, including: (i) Expert system, (ii) Fuzzy logic, (iii) Genetic algorithm, and (iv) Constraint-Network approach. Among all the papers, only a few papers addressed the technology “Machine Learning & AI” proposing the use of the mentioned tools for the development of DFMA methods. The common goal of the analysed works is to eliminate the need for expertise to perform an assembly-oriented design choice. The use of mathematical artifacts (e.g., artificial intelligence, genetic algorithms, expert system, fuzzy logic, etc.) allowed the collection of existing knowledge and the development of an automated system for knowledge sharing. Referring to the technology “Virtual & Augmented reality” the idea was to use this technology in helping designers with the mock-up creation at the embodiment design phase facilitating the analysis of assembly operations (i.e., ergonomics). As regards the technology “Internet of Things & Cloud computing”, only two discussed the applicability of these technologies for the DFMA analysis. Both manuscripts tried to move DFMA analysis in a cloud environment to get access to more case studies, more data, and the possibility to share assembly/manufacturing knowledge on past projects. Finally, even though there are several papers presenting methodologies to consider automatic assembly, no papers were found for the technology “Intelligent/Collaborative Robotics”. Automatic assembly was generally not analysed through the means of DFMA, and the design of robotic cells and lines is usually customized to build a specific product and/or product family (Desai, 2019). Industry 4.0 technologies brought a new paradigm for industries and manufacturing companies including a different way to collect, process, and elaborate data, as well as the production of customized products. The idea ground pinning the adoption of these technologies for DFMA purposes is to reduce the risk of implementing wrong design actions and it helps to select the right modification among a pool of options. For example, Internet of Things can support DFMA analysis collecting data through several sensors placed directly on the product or the assembly line. Machine Learning techniques can make use of past data and the analysis of implemented design actions to suggest the right design action to implement in a given time. Machine learning processes can be used also to drive the product optimization following a multi-objective analysis to address different design goals (i.e., DfX). The Cloud computing can open new possibilities in terms of data sharing by using virtual servers to collect and process data. The idea of Cloud computing is in line with the concept of open manufacturing introduced by Kusiak, (2020) allowing different stakeholders to share data and optimize the manufacturability of their products in different contexts and countries.

As previously introduced, Virtual and augmented reality can enable the investigation of ergonomic aspects during the assemblability process and the optimization of manual assembly operations. Exploring the product in a virtual environment, it is possible to highlight ergonomic issues (i.e., wrong operator position, impossibility to access to a particular product area, etc.) and solve them before the product is finalized. Moreover, operators can be trained before the product is physically available, reducing the time required for the in-process learning curve, cost of training, and consequently time to market.

By following the bibliometric analysis, the majority of works introducing Industry 4.0 enabling technologies are dated in the second and the third decades (D2 and D3). At that time, the concept of Industry 4.0 had not yet been formalized, therefore all these studies can be considered as preparatory for the paradigm shift brought by the advent of Industry 4.0. When the concept of Industry 4.0 was introduced (beginning of 2010), the application of enabling technologies in relation to manufacturing and assembly aspects took a different research angle (from the product to the production site, i.e., plant management and production). This outcome has been validated by performing quick research with keywords “Industry 4.0 Design for Assembly” on main scientific databases. The retrieved papers are not focusing anymore on the design aspects of product assemblability, rather on the management of the assembly line and production site. In conclusion, traditional DFMA methods were not deeply investigated in relation to the Industry 4.0 enabling technologies.

