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A critical review of Design for Reliability - A bibliometric analysis and identification of research opportunities

Lucas Paganin[a]*, Milton Borsato[a]

[a]*Graduate School of Mechanical Engineeringand Materials, Federal University of Technology – Paraná, Av. Sete de Setembro, 3165, Curitiba (PR), 80230-901, Brazil*

Abstract

It is fundamental to adopt a Design for Reliability (DfR) approach at the stage of new product development in order to guarantee the reliability of an item at all stages of its life cycle. The amount of publications about DfR is not very extensive and it is somewhat dispersed. Thus, the main objective of this article is to collect and perform an analysis of the most recent literature. Fifty publications were analysed with the purpose of identifying the theoretical foundations regarding this topic. Moreover, the main applications, challenges and limitations of DfR were identified aiming the direction for future research.

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1. Introduction

In the last decades, the increasing competitiveness, the design and development of complex products and processes and the relevance given to consumer satisfaction have made studies on product reliability more prominent. According to [1], reliability can be defined as "the probability that a component, device, system or process will operate without failures for a given period if correctly used in a previously specified environment". The lack of reliability of a product can cause a number of undesirable consequences, such as safety, competitiveness, costs of maintenance and repair and brand reputation issues. Thus, the reliability of a product is closely associated with the number of failures that it will present in a given time interval.

* Corresponding author. Tel.: +55-41-98464-7669.
E-mail address: lucasbzp@gmail.com

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According to [2], reliability should be considered at the initial stages and during the entire product development process. The implementation of Design for Reliability (DfR) will help to identify problems associated with prototyping, thereby reducing life cycle cost, field failure rate and product time to market. To accomplish these objectives, activities focused on reliability and quality must be implemented in the product development cycle. Thus, achieving repeatability, stability, and maturity in the product development process at the testing stages is required as a demonstration of reliability.

At the initial stages of product design, several factors that can affect reliability should be considered. Nevertheless, such factors have a significant complexity, which makes them difficult to assess according to their weights and intensity for the reliability prediction. In other words, several uncertainties exist at the initial stages of the design process, thus making reliability estimating more difficult. Therefore, traditional reliability forecasting models may not be suitable for products involving a large number of uncertainties, particularly in the early stages of design [3].

In order to apply Design for Reliability (DfR) throughout a product development cycle, [4] states that the attributes of data collection for analysis need to be clarified in the first instance. Such data sources can be:

- Lessons learned from the field or tests;
- Data obtained from sensors regarding the stress of the product in the field or in test;
- Monitoring the progress of projects and activities;
- Questionnaire and consumer survey data;
- Knowledge of specifications, articles or training; and
- Benchmarking of specifications and requirements.

Taking into account the importance that the reliability of products has received in recent years, the advantages of adopting DfR in the early stages of product development and the scarcity of publications in this area, it is expected that this subject will become more relevant in the forthcoming years. Notably, the DfR research field is in development. Although there are several articles available on the most varied applications, few of these publications reflect what is known about DfR as a whole. In addition, since DfR should be implemented at the initial stages of the development of any product, several mathematical techniques and models appear as a way of modeling and predicting the reliability of what is being created. Some of the applications range from the improvement in the vehicle transmission system [5] to LED (Light-emitting Diode) lifetime [6] and virtual prototyping [7]. There are also investigative and theoretical publications, such as the ones from [8] and [9], that perform a mathematical analysis for DfR implementation.

In light of this dispersion of DfR studies, this article has as main goal to collect and review the literature on the subject in the last five years (2011-2016), seeking to identify the theoretical bases of DfR and the research opportunities about this subject. In order to achieve these objectives, a critical review of 50 relevant articles was performed. The selection and presentation of the details of this article sample are presented in section 2. The results obtained from the analysis of this sample are examined in two stages. Firstly, the theoretical foundations of DfR are discussed in order to obtain a more consolidated view of this area of research in section 3. This includes a brief definition of the terms, an evaluation of the adopted methods and examples of DfR applications. Then, the opportunities for future research are detailed in section 4. As final steps, the conclusion and references are presented.

2. Research Methodology

The literature on Design for Reliability contains a limited number of theoretical publications that demonstrates the main fundaments of DfR. From the existing publications, the different approaches are mainly linked to: theoretical / investigative [2, 6, 10-13], case studies [1, 14-18], mathematical modeling [8, 9, 19-23], data analysis to predict the reliability of a given product [4, 15], other methods to increase the reliability of a determined product [3, 24-27]. However, only a scarce literature refers to the theoretical foundations of DfR, which would serve as a practical and a generalized guide for its implementation at any company, regardless of the nature of the product to be designed. In this section, a summary of the selection criteria adopted for the choice of the article sample, its characteristics and the adopted revision process are presented.

