INTEGRATING RELIABILITY IN CONCEPTUAL PROCESS DESIGN: AN OPTIMIZATION APPROACH

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ABSTRACT

The key objective of this study is to develop a systematic theoretical framework for integrating reliability of industrial plants into the design process from the conceptual stage to the useful life. This framework will allow designers to specify quantitative targets for reliability and arrive at optimal design parameters. In industry, at the conceptual stage, the benchmark data from similar plants and the designer's own experience often replace the more systematic quantitative reliability analysis for setting reliability targets. In the most favourable cases, the quantitative reliability analysis is performed at the basic engineering stage of the process design; in the worst cases, it is done at the detailed engineering stage. The industry often takes a more 'reactive' approach: improving RAM performance by adjusting the maintenance management, using mostly qualitative tools, such as RCM, FTA, FMECA, etc at the operational stage. Although this approach does improve the system's RAM performance compared to the status quo, long-term benefits can only be achieved by taking a knowledge-based approach: setting quantitative RAM targets in the design phase that can be controlled throughout the life span of the plant.

Keywords: Reliability, Optimization, Integrated Reliability Model,

1. INTRODUCTION

A major objective of this work is, to ensure that reliability characteristics are included in system/product design. Specific qualitative and quantitative requirements are identified through the needs analysis, the accomplishment of feasibility studies, and the development of system operational
Of particular significance is the day-to-day design participation process and the program tasks that are directed to facilitate the incorporation of “reliability in design”. As the responsible design team progresses towards the definition of specific design configuration, must be considered several different design factors, acquiring the proper balance between reliability and the many other factors that must be addressed to meet the consumer needs. This consideration is best accomplished through the representation of a reliability specialist as part of the design team.

The success in meeting this objective is highly dependent on having the appropriate tools available for accomplishing the necessary design analysis and evaluation activities. The utilization of models for the purpose of requirements allocation, the availability of various design analysis methods to help in design definition process, and the use of tools for system/product evaluation are key areas where the reliability specialist can contribute positively to ultimate design output. The next section of this paper covers some of these key tools, technologies, and aids encountered in literature.

2. LITERATURE SURVEY

Various degrees of freedom to improve the reliability measures are listed in Fig. 1.1. Considering the overwhelming number of factors that influence overall plant reliability, it is not surprising that there is a myriad of methods, both qualitative and quantitative, and software tools that are available today to support RAM studies during plant's life cycle.

Fig. 1.1: Typical plant life cycle (H. D. Goel, 2004)
At each stage the loop reliability process is depicted in the following fig. 1.2.

![Reliability design process diagram](image)

**Fig. 1.2:** Reliability design process (Ebeling C. E., 1997)

In literature a number of review papers have appeared in the last few decades that provide a detailed survey of topics that include reliability-availability analysis methods (Dhillon B. S., 1999), (Sathaye et al., 2000), reliability optimization (Kuo and Prasad, 2000) and, maintenance optimization (Dekker, 1996). More detailed information on these topics can be found in standard reliability engineering textbooks such as (Henley and Kumamoto, 1992), (Billinton and Allan, 1992), and (Kuo et al., 2001).

The calculation of number of components, component’s reliability, stage reliability, and the system reliability represents an Integrated Reliability Model (IRM) according to (Kuo and Rajendra Prasad, 2000). The classic approach of this work was proposed in (Lakshminarayana K. S. and al., 2013) to optimize a class of IRM for redundant systems with volume and weight as the other constraints. Notwithstanding unreliability of systems still remains researchers’ preoccupation issue.

### 2.1 Reliability growth curve

New systems and products often display a lower reliability during the early development phases. System reliability can be improved by analyzing and fixing some failures modes experienced. Reliability growth is a very relevant concept as far as maintainability analysis is concerned and can contribute to the overall effectiveness of the system infrastructure. And the curve in the Duane model can be expressed as:

$$\log(MTBF_i) = \log(MTBF_c) + \beta \log(T) \quad (1)$$

Where $MTBF_c$ and $MTBF_i$ are the cumulative and starting mean time between failures, $T$ is the total test or operating time, and $\beta$ is the slope of growth curve.

To fully realise the benefits of system reliability growth, it must be properly managed. Fig. 2.1 is illustrative of the adapted management and planning of that process (Blanchard et al., 1994) improved in this work.
3. INTEGRATING RELIABILITY FRAMEWORK PROPOSED

Integrating reliability optimization formulation into an existing framework will lead to one integrated design, reliability and maintenance optimization framework which in some cases could be computationally expensive. In this work, a decomposition strategy is adopted to decompose the large synthesis, reliability and maintenance optimization problem into manageable sub-problems: reliability optimization and process synthesis, and maintenance and design optimization problems. Thus, the following section will start with the illustration of common failures taxonomy, and forward strategies to integrate reliability in design process will be tackled.