Table 6 – Overall results of the review process for the identified topics (N/A – Not applicable)

Reference	Product Complexity	Case Study	Field: Generic	Field: Specific	Design Phase	Tool	Aim	I4.0 Enabling Technology	Method
Gerhardt et al., 1991	Simple	Portable compressor control & Instrument panel	Electronics	Sensors	Detail	N/A		N/A	
Matterazzo & Ardayfio, 1992	Simple	Suspension system	Mechanical	Automotive	Detail	Spreadsheet	Metric Computation	N/A	
Ardayfio & Opra, 1992	Simple	Brake and Clutch	Mechanical	Automotive	Detail	Spreadsheet	Metric Computation	N/A	
De Fazio et al., 1993	Simple	Seeker head	Mechanical	Aerospace	Embodiment	Software	Metric Computation	N/A	
Sik Oh et al., 1995	Simple	Video cassette tape	Electronics	Industrial	Embodiment	Software	Metric Computation	Machine Learning	Constraint-Network's approach
Jared et al., 1994	Simple	Diesel injector	Mechanical	Automotive	Embodiment	Software	Metric Computation	N/A	
Rampersad, 1996	Simple	Plastic case	Electronics	Industrial	Embodiment	N/A		N/A	
Changchien & Lin, 1996	Simple	Rotational parts	Mechanical	Industrial	Embodiment	Software	Redesign Suggestions	N/A	
Kusiak & He, 1997	Simple	PCB	Electronics	Industrial	Conceptual	N/A		N/A	
Liang & O'Grady, 1997	Simple	Personal computer	Electronics	Industrial	Detail	Software	Redesign Suggestions	Machine Learning	Genetic Algorithm
Barnes et al., 1997	Simple	Screen wiper motor assembly	Mechanical	Automotive	Detail	N/A		N/A	
Herrera, 1997	Simple	Pilot instrument panel	Mechanical	Aerospace	Detail	N/A		N/A	
Herrera, 1998	Simple	Pilot instrument panel, Anti-flail bracket,	Mechanical	Aerospace	Detail	Spreadsheet	Metric Computation	N/A	

		Intermediate gear box fairings							
Ardayfio, 1998	Simple	Several cars components	Mechanical	Automotive	Conceptual	N/A		N/A	
Hsu & Lin, 1998	Simple	Electronic switch, Paper-Jam release mechanism	Mechanical	Industrial	Embodiment	Graph/Spreadsheet	Method Integration	N/A	
Daabub & Abdalla, 1999	Simple	Swivel castor	Mechanical	Industrial	Detail	Software	Guideline's collection	N/A	
Appleton & Garside, 2000	Simple	Several case studies are presented in a table form	Mechanical	Industrial	Detail	Spreadsheet	Redesign Suggestions	N/A	
Choi & Guda, 2000	Simple	Computer mouse	Electronics	Industrial	Embodiment	Software	Metric Computation	N/A	
Wang & Trolio, 2001	Simple	Mechanical pencil	Mechanical	Industrial	Detail	N/A		N/A	
Hsu & Lin, 2002	Simple	Voltage regulator	Electronics	Sensors	Detail	N/A		N/A	
Edwards, 2002	Simple	Gate valve	Electronics	Sensors	Detail	N/A		N/A	
Stauffer et al., 2003	Simple	Injection moulding	Mechanical	Industrial	Detail	Spreadsheet	Guideline's collection	N/A	
Swift & Brown, 2003	Simple	Luggage racking system, Contactor assembly	Mechanical	Aerospace	Detail	N/A		N/A	
Bramall et al., 2003	Simple	Solid-state power amplified chassis	Mechanical	Aerospace	Embodiment	N/A		N/A	
Bariani et al., 2004	Simple	Satellite antenna	Mechanical	Aerospace	Detail	N/A		N/A	
Coma et al., 2004	Simple	Pressure sensor	Electronics	Sensors	Detail	Software	Metric Computation	Machine Learning	Fuzzy Logic
Sulistiyowati & Sari, 2018	Simple	Dust filters	Mechanical	Industrial	Detail			N/A	