2.1 Bibliometric Analysis of Articles

A selection process containing several steps and different criteria was adopted as a method for conducting this Bibliometric Analysis in order to choose the article sample, as it will be seen below. On the one hand, this selection process may be considered complete, since it comprises several steps to select and analyze a sample of articles. On the other hand, the screening process is simple and easy to be performed, because the steps are clearly defined and one must only keep the goals of one's research in mind to better select the articles.

First, the key words used during the entire article search process were selected. Three terms and their variations were chosen following the initial objectives of the article and the central axes of the research. Thus, Design for Reliability, DfR, New Product Development, NPD and Failure analysis were the chosen keywords which composed the searches.

Through the search tools ProQuest, Engineering Village (COMPENDEX), Scopus, Web of Science, Emerald, Springer, Science Direct, EBSCO and IEEE, 432 publications were found following a time interval of 5 years (2011-2016). All of these publications have been exported to EndNote software to facilitate data analysis and manipulation. Then, as an initial criterion, duplicate publications, chapters and parts of books were deleted from the first sample, leaving 357 publications for further analyses. The following step was the withdrawal of any articles from sources not related to engineering magazines (such as medical, physiotherapy, sports, biology, etc. articles), leaving 321 articles remaining.

Next, individual articles were analyzed in order to decide whether they should be adopted in the sample. In the first place, a reading of titles of all items was done, and through this criterion, only articles that had a consistent title according to the goals and axes of this research were selected. Hence, 91 articles were left for further analyses.

Following the screening process, Google Scholar was consulted to obtain the number of times cited that each of the remaining articles had. Hence, only those that had been cited at least once were selected. From this criterion, 54 articles were chosen and the rest were placed on-hold for a subsequent analysis and a possible selection.

From then on, a reading of the abstracts belonging to the 54 articles that continued in the screening was performed. In order to find the most relevant papers to accomplish this research, the reading of the abstracts had the purpose to identify the main results, goals, applications and the methodology adopted in each article. Thus, 37 publications did have some relation with the project proposal. Following the screening process, an analysis of the abstracts of those articles placed on the waiting list, which were not included in the sample of 54 articles and that were published in 2015 - 2016 was made. Then, other 13 were selected and added to the list, resulting in 50 articles for final analysis. A synthesis of all the adopted method for selection and analysis of the articles is shown in Fig. 1.

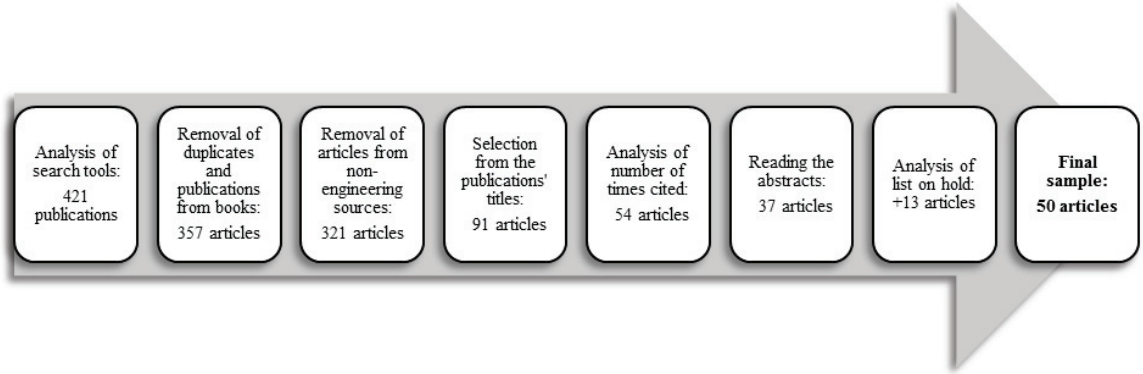

Fig. 1: Screening process to select the article sample

Continuing the bibliometric process, an analysis of the authors, year and main keywords found in the 50 selected articles was performed. It was observed that all publications were written by different authors. Concerning the year of publication, it can be stated that the year 2011 was the one that presented the most publications on those subjects in the last 5 years. Analyzing the frequency of the keywords in the articles, it was necessary, in some cases, to group

similar terms that were written in different ways (e.g. Design for Reliability, Design of Reliability and DfR). It can be seen that the term Design for Reliability is the most common one, followed by Failure Analysis and Product Development as shown in Fig. 2.

