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Review Article

Design of a New Safe Operating Product: Review, Classification and Opportunities

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ABSTRACT

The paper presents a literature review on the problem of safety in the design of a new product. To do this, approaches of design and domains that have been integrated into it are firstly presented. Next, diverse methods for predicting and evaluating the safety properties are defined. Then, different approaches that have been developed to solve the problem are discussed, and a synthesis table is given that regroups all the work carried out, allowing a comparative analysis leading to the identification of future research tracks.

Keywords: Availability, design, evaluation, maintainability, product, reliability, security

INTRODUCTION

The decisions taken at the preliminary design of a new product determines 70% of the future costs of the product's life cycle (Salomone, 1995). This phase is, therefore, risky. To manufacture a new product, the company must manage well the risks involved throughout this process. The risk involved in design, according to Sarbacker and Ishii (Sarbacker et al., 1997), results from exposure to a chance of failure due to a lack of understanding of the critical parameters of a decision problem and/or lack of information on some variables relevant to the design problem. Improper decision-making in the design can lead to product failure, security risks, manufacturing problems, waste etc. To reduce design risk, the designer must make advanced decisions that allow easy and reliable comparison between concepts with

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regard to design objectives. It is, therefore, necessary to be able to evaluate several concepts and take into account all the constraints of the preliminary design problem. Evaluating the safety of a product during design involves assessment of its reliability, availability, maintainability and security. This article describes the basic tools for the prediction of a safe product as well as the evaluation indicators of this characteristic of safety. The second part deals with the various approaches to resolution, the research methodology adopted and a summary table regrouping all the works already considered in the literature.

Design Process

A product is traditionally designed from a specification according to needs expressed by a customer or a market study. According to Chandrasekaran(Chandrasekaran, 1990), the design process is an activity that solves problems whose input data include the list of functions that the object to be designed must accomplish, a set of constraints that must be satisfied, a set of predefined components and a set of relations connecting these various components. The solution of this problem is chosen from a set of alternatives that follows different evaluation criteria (performance, cost etc.). The literature gives several approaches and design methodologies; the well-known ones are the systematic approach developed by Pahl and Beitz(Pahl & Beitz, 1996), the axiomatic approach described by Suh(Suh, 2001), the ANSI approach EIA-632(ANSI, 1998) and the integrated engineering approach, also known as integrated design or concurrent engineering by Prasad(Prasad, 1997). In all these cases, there is a division into fairly identical phases that stems from the need to provide validation steps; each phase ends with choices and decisions. Integrated engineering is characterised by two main principles: simultaneity and integration. It avoids costly reworks associated with the late recognition of constraints specific to activities that are downstream of the product's life cycle (Bourgeois, 1997). This approach was developed and is often used by designers (See Figure 1).

Design for X (DFX). Designers are guided by several concepts, but these concepts have their own constraints, which may be related to assembly, manufacturing, reliability, environment etc. The concept that presents constraints for designers is discussed in this paper, referred to as 'X'.

In the late 1970s, Boothroyd and Dewhurst(Boothroyd, Murch, & Poli, 1978) and Stoll(Stoll, 1988) developed the design concept for assembling (DFA), which took into account assembling constraints during design phases. Inspired by the DFA, Stoll developed the design concept for manufacturing (DFM) to consider design objectives and manufacturing constraints simultaneously. Kobe(Kobe, 1990) combined the DFA and DFM to form a design for the concept of manufacture and assembly (DFMA). The use of the DFM and the DFA has given tremendous benefits, such as simplifying products, reducing manufacturing costs, improving quality and reducing time to market. Over time, researchers began to think about integrating not only assembly and fabrication but also disassembly and recycling (Zussman, Kriwet, & Seligar, 1994), environment (Korpalski, 1996), quality (Taguchi, 1993), maintainability (Moss, 1985) and reliability (Ireson, Coombs, & Moss, 1988).

Safety in design

Dependability in design is called Defect Science, Risk Analysis or FMDS. It is defined as the ability to maintain the proper functioning of a product and its constituents over time, throughout its life cycle. Assessing the safety of a product during design involves assessment of its reliability, maintainability, availability and safety.

Conducting a safety study when designing a new product has become the practice for industry, given the direct impact on the product and its environment. As a result, this process has been standardised in different fields. Evaluation of the design of products for safety compliance is done by IEC 61508 (International Electrotechnical Commission, 2000) and its derivatives that deal with the safety of electrical/electronic and programmable electronic systems, the ARP-4754 (ARP4754, S. A. E. 1996) standard for the development of aeronautical systems and the ARP-4761, which complements the ARP-4754 (SAE International S-18 Committee, 1996) standard.