Shetty et al., 2005	Simple	Nokia phone	Electronics	Industrial	Detail	Spreadsheet	Guideline's collection	N/A	
Chang et al., 2006	Simple	Digital binoculars	Electronics	Industrial	Embodiment	Software	Guideline's collection	Internet of Things and Cloud Computing	Web-based system
Xiao et al., 2007	Simple	Plastic robot-arm	Mechanical	Industrial	Conceptual	N/A		N/A	
Kazmer & Roser, 2007	Simple	Gaming console	Electronics	Industrial	Embodiment	N/A		N/A	
Ma & Kim, 2008	Simple	Staplers	Mechanical	Industrial	Detail	N/A		N/A	
Selvaraj et al., 2009	Simple	Sheets metal parts (aircraft)	Mechanical	Aerospace	Detail	Spreadsheet	Guideline's collection	N/A	
Giudice et al., 2009	Simple	Metal formwork	Mechanical	Industrial	Detail	Software	Method Integration	N/A	
Sanders et al., 2009	Simple	Signature capture device	Electronics	Industrial	Embodiment	Software	Method Integration	Machine Learning	Expert System
Gupta & Okudan, 2008	Simple	Electric toothbrush	Electronics	Industrial	Conceptual	Software	Metric Computation	N/A	
Heemskerk et al., 2009	Simple	ITER (fusion reactor)	Mechanical	Industrial	Embodiment	N/A		Virtual & Augmented reality	Virtual Reality
Esterman & Kamath, 2010	Simple	Brake assembly	Mechanical	Automotive	Embodiment	Software	Metric Computation	N/A	
Harik & Sahmrani, 2010	Simple	Aero spacecrafts; Power Saw	Mechanical	Aerospace	Embodiment	Software	Guideline's collection	N/A	
Mo et al., 1999	Simple	Car component	Mechanical	Automotive	Detail	Software	Guideline's collection	Machine Learning	Expert System
Samy & ElMaraghy, 2010	Simple	Three-pin electrical power plug, Engine piston	Mechanical	Industrial	Detail	Spreadsheet	Metric Computation	N/A	

Sarmento et al., 2011	Simple	Automotive intake fuel cover	Mechanical	Automotive	Detail	Spreadsheet	Metric Computation	N/A
Owensby et al., 2011	Simple	Whitegoods	Electronics	Industrial	Detail	N/A		N/A
Annamalai et al., 2013	Simple	Washing machine	Mechanical	Industrial	Embodiment	Spreadsheet	Metric Computation	N/A
Emmatty & Sarmah, 2012	Simple	Watch mechanism	Mechanical	Industrial	Conceptual	Spreadsheet	Metric Computation	N/A
da Silva et al., 2014	Simple	Electronic voting machine printer	Electronics	Industrial	Embodiment	Software	Metric Computation	N/A
Wood et al., 2014	Simple	Pineapple juicer	Mechanical	Industrial	Embodiment	Spreadsheet	Guideline's collection	N/A
Azevedo et al., 2015	Simple	Fins of a microsatellite launch vehicle	Mechanical	Aerospace	Detail	Software	Metric Computation	N/A
Suresh et al., 2016	Simple	Charge alternator pulley	Mechanical	Automotive	Embodiment	Software	Metric Computation	N/A
Shetty & Ali, 2015	Simple	Nokia phone	Electronics	Industrial	Embodiment	Spreadsheet	Metric Computation	N/A
Sarmento et al., 2015	Simple	Pick-Up component	Mechanical	Automotive	Detail	N/A		N/A
Favi et al., 2016	Simple	Tool-holder carousel	Mechanical	Industrial	Conceptual	N/A		N/A
Harlalka et al., 2016	Simple	Food processor	Electronics	Industrial	Detail	Software	B&D Software	N/A
Naiju et al., 2017	Simple	Shopping cart	Mechanical	Industrial	Detail	Software	Metric Computation	N/A
Soh et al., 2016	Simple	Electrical motor	Mechanical	Industrial	Detail	Software	Metric Computation	N/A
Khalqihi et al., 2017	Simple	Exhaust ventilation on sieve machine	Mechanical	Industrial	Detail	Spreadsheet	Guideline's collection	N/A