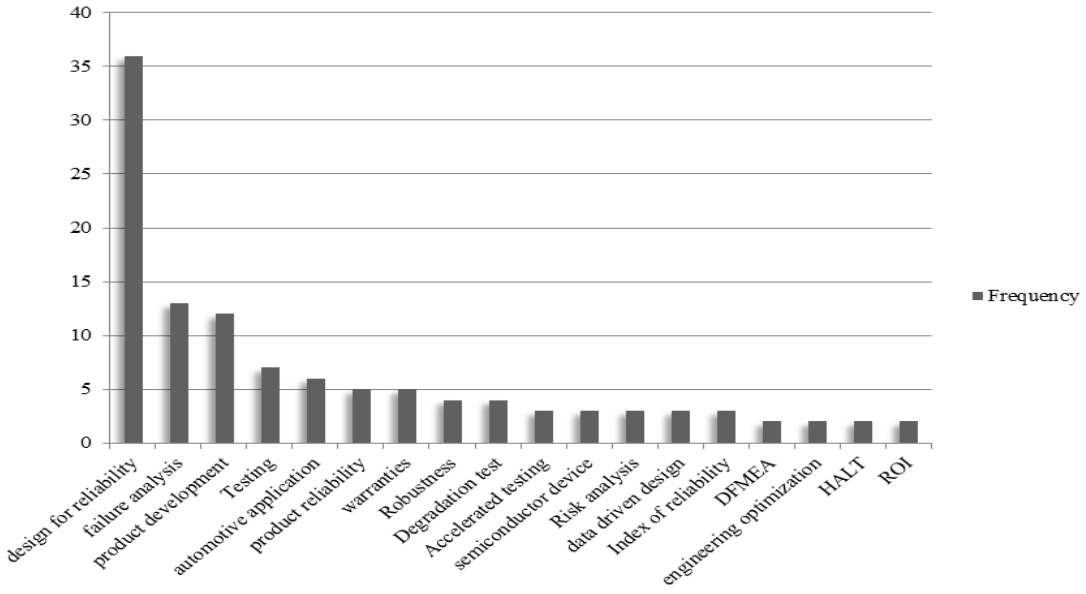

Fig.2. Analysis of the keywords

2.2 Systemic Analysis of Articles

During the entire process of screening and selection of articles, the sample was reduced from 432 to 50 papers to be analyzed. From that moment on, the systemic analysis of the articles started, in order to better understand the approach of each article.

Thus, a careful reading of the articles allowed the extraction of the main information in each paper. A spreadsheet was filled out containing data from each publication such as objectives, methodology, main results, future recommendations, unit of analysis adopted, among others. By means of such a spreadsheet, it was possible to derive some insights about the articles and to perform an initial analysis of the main future recommendations that should be considered for further research. In addition, it was possible to recognize the weaknesses and strengths of the analysis of the chosen themes.

From this systemic analysis, it was possible to identify similarities and differences among the articles. The work accomplished by [4, 8, 9, 20] is related to data analysis and simulations in order to perform a mathematical analysis of the reliability of some products. Furthermore, [5, 11, 17, 18, 26] use some statistical and quality tools, such as control charts, Design of Experiments and Taguchi methods in order to investigate the main causes of failures or to forecast the reliability of an item. Other articles have the main goal to discuss different approaches to implement DfR at different stages of new product development [2, 27].

At the end of this analysis, a critical view of the content to be worked, a greater knowledge of the DfR applications and the main fundaments involving DfR at the initial stages of product design were gathered (in section 3). In addition, a list of challenges and expectations for future research are described in section 4.

3. Review of Main Concepts and Foundations

In this section, the conceptual foundations about the Design for Reliability are explored based on the review of the article sample adopted in this project. This evaluation includes the conceptual definition, the methodology that should be adopted for the use of DfR at the initial stages of product design and its advantages. Furthermore, demonstrations of some applications already reported in the literature as well as their main results are presented.

3.1 Definition of key concepts

Design for Reliability is a process that describes the entire set of tools that supports the effort to improve the reliability of a product from its conceptual level until its obsolescence. The success of a DfR application is directly linked to the selection of appropriate reliability tools for each stage of product development and their correct implementation [12].