Reliability. Reliability is a characteristic of the system expressed by the probability that it performs the function for which it was designed, under given conditions and for a given period of time (NF X 060-010 - AFNOR [1991]). It is the probability that an entity can perform a required function under given conditions during a given time interval [t1, t2]. It is characterised by four criteria: (i) Lifetime probability density f (t), (ii) Reliability at time t r (t), (iii) Lifetime distribution function f (t), and (iv) Failure rate λ (t). The analysis of these criteria by time interval is not easily manipulated for the calculations (derivation and integration), so researchers use mathematical functions such as the probability density functions. These laws may be discrete (Poisson's law) or continuous (normal law, exponential, Weibull). In this article, we are interested in predictive reliability, which is the reliability estimated during the design process, based on a mathematical model and the estimated reliability of the components. Without reliability data, it is difficult to assess reliability. The data sources can be exploited during the design phase, depending on the components integrated into the solution. The components can be separated into two groups (Menye, 2009): i) Identical or similar components that have already been used in other products, whose data are derived from existing system histories, and ii) New components, specially designed for the solution adopted during development. Fail rates can be evaluated either by similarity or by an approach that allows to estimate the parameters influencing the reliability of the product.

The predictive reliability assessment indicator is a probability function, so the analysis of this reliability is carried out using probabilistic approaches, taking into account the dispersion of the design variables. Among the approaches used is the constraint-resistance approach (Lewis, 1987; Murty et al., 1995), which is based on the probabilistic comparison of resistance and constraint, which are considered random variables. The method of first-/second-order approximation (FORM/SORM) is the most efficient in terms of the ratio of computational time and response accuracy; it begins by searching for the design point in variable space, followed by the approximation of boundary-state function by a first-order (FORM) or second-order Taylor expansion (Ouakki, 2011). Another method is the Monte Carlo simulation method, which is a numerical simulation technique based on the calculation of the performance function of a sample representative of the population. This method is very efficient, but it takes up significant computational time (Curbach et al., 2004).

To identify the factors that influence the reliability of a product, the designer may use analytical tools such as: (i) Failure trees and the Ishikawa diagram, which aim to determine component failures that can lead to adverse events (ii) The FMEA product (Bertsche & Lechner, 1999), which is a method of risk prevention during design with the goal of reducing failures and modifying them at a very early stage (iii) The quality house (QFD) (Akao & Mazur, 2003), which allows the targeting of factors necessary to satisfy the expectations of the client.

Availability. Availability is defined by the ability of a component to be able to perform its function under given conditions at a given instance or during a given time interval [T1, T2]. It is expressed by the probability that the system fulfils its required function under certain conditions (AFNOR, 1977). Unlike reliability, the calculation of availability is not limited to non-repairable systems. Calculation of the availability of non-repairable systems is equivalent to the calculation of their reliability. It is expressed as the rate of failure and repair of system components.

Maintainability. According to the NF X 60-010 standards (AFNOR, 1991). maintenance includes all activities intended to maintain or restore an asset in a given state or given security conditions in order to perform a required function. Maintainability is characterised by the probability M (t) that the entity E is in a state at time t to perform its functions, knowing that the entity failed at time 0 (Demri, 2009). The maintainability forecasting approaches available in the literature can be classified into two categories: i) Extrapolation of the maintainability index (Tarelko, 1995), whose forecast is based on feedback from similar products, and ii) The summation of times (Coulibaly, Houssin, & Mutel, 2008; Zwingmann, 2005).

Security. Security is defined as the absence of conditions that guide the impact of a hazard when using a product. The absence of security implies the presence of risk. It is, therefore, necessary to manage risk at the earliest stages of design to obtain a secure product.

Risk management makes it possible to plan, predict and implement the actions to be taken into account in order to avoid risk. The main stages of risk management are (Guillerm, 2011):

a. Risk identification: This is the collection of all types of risk. Possible sources of information for this collection may be consultations, archives or project briefs.
b. Risk assessment and classification: The assessment of the probability and severity of the risks identified in the first phase can reduce their criticality.
c. Risk treatment or acceptance: This step consists of treating risks with high criticality. Acceptance of these risks is defined by the standards according to the activity of the company and the commercial aspects.
d. Consequence analysis and follow-up: Re-examination of the elements impacted by the treatment of the risks to check if new risks have appeared.