Dochibhatla et al., 2017	Simple	Stapler, Table fan and Cork opener	Mechanical	Industrial	Embodiment	N/A		N/A
Nyemba et al., 2017	Simple	Boiler	Electronics	Industrial	Detail	N/A		N/A
Alkan et al., 2017	Simple	Four three-pin power plugs, Pressure recorder device	Electronics	Industrial	Embodiment	N/A		N/A
Kumar & Naiju, 2017	Simple	Hand pressure mop	Mechanical	Industrial	Detail	Software	B&D Software	N/A
Matthews et al., 2018	Simple	Paperboard tray press-forming	Mechanical	Industrial	Detail	N/A		N/A
Hein et al., 2018	Simple	Pencil, Spring assisted knife, Can-opener	Mechanical	Industrial	Detail	Software	Method Integration	N/A
Volotinen & Lohtander, 2018	Simple	Ventilation unit	Mechanical	Industrial	Detail	N/A		N/A
Desai, 2019	Simple	Bottom panel of a laptop, Computer monitor, Drill rotor	Electronics	Industrial	Embodiment	Spreadsheet	Metric Computation	N/A
Pista et al., 2019	Simple	Industrial electrical plug inlet	Electronics	Industrial	Embodiment	Spreadsheet	Metric Computation	N/A
Gupta & Kumar, 2019	Simple	Pedestal fan	Electronics	Industrial	Embodiment	Spreadsheet	Metric Computation	N/A
Gulo et al., 2019	Simple	Dust collector on sorting machine	Mechanical	Industrial	Detail	Spreadsheet	Guideline's collection	N/A
Butt & Jedi, 2020	Simple	Conveyor system	Mechanical	Industrial	Detail	Software	Metric Computation	N/A
Mohammad et al., 2020	Simple	Joystick	Electronics	Industrial	Detail	N/A		N/A
Salikan et al., 2020	Simple	Grass cutting machine	Mechanical	Industrial	Detail	N/A		N/A
Miles, 1989	N/A				Embodiment	N/A		N/A
Marcoux, 1989	N/A				Detail	N/A		N/A

Miles, 1990	N/A	Detail	N/A		N/A	
Molloy et al., 1991	N/A	Embodiment	Software	Redesign Suggestions	Machine Learning	Expert System
Eversheim & Baumann, 1991	N/A	Embodiment	Software	Redesign Suggestions	N/A	
Kim et al., 1992	N/A	Embodiment	N/A		N/A	
Li & Hwang, 1992	N/A	Embodiment	Software	Metric Computation	N/A	
Leaney & Wittenberg, 1992	N/A	Detail	N/A		N/A	
Lee at al., 1993	N/A	Embodiment	Software	Guideline's collection	N/A	
Molloy et al., 1993	N/A	Embodiment	Software	Method Integration	N/A	
Rampersad, 1996	N/A	Detail	N/A		N/A	
Venkatachalam et al., 1993	N/A	Embodiment	Software	Metric Computation	N/A	
Bryant et al., 1994	N/A	Embodiment	Software	Method Integration	N/A	
Fabricius, 1994	N/A	Detail	Spreadsheet	Metric Computation	N/A	
Sehdev et al., 1995	N/A	Detail	N/A		N/A	
Ufford, 1996	N/A	Detail	N/A		N/A	
Sturges & Hunt, 1996	N/A	Detail	N/A		N/A	
Taylor, 1997	N/A	Detail	N/A		N/A	
Chawla et al., 1998	N/A	Embodiment	Software	Metric Computation	Machine Learning	Expert System