3.1 Identification of life cycle systems failures

The various failures causes in Fig. 3.1 are not necessarily disjoint. There is, for example, an obvious overlap between “weakness” failures and “design” and “manufacturing” failures. Failure mechanisms are, defined as the “physical, chemical or other processes that has led to a failure.” A common interpretation of this term is the immediate causes to the lowest level of indenture, such as wear, corrosion, hardening, pitting, and oxidation.

This level of failure cause description is, however, not sufficient to evaluate possible remedies. Wear can, for instance, be a result of wrong material specification (design failure), usage outside specification limits (misuse failure), poor maintenance - inadequate lubrication (mishandling failure), and so forth.
And the table 1 below highlights exhaustively the reasons of those failures.

**Table 1: Reasons of system life cycle failures**

<table>
<thead>
<tr>
<th>Engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
</tr>
<tr>
<td>Functional Deficiencies</td>
</tr>
<tr>
<td>Faults</td>
</tr>
<tr>
<td>Hazard undetectable</td>
</tr>
<tr>
<td>Inadequate instrumentation</td>
</tr>
<tr>
<td>Inadequate components</td>
</tr>
<tr>
<td>Inadequate inspection</td>
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<tr>
<td>Inadequate testing</td>
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</tbody>
</table>

3.2 Mathematical Model of failed System

Let’s delineate the failed mode system by FS. It is a function of numerous causal technical and operational variables in design, manufacturing, commissioning and useful life period (see table 1). According to the network components assembly configurations, reliability of the functioning system is expressed in by [19]:

\[ R(t) = 1 - F(t) \] (1)

F(t) is the probability of FS (unreliability). Thus in case of:

- Series configuration:  \[ R(t) = \exp\left\{-\int_0^t \sum_{i=1}^n \lambda_i(u) \, du \right\} \] (2)

  The failure of one element of the n elements in series leads to the failure of the system. \( \lambda_i \) is the element failure rate.

- Parallel configuration:  \[ R(t) = 1 - \prod_{i=1}^n \left(1 - \exp\left(-\int_0^t \lambda_i(u) \, du \right)\right) \] (3)
The failure of all design elements is necessary to fail the system.

- **Parallel-series configuration:**
  \[
  R(t) = \prod_{i=1}^{n} \left[1 - \prod_{j=1}^{p_i} \left(1 - R_{ij}(t)\right)\right]
  \]  
  \( (4) \)

  The system is an hybrid one, where \( p_j \) elements are in parallel, and \( n \) subsystems are in series, \( R_{ij} \) being the element reliability.

- **Series-parallel configuration:**
  \[
  R(t) = 1 - \prod_{i=1}^{p} \left[1 - \prod_{j=1}^{n_i} R_{ij}(t)\right]
  \]  
  \( (5) \)

  Each of \( p \) branches has \( n_i \) series elements, whereas \( R_{ij}(t) \) is the \( j^{th} \) element of the \( i \)-branch.

- **r - out - of – n: G System with independently and Identically Distributed Components**
  The reliability is equal to the probability that the number of working components is greater than or equal to \( r \). Thus:
  \[
  R(t) = \sum_{k=r}^{n} C_n^k r(t)^k (1 - r(t))^{n-k}
  \]  
  \( (6) \)

  \( r(t) \) is the component reliability.

- **System which configuration can’t be a hybrid one (see the following classical example illustrated by the reliability diagram of figure 3.2).**

![Reliability Diagram](image)

**Figure 3.2:** Classical non hybrid system

Assuming the independence of components, the reliability of the system is expressed with obvious annotations (Pagès A. 1980):

\[
R(t) = R_1^{PS} R_3(t) + R_2^{PS} \left(1 - R_3(t)\right)
\]  
(7)
In (7) formula the reliabilities of components system 1, 2, 4 and 5 respectively in parallel-series and series-parallel configurations are considered while component 3 is on functional mode or on failed mode.

So whatever the system configuration defined already early in design stages, some reliability indicators such as, the Mean Time To First Failure (MTTF), the failure rate of the system can be predefined according to following well known formulations:

\[ MTTF = \int_{0}^{\infty} R(t) dt \quad (8) \]

\[ \lambda(t) = \frac{dF(t)}{dt} = -\frac{dR(t)}{R(t)} \quad (9) \]

Thus systems reliability improvement can start early in design and continue till useful life by a well predefined maintenance strategy.

### 3.3 Reliability optimization at the design stage

#### 3.3.1 Problem statement

The design of systems that should fulfill well defined requirements during use life period needs maximal reliability. Also, some constraints of technical (volume, weight, spatial configuration, etc.) or economical (cost, budget, etc.) natures must be considered at the early design stages.