After governing against all types of risk, the designer is in a position to choose concepts that have no impact of use or those that have an acceptable degree of risk. Safety indicators can help in this decision-making. Coulibaly et al. (2008) proposed a risk assessment indicator that can be used in the design phase. This indicator is the product of a risk factor FR_{is}, which indicates the existence or not of a risk, and it takes the value 0 in the absence of risk and provides a risk index IR_{is} that allows to qualify and quantify the risk. If $FR_{is} = 1$, the designer

must change its parameters to cancel the value of this flag. If this is not possible, the designer must determine the risk index IR_{is}. Sadeghi (Sadeghi, Mathieu, Tricot, & Al Bassit, 2015) developed risk assessment indicator based on that by Coulibaly, and proposed a more effective indicator of risk that can be applied throughout the design phase.

Methods of Resolution

Several resolution approaches have been developed to address the various safety parameters. Methods of solving safety problems can be classified into two classes, graphical methods and heuristics.

Graphical methods. In the literature, the validity of the safety properties requires the verification of the four categories of elementary graphical conditions i.e. the conditions of connectivity, link, distance and full coupling. Chart blocks have been widely used in the literature to solve this problem, but this tool is not sufficient for validating all the conditions. The conditions of connectivity, link and distance are verifiable by a directed graph. This type of graph represents system variables by vertices and their relationships by arcs. The condition of the complete coupling is verifiable by graphs. A graph is composed of two sets of vertices representing the variables of the system connected by arcs that represent the relations between these variables. The most used graphs for solving the security problem are the Bayesian networks, dynamical Bayesian networks, Markov chains and Petri networks.

Heuristics. A heuristic is an approximated algorithm allowing to identify in time at least one quick, not necessarily optimal, realisable solution. The use of a heuristic is efficient for computing an approximate solution of a given problem. There are three types of heuristics: Constructive heuristics, which generate solutions from an initial solution by trying to gradually add elements to them until a complete solution is obtained; Heuristics with local improvements that start with a complete solution and repetitively try to improve this solution by exploring its neighbourhood, and; Meta-Heuristics, which represent optimisation algorithms that solve difficult optimisation problems for which no more efficient conventional methods are known. They generally represent iterative stochastic algorithms that progress towards an overall optimum. Figure 2 presents the different classes of meta-heuristics.

RESEARCH METHODOLOGY

In order to develop a general bibliography covering various tools and methods for evaluating the safety of new products during design, several databases were examined, including DOAJ, Open J-Gate, IEEE Xplore, Science Direct, Web of Knowledge, Taylor and Francis Online, Springer, Elsevier, IOP science and Scopus. In order to ensure a targeted search, appropriate keywords were chosen to make it possible to enclose problems such as conception, manufacturing, product, security, reliability, maintainability, security, availability, evaluation and decision support. Several combinations of keywords were used to make the results more suitable. The literature is distributed in a good proportion in scientific articles, articles from industry professionals and a few doctoral theses.

LITERATURE REVIEW OF THE SAFETY PROBLEM

Since safety as a topic has attracted much attention given its importance, the number of publications has been gradually increasing over the last few decades (Figure 3). Table 1 summarises all the abbreviations of the graphical and heuristic methods used in this paper. Table 2 summarises the work carried out and the methods of problem solving and provides the names of the authors of the methods.

Analysis and Discussion

The analysis shown in Table 2 highlights that the majority of the work focused on reliability studies. Graphical methods were used to evaluate a single criterion, unlike heuristics. However, it can be seen that graphical methods were used more in the literature than heuristics. The most used graphical method is BN and GA for meta-heuristics. Figure 4 shows that 62.96% of the publications treated reliability problems, 17.59% dealt with the subject of maintainability (disassembly), 9.25% with availability and 10.18% took into account the problem of security.

In terms of resolution methods, the analysis revealed that the BN method represented a percentage of 39.13%, the BN hybrid, 5.79%, the PN method, 8.69% share, the MC, 20.28% and NN, 4.34%. The GA appeared in 15.94% of the documents. The ACO method was used in 2.89% of the documents, while TS and SA were seen in 1.44% of the documents. Figure 5 shows the percentage of publications by types of method relevant to the problem of safety.

CONCLUSION AND PERSPECTIVES

This article represents a general synthesis on ensuring the safe operation of new products from the design stage. We first presented the estimation and prediction tools required and then the methods and approaches available in the literature related to modelling the behaviour of multi-component products. The analysis showed that researchers are most focused on the study of reliability, and have been so since the 1990s. The majority of the problems addressed in this field were solved using modelling by Bayesian networks. If multi-criteria problems are solved, most of them are solved by genetic algorithms. From this perspective, future work will focus on solving safety problems by coupling all its characteristics.