Schmidt, 1998	N/A	Embodiment	Software	Method Integration	N/A	
Aurand et al., 1998	N/A	Embodiment	N/A	N/A	N/A	
Huang & Mak, 1999	N/A	Detail	Software	Guideline's collection	Internet of Things and Cloud Computing	Web-based system
Zha et al., 1999	N/A	Conceptual	Software	Guideline's collection	Machine Learning	Artificial Intelligent
Hart-Smith, 1999	N/A	Detail	N/A		N/A	
Wu & O'Grady, 1999	N/A	Detail	Graph	Redesign Suggestions	N/A	
Gilson, 1999	N/A	Detail	N/A		N/A	
Hu & Poli, 1999	N/A	Detail	N/A		N/A	
Dalgleish et al., 2000	N/A	Conceptual	Software	Method Integration	N/A	
Brown et al., 2002	N/A	Embodiment	Software	Guideline's collection	N/A	
van Vliet & van Luttervelt, 2004	N/A	Embodiment	Software	Redesign Suggestions	N/A	
Kamrani & Vijayan, 2006	N/A	Embodiment	Spreadsheet	Guideline's collection	N/A	
Koganti et al., 2007	N/A	Detail	Spreadsheet	Metric Computation	N/A	
Valentinčič et al., 2007	N/A	Embodiment	Software	Redesign Suggestions	N/A	
Cakir & Cilsal, 2008	N/A	Embodiment	N/A		N/A	
Das & Kanchanapiboon, 2011	N/A	Detail	Spreadsheet	Metric Computation	N/A	

Ong & Chew, 2000	N/A				Detail	Software	Method Integration	Machine Learning	Fuzzy Logic
Osorio-Gomez & Ruiz-Arenas, 2011	N/A				Conceptual	N/A		N/A	
Dagman & Söderberg, 2012	N/A				Conceptual	N/A		N/A	
Moultrie & Maier, 2014	N/A				Embodiment	Spreadsheet	Guideline's collection	N/A	
Read et al., 2016	N/A				Embodiment	Software	Method Integration	Virtual & Augmented reality	Virtual Reality
Biesek & Ferreira, 2016	N/A				Embodiment	N/A		N/A	
Wahidin et al., 2016	N/A				Detail	N/A		Machine Learning	Expert System
Favi et al., 2017	N/A				Detail	N/A		N/A	
Murali et al., 2017	N/A				Embodiment	Software	Metric Computation	N/A	
Robinson et al., 2018	N/A				Embodiment	Software	Method Integration	N/A	
Samadhi et al., 2018	N/A				Embodiment	Software	Metric Computation	N/A	
Bader et al., 2018	N/A				Embodiment	N/A		N/A	
Wong & Sturges, 1992	Complex	Device for transporting email in an office	Mechanical	Industrial	Embodiment	N/A		N/A	
Jung & Billatos, 1993	Complex	Electrical motor	Mechanical	Automotive	Embodiment	N/A		Machine Learning	Expert System
Gerding et al., 1998	Complex	Aircraft assembly	Mechanical	Aerospace	Detail	N/A		N/A	

Barbosa & Carvalho, 2013	Complex	Aircraft assembly	Mechanical	Aerospace	Detail	Spreadsheet	Guideline's collection	N/A	
Barbosa & Carvalho, 2014	Complex	Aircraft assembly	Mechanical	Aerospace	Embodiment	Spreadsheet	Guideline's collection	N/A	
Thompson et al., 2018	Complex	Car	Mechanical	Automotive	Conceptual	N/A		N/A	
Favi et al., 2019	Complex	Aircraft nose fuselage	Mechanical	Aerospace	Conceptual	Spreadsheet	Metric Computation	N/A	
Formentini et al., 2020	Complex	Aircraft nose fuselage	Mechanical	Aerospace	Conceptual	Spreadsheet	Metric Computation	N/A	
Bouissiere et al., 2019	Complex	Aircraft nose fuselage	Mechanical	Aerospace	Conceptual	Spreadsheet	Metric Computation	N/A	
Mora et al., 2020	N/A				Detail	N/A		N/A	
Remirez et al., 2019	Complex	Solar tracker	Mechanical	Industrial	Detail	N/A		N/A	
Xia et al., a2013	N/A				N/A	N/A		Virtual & Augmented reality	Virtual Reality
Xia et al., b2013	N/A				N/A	N/A		Virtual & Augmented reality	Virtual Reality
Agyapong-Kodua et al., 2013	N/A				N/A	N/A		N/A	N/A
Battaia et al, 2018	N/A				N/A	N/A		N/A	N/A
Bogue, 2012	N/A				N/A	N/A		N/A	N/A
Booker et al., 2005	N/A				N/A	N/A		N/A	N/A
Boothroyd, 1994	N/A				N/A	N/A		N/A	N/A
Carlsson & Egan, 1994	N/A				N/A	N/A		N/A	N/A
Kuo & Zhang, 1995	N/A				N/A	N/A		N/A	N/A