The DfR concept encompasses all aspects of a product's life cycle, including design, manufacturing, testing and field applications. Such a concept should be introduced into the product development cycle as early as possible. Knowledge about DfR is partially accumulated with learning from mistakes. Learning is then reflected in new design rules, better use of available materials, and improved processes [2].

According to [19], in order to successfully implement a DfR program, it is necessary to:

• Define the goals at the beginning of the program and the development of a plan to achieve those goals;
• Enable reliability objectives to be driven by a reliable team;
• Provide metrics so that it is possible to measure the position of the company in relation to the previously established objectives; and
• Write a reliability plan to guide the program.

For the planning of a DfR process, it is necessary to use test data, which will involve many different aspects and tools that influence the improvement in the product design and its reliability. Thus, people, departments and other bodies can be involved [4].

In the field of applications and tests that give continuity to the DfR process, the most common method used to qualify the reliability of a product is the zero-defect test. This method requires fewer samples for testing and less time when compared with other test methods that guarantee the same reliability in the same confidence interval. In the zero-defect test, n identical items are simultaneously tested and have the procedure continued until a pre-specified time T. If no failure occurs, the test is considered satisfactory. However, if one or more faults occur, the test is considered flawed [25].

To assist in the DfR process, some tools can be used to simplify analyzes related to the reliability of the products. As an example, [5] use Quality Function Deployment (QFD) to translate users' needs into design specifications. Yet [17] employ Petri nets to predict the reliability of a mechanical equipment. [25] operate the Weibull statistical distribution to estimate the failures of pneumatic cylinders. The use of Fault Tree Analysis (FTA) and Design Failure Mode and Effect Analysis (DFMEA) is made by [16] to elaborate the best configuration for a given product.

3.2 Implementing DfR

According to [2], methods to implement DfR should comprise the following aspects:

• Understand the end user usage conditions;
• Define reliability requirements considering the needs of the consumers and the capabilities of the company;
• Identify key reliability risks and failure mechanisms;
• Be aware of manufacturing processes and materials;
• Be aware of what has already been done and has not worked and the reasons;
• Be aware of the reliability of the items to be selected;
• Reuse trusted designs already adopted on previous products;
• Analyze and advise plans that accompany the risks of reliability;
• Actively participate in the product development cycle;
• Ensure quality and reliability of components with suppliers;

• All manufacturing and assembly processes must be capable of producing within acceptable statistical limits;
• Constantly monitor and control process reliability.

Some tools and methodologies should be used in order to implement DfR in the product development cycle. [2] recommend the use of fault-tolerance approach, fault-tree analysis, failure mode and effect analysis, de-rating, reliability simulation, design of experiments, accelerated stress testing or feedback of field information in order to improve processes and products.

A method for DfR implementation is proposed by [24] with the aim of reducing the rate of "infant mortality" (premature failure) of the products. The use of engineering optimization is proposed in order to understand the critical factors of the design and process phases and then to determine the optimal conditions for the process, which can ensure robust reliability. This allowed changes in design specifications, a process optimization and a reliability control planning which reduced potential problems that might affect the reliability margin. Furthermore, [24] state that when a product qualification fails the reliability tests, DfR concepts must be implemented late in the development cycle causing a delay to the time-to-market and increasing the costs related to tests and development.

3.3 DfR Applications

From the selected article sample, it is possible to find several applications for reliability studies. There are examples of practical applications in the form of case studies. Moreover, theoretical/mathematical investigations and also applications of different methodologies to forecast product reliability are found in the sample.

Among the analyzed applications, it is important to cite the work of [21] that applies the concepts of probability to DfR in order to quantify, predict and assure the reliability of electronic products and to understand the nature of their failures. The obtained model was suggested for the calculation of new products' reliability, since there is no operational reliability data or even experience of the best practices to be applied.

The work done by [27] performs an application of DfR in a new lighting technology, solid state lighting (SSL). Because this technology is still recent, there is not much research on its reliability and thus, the introduction of DfR was performed in three levels. First, the design phase was analyzed, when device failures and their reliability were investigated. Based on these results, the causes of failures and their lifetime relationships with an SSL device were defined. Thus, the second stage of the work consisted in the processing of sensor data while the device was in operation. The last step of the reliability analysis consisted in the ability of the system to predict its failures and be functional for a longer period of time. The proposed approach is an example of DfR application in systems where there is not much information about the reliability of the product.