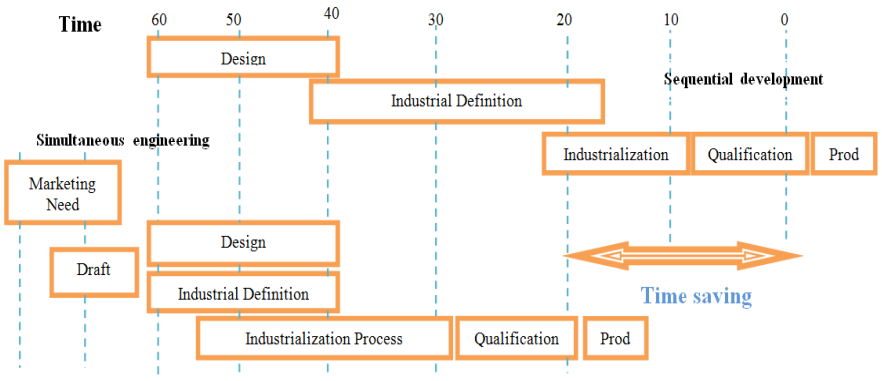

Figure 1. Difference between sequential and simultaneous engineering

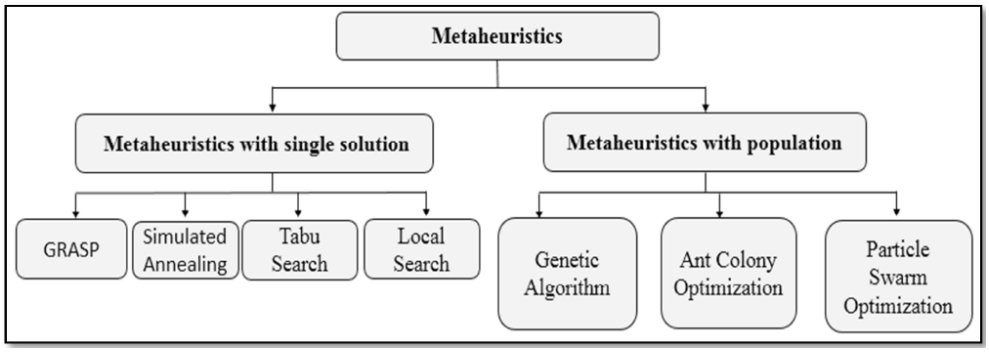

Figure 2. Different approaches to meta-heuristics

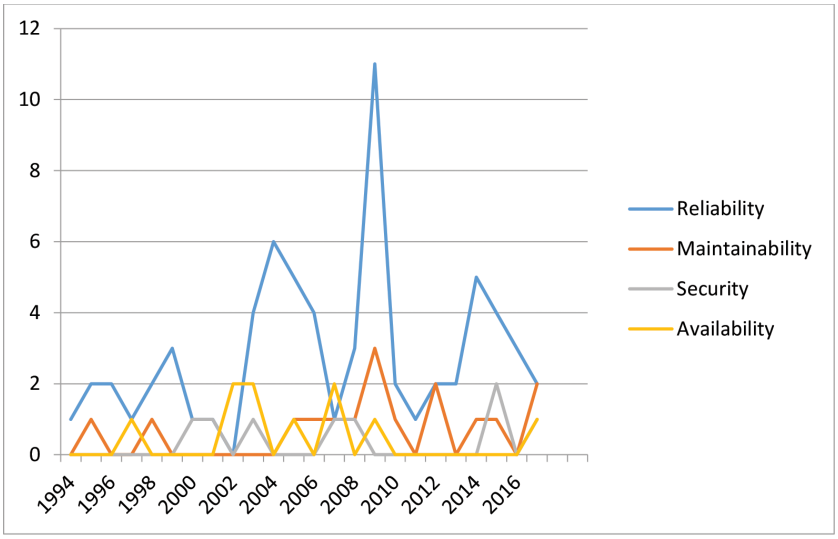

Figure 3. The evolution of publications on the problem

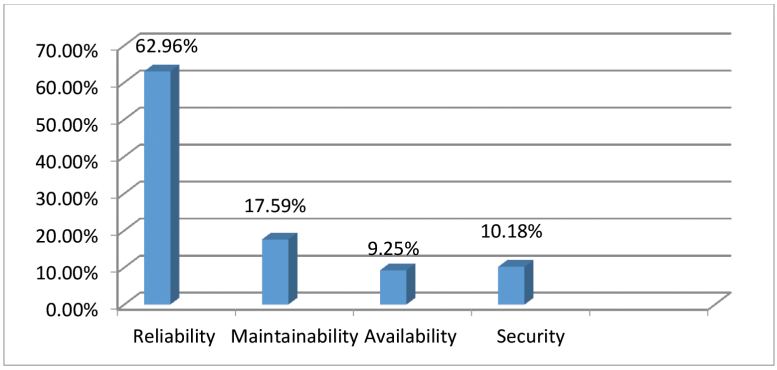

Figure 4. Percentage of safety characteristics treated in the literature

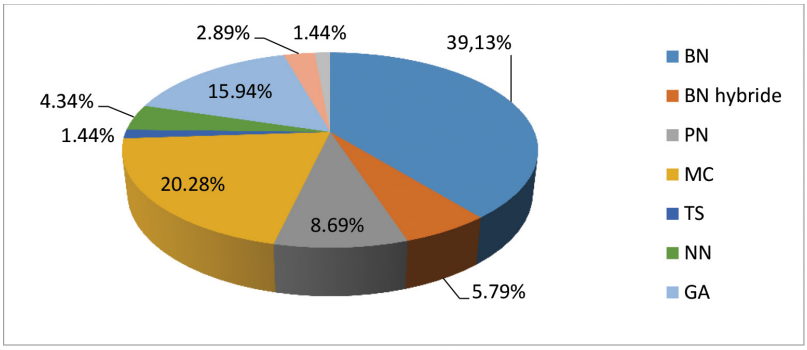

Figure 5. Percentage of methods used

Table 1
Abbreviations of the graphical and heuristic methods

Abbreviation	Approach
BN	Bayesian Network
PN	Petri Network
MC	Markov Chain
GA	Genetic Algorithm
TS	Tabu Search
NN	Neural networks
ACO	Ant Colony Optimisation
SA	Simulated Annealing

Table 2
Summary of works addressing safety issues

Reference	Problem	Approach
Hulting et al. (1994); Tang et al. (1997); Torres-Toledano et al. (1998); Portinale et al. (1999); Castillo et al. (1999); Weber et al. (2003); Guérin et al. (2003); Weber et al. (2004); Graves et al. (2005); Boudali et al. (2005a); Boudali et al. (2005b); Montani et al. (2006); Weber et al. (2006); Simon et al. (2008); Simon et al.(2009); Portinale et al. (2010); Doguc et al. (2009); Guo et al. (2013); Su et al. (2014); Cai et al.(2015); Weber et al. (2015); Mi et al. (2016)	Reliability	BN