Kuo & Zhang, 2001	N/A	N/A	N/A	N/A	N/A
Sackett & Holbrook, 1988	N/A	N/A	N/A	N/A	N/A
Stoll, 1986	N/A	N/A	N/A	N/A	N/A
Youssef, 1994	N/A	N/A	N/A	N/A	N/A

4 Limitations

The literature analysis performed and presented in this paper shows few limitations that may affect the scope of the results and deserve to be introduced. The research process was performed systematically, identifying parameters and criteria to mitigate possible bias. The main limitation is identified by the adoption of a filtering process which uses criteria defined by the authors. For example, the exclusion criteria SC1 (articles not available for download) is not scientific and repeatable. In fact, according to the type of database and the institution's accessibility, some articles excluded by the authors may be available for other users. In addition, this review focuses on scientific articles (both journal and conference papers), not considering for example thesis, book chapters, technical reports, commercial tools, patents, etc. Since DFMA is considered an applied science in the field of engineering, some interesting works developed outside the boundaries of the academic community could be excluded from this analysis. Finally, due to the high number of articles found, no other sampling techniques (e.g., snowball sampling) have been used to derive articles other than the one described.

5 Discussion

Through the results analysis related to general questions, it is possible to draw a discussion about the DFMA research done during the years. The critical analysis of results showed that DFMA methods have been mainly used for products made of few components and assembled with the same technology (i.e., bolted, welded). This outcome is in line with the idea of the early DFMA methods (e.g., Lucas, B&D, etc.) where an analysis of the assembly process is required for a given product to understand if can be optimized by eliminating/merging parts. Another interesting result lies in the area in which DFMA methods are applied. Since this review is focused on DFMA methods for mechanical products, most of the presented case studies refer to the mechanical and electro-mechanical fields. In this scenario, only a few papers tried to tackle complex products (i.e., long lead time, heavy products, and characterized by a high number of parts). Several limitations were observed when a traditional DFMA method is applied to complex products such as the management of a high number of information as well as the inconsistency between manufacturability and parts integration which is the cornerstone of the DFMA.

The critical analysis of results in relation to the focused questions showed that regardless of the design phase at which DFMA methodologies were implemented, a continuous effort to derive quantitative methods was done since the beginning. Quantitative indices allow determining the performance of manufacturability and assembly for decision-making purposes. In addition, the use of numerical indices leads to a possible comparison between design alternatives, assessing the benefits introduced by novel design solutions. It was observed that the use of metrics and indices is suitable for the late design phases (embodiment and detail design) when numerical parameters are available with lower uncertainty. On the other hand, the assessment of quantitative results during the early phases of the PDP (conceptual design) requires defining specific boundaries and criteria for the field of interest. This limitation may affect the design solution space and the overall optimization process. This result leads to an open question "*Is it possible to create quantitative DFMA methods applicable at the conceptual design phase, without limiting the available solution space*?".

The bibliometric study revealed the evolution of DFMA approaches' interest through time (Figure 8). The analysed works covered both conference proceedings and journals, showing an active interest in the subject by industries and academia. Results show that D2 and D4 present the highest production of papers. For the D3 decade, it seems that the interest in the DFMA subject decreased. This trend is primarily caused by the change of topics and paradigms associated with DFMA, creating a pool of methods very similar but with different names (i.e., installation, system integration, design for additive manufacturing, etc.). In the recent decade (D4), there was a rise in the overall number of publications compared to the previous periods. The reason may be the increase in publication rate in the scientific world; indeed, the National Science Board reported a study showing that the global research output grew about 4% annually over the last 10 years (NSB, 2020). In conclusion, it is hard to claim that the research interest in DFMA methods increase in the last decade compared with the previous ones.