4. Research Opportunities

Analyzing the article sample, five research opportunities were found as described below:

(1) Application of quality tools to assist DfR implementation: the application of combined quality tools can result in a significant increase in the reliability of products and processes. [26] implement the Six Sigma methodology in manufacturing and distribution networks, with the objective of achieving a high reliability product in a shorter period of time. On the other hand, [18] use the Taguchi and FMEA methods to increase the reliability of electronic paper display (as e-book's). [11] apply control charts for monitoring and the manufacturing process and thereby ensuring product reliability. The literature points to cases of using separate tools to improve product reliability. It is suggested that the application of two or more tools for analysis and improvement of the design and manufacturing process could be better explored in future research. This would permit a broader analysis about the main failure causes and respective solutions.

(2) Mathematical modeling to predict the reliability of a product: in several articles analyzed, the use of mathematical and statistical methods to predict the reliability of certain products was adopted [8, 9, 19-23]. They all used simulations, statistical analyses or mathematical modeling to predict the reliability of a determined product. Thus, based on the product specifications and the conditions of use from the final consumer, it is possible to calculate the failure index and product reliability. The implementation of statistical and mathematical methods should be adopted to predict the reliability of different products, which were not listed in the known literature, as well as an analysis of the nature of the failures of those items.

(3) Analysis of a product's critical components: as a way to improve the reliability of a product, the analysis of the individual components may be a useful tool to find the nature of faults and the critical factors that may have some interference in Reliability. [10] execute a similar study, in which it was evaluated how each operational state of specific components influences in the reliability estimation of automatic equipment. Another work that performs a similar analysis is that accomplished by [13], which found six critical factors that affect the reliability of the bulldozer's subsystems. In this way, a more detailed investigation of the products' components, as well as their interactions with the environment in which they will be operated, may lead a significant improvement to the items' reliability. Moreover, this should optimize their design, manufacturing and test planning process. This analysis would be more complete, since it would not consider individual items separately.

(4) The elaboration of an overall methodology for DfR: from the article sample analyzed, few described methods for applying a DfR program. It is known that the use of DfR in all phases of product design brings significant gains for a company in economic issues as well as for the company image. Some research performed by [12] and [24] point to a specific methodology for the DfR's use. Nevertheless, it was not possible to find in any article a generic method that would serve as a basis for companies from different sectors. The elaboration of a generic method that takes into account the main aspects to be observed in each specific situation as well as the application of tests in different sectors appears as a recommendation for future research. This would facilitate the implementation of DfR in different companies searching an improvement in reliability.

(5) Analysis of historical data from tests and information from technical assistance: the analysis of historical data, as performed by [4] and [15], may be a useful methodology for modeling and predicting products' reliability. Based on this information, it is possible to estimate how close to the initially expected value the reliability of a given product is or to perform a modeling that determines the failure index. Since this is a method that uses real data to perform calculations, its application in companies is feasible in cases where historical records of tests or information about failures from technical assistance are available. This recommendation is due to the fact that few works perform an analysis of historical data. Instead of relying on the empirical knowledge about reliability of items and products, this analysis associated with the recommendation (2) would become better founded.

5. Conclusion

With the increasing pursuit of attracting more consumers, companies have been more concerned about product reliability. In some situations, reliability is equivalent to safety. In this way, the study and application of DfR in all phases of a product life cycle emerge as a possibility to ensure the quality and reliability in addition to establishing the good image of the brand in the consumer market. This article aimed to analyze the implementation of the DfR approach in the conceptual phase of product design, as well as to find the state of the art for the subject in the last five years.

In order to achieve the proposed objectives, a specific method to analyze publications on the subject between 2011 and 2016 was adopted. From this analysis, a sample of 50 articles was obtained. Once this was done, a systemic analysis of the articles was performed in order to obtain a theoretical review and to find future research opportunities.

Based on the reading and analysis of the article sample, it is possible to conclude that the implementation of DfR will be increasingly highlighted in the product design's scenario, since there are financial gains and improvement to the company's image. Thus, propositions for future research include:

- Further analysis of how the application of combined quality tools can assist in the implementation of DfR;
- Research related to simulation and mathematical modeling to predict the reliability of products;
- Detailed analysis of products' components and their influence in reliability;
- Targeted research for the creation of a generic DfR application methodology for several product types; and
- Mathematical analysis of historical data or from technical assistance in order to model or estimate products' reliability.

Studies related to DfR remain scarce and still with specific applications in certain areas. Certainly, it could be implemented to the development of all the products. The current attempt to excel in this competitive scenario is now a concern to all the companies and this may be achieved by enhancing product reliability and reducing losses and

failures. For this reason, it is possible to affirm that the studies related to DfR will gain increasing attention in the next years.

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