Bouissou et al. (1999); Gulvanessian et al. (2001); Qien, (2001); Welch et al. (2000)	Security	
Boudali et al. (2006); Neil et al. (2008); Marquez et al. (2010); Langseth et al. (2009)	Reliability	BN hybrid

Table 2 (*continue*)

Reference	Problem	Approach
Schneeweiss (2001); Volovoi (2004); Charki et al. (2009); Demri (2009)	Reliability	PN
Moore et al. (1998); Tang et al. (2006)	Maintainability	
Giraud (2006); Zwingmann (2005); Zaghar et al. (2014); Guilani et al. (2014); Wan et al. (2016)	Reliability	MC
Timashev et al. (2015); Li et al. (2017); Guilani et al. (2014); Karami-Horestani et al. (2014); Wan et al. (2016)	Reliability and maintainability	
Amiri et al. (2007); Sadaghiani et al. (2009); Kayedpour et al. (2017)	Availability	
Tan, (1997)	Reliability and availability	
Bland (1998)	Reliability	TS
Ricotti et al. (1999); Xu et al. (2003)	Reliability	NN
Rajpal et al. (2005)	Reliability, availability and maintainability	
Taboada et al. (2008); Rathod et al. (2013); Safari (2012); Coit et al. (1996a); Coit et al. (1996a)	Reliability	GA
Johansson et al. (2017)	Reliability and security	
Papadopoulos et al. (2005)	Security	
Elegbede et al. (2003); Fiori de Castro et al. (2003); Chiang et al. (2007)	Availability	
Liang et al. (2004); Ouiddir et al. (2004)	Reliability	ACO
Chiang et al. (2007)	Availability	SA

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