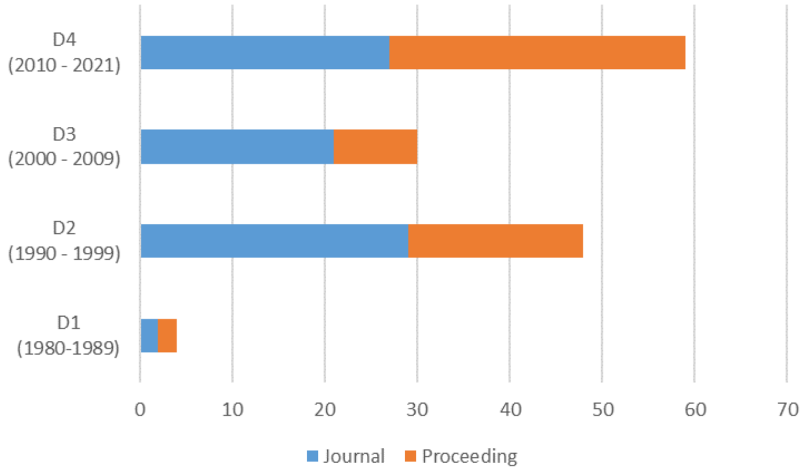

Figure 8 – Overall distribution of papers (journal and conference proceedings) per decades

A map was developed utilizing a bubble graph to analyse and show interest in the DFMA issue through time and discover future trends. (Figure 9). The considered topics are collected in Table 7.

Table 7 - Bubble graph topics

TOPIC		*Overall number of papers*	*Number of papers in the last decade (D4)*
T1	Simple products	70	33
T2	Complex product	11	8
T3	Early design phase (conceptual)	14	8
T4	Late design phase (embodiment and detail)	113	46
T5	DFMA CAD-linked methods	29	12
T6	Quantitative methods	93	43
T7	Qualitative methods	30	11

The size of the bubble represents the total number of publications for each topic during the period under consideration (i.e., decade D4). The Research Topic Share (RTS) is computed considering the overall number of papers divided for the number of papers of the last decade for a given topic. The Research Topic Growth Potential (RTGP) was computed by applying the least square method in relation to the number of publications per topic and year of the last decade (i.e., decade D4).

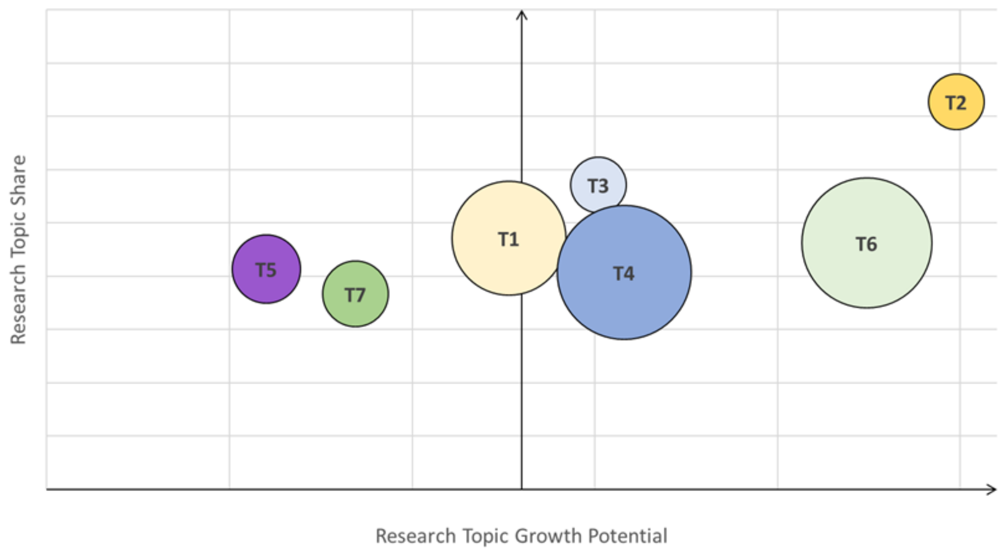

Figure 9 - Bubble graph results (Research Topic Share vs. Research Topic Growth Potential)

The graph is divided into two areas. The right side collects topics that have not been widely studied in the literature but are of high interest, while the left side reflects topics which are losing interest. According to the bubble graph, topics which have potential interest for further investigation are the topics T2 and T6 (i.e., DFMA methods applied to complex products and quantitative DFMA methods). The bubble size of T2 is small and only a few papers are present in the literature that describes DFMA methods applicable to complex products. However, although many publications in the literature provide quantitative approaches (large bubble), this topic remains of interest, and the bubble T6 is on the right side of the graph when compared with qualitative methods (bubble T7). Another topic which is gaining interest is the development of DFMA methods applicable at early design phases (i.e., conceptual phase). This is represented by the bubble T3, which is small in size (i.e., few papers available in the literature) but located on the upper part of the right side of the graph. However, there is still a strong interest in DFMA methods applicable at late design phases (bubble T4 - embodiment & detail) confirmed by the number of papers developed on this topic. DFMA methods applicable to simple products (T1) is a topic that is losing interest. Finally, it appears that the connection between DFMA methodologies and CAD systems is no longer of importance, and only a few papers in the last decade have been published on this topic. The reason could be technical and linked with the advent of the CAD systems that started to become popular at the beginning of the ’90s when numerous attempts were made to combine DFMA analysis with CAD systems. CAD tools are now widely used engineering systems for manufacturing industries, and research has shifted to other areas.

6 Conclusion

DFMA methods are widely used and well-known in industries as in academia. To the best of the authors’ knowledge, no recent review on this topic was found, and the only papers that proposed a review of DFMA methods are dated and missing systematic analysis. The goal of this paper is to provide a systematic review of DFMA methods in the field of mechanical design. The review was conducted following the systematic approach. The papers were gathered from four databases (Scopus, Elsevier, Taylor & Francis, and Emerald), and the filtering technique was developed to exclude common review paper flaws. The obtained articles were categorized and analysed to answer the research questions proposed. Results show that DFMA methods have been mainly applied to simple products during the late design phase. This trend is in line with the early aim of DFMA methods, which is the optimization of product manufacturability and assemblability by considering a given technology. A few works attempted to shift the use of DFMA approaches from detailed to conceptual design phases. With this aim, it is required a change in the DFMA paradigm, moving from a systematic approach to a First Time Right method. The main tools used to do DFMA analysis are spreadsheets and ad-hoc software, which are often linked to CAD systems. Only a few authors have investigated the adoption of enabling technologies for Industry 4.0 for developing new DFMA approaches, such as Artificial Intelligence and Virtual Reality among others. This result leads to an important outcome which is the possibility to close the gap between design and manufacturing departments in modern industries following the Industry 4.0 paradigm. According to the articles reviewed, it is worth noting that performing DFMA analysis early in the design process could result in benefits such as increased solution space. Finally, the research interest in DFMA methods has not gotten an important boost in recent years and this subject needs to be revitalized. There are two possible reasons for this finding. The first one concerns the loss of appeal for young scholars in developing DFMA for consolidated manufacturing and assembly technologies. In this regard, the focus of researchers moved towards new technologies (i.e., additive manufacturing), and new challenges (i.e., system integration). The second one concerns the adoption of novel approaches able to suggest the right design the first time, proposing a multi-objective optimization of the product when the manufacturability is only one of the targets to be optimized.

The proposed work presents some limitations typical of review studies. The main limitation is identified in the filtering process. The exclusion of non-academic works (i.e., technical reports, commercial software, etc.) might have had led to the exclusion of relevant papers.

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Conflict of interest

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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Code availability

Not applicable.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

Authors Contribution

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Giovanni Formentini. The first draft of the manuscript was written by Giovanni Formentini and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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