Next to this work, the statement is highlighted with the parallel-series configuration system composed with \( i = 1, 2 \ldots K \) stages and \( n_i + 1 \) identical components of \( P_i \) reliability at each stages. The optimal redundancy configuration system results to the following problem:

\[
\begin{align*}
MaxR(n) = & \prod_{i=1}^{K} \left[ 1 - (1 - P_i)^{n_i + 1} \right] \\
\text{s. t. } & \sum_{i=1}^{K} C_{ij} n_i \leq C_j \quad \forall j = 1 \ldots m \\
& n_i \text{ is a positive integer } \forall i = 1 \ldots K
\end{align*}
\]  

(10)

\( C_{ij} \) represent the costs of each system component involved in technological and economical constraints relation of (8).

#### 3.3.2 Problem solution

The following algorithm gives in general very good solution, although not necessary optimal (A. Pagès et al., 1980):

**Step1.** \((C_j, j \text{ from 1 to } K, \text{ are data}).\)

For \( i \text{ from 1 to } K, n_i = 0. \)

\[
LogR = \sum_{i=1}^{K} LogR_i = \sum_{i=1}^{K} LogP_i
\]
Step 2. Choose $i_0$ such that:

$$r = \frac{1}{\sum_{j=1}^{m} a_i C_{ij}} \left[ \log R_{i0} (n_{i0} + 1) - \log R_{i0} (n_{i0}) \right] = \max \frac{1}{\sum_{j=1}^{m} a_i C_{ij}} \left[ \log R_i (n_j + 1) - \log R_i (n_j) \right].$$

While the set of positive numbers $a_i$ is chosen such that $\sum_{i=1}^{m} a_i = 1$

Step 3. If $C_{i0}/C_j \forall j$ from 1 to m, then

Do $n_{i0} \leftarrow n_{i0} + 1$

$\log R \leftarrow \log R + \log R_{i0} (n_{i0} + 1) - \log R_{i0} (n_{i0})$

$C_j \leftarrow C_j - C_{i0}$

Go to step 2.

If not, END.

So the system maximal reliability and the numbers of components are defined.

### 3.3.3 Process model proposed synthesis

Basically, the main task of the design process is to create a relationship between the product function, product structure, and product behaviour. The product function explains the effects of the system and creates a correlation between the input conditions and output effects. Product behaviour represents the interaction of the function with the environment and how the product fulfils its function. This is a result of the properties and characteristics of the assemblies and parts in relation to the environment and system use.

In order to fulfil the functional requirements and to obtain the desired system behaviour, it is necessary to create a satisfactory design structure combining components (mechanical, electrical, information, etc.) in corresponding assemblies and system configurations illustrated before. One of the models for product structure creation is the V-model established by VDI-2206 as the “Design methodology of mechatronic systems” which contains a synthesis of the system in order to obtain a design structure based on functional requirements, and an analysis aimed at integrating the system reliability (M. Ognjanovic et al. 2012). This means a synchronized process of design structure processing and a functional requirements’ transformation into design structure behaviour. For this approach, known as Property-based design in (Krehmer, H et al, 2011), a monitoring system is established to provide the desired system behaviour starting from the defined functional requirements. In the clarification of the tasks design stage, reliability is one of the main functional requirements, and, in the operation process of a technical system, reliability is one of the main indicators of quality and system behaviour. By decomposing the desired reliability of the system (functional requirement) to the design component level, the elementary reliability becomes the design property of the component (Fig. 1). Design properties of the design components are the result of the parts properties (intensive and extensive) and parts characteristics. These characteristics are the physical and chemical description of the material, geometrical (shape, dimensions, etc.) and structural (joints and parts) interactions.

In respect to the adapted growth reliability management process (see fig. 2.1) the reliability integration from early design stages is sustained in the proposed platform that is highlighted next to this section. However firstly the following fig. 3.3 delineates the loop of outstanding activities to fulfil the objectives of this work [18].
At the early stages of design and after in the useful life (see Fig. 3.1), Fig. 3.3 illustrates how the reliability optimization evolution should be managed by engineering designers according to components/sub-systems assembly configurations, choice and treatment of materials, etc. (Goel et al., 2002). And mathematical models developed in sections 3.2 and 3.3 are designers tools guidelines as far as reliability assessment and the (10) problem finds optimal solution on the relevant algorithm developed.
Fig. 3.4 shows a graphical example of how the critical top-level requirements (key characteristics) of a product can be traced down to the manufacturing process parameters relatively to fig. 3.1.

In the useful life (Hossam A. Gabbar et al., 2003) develop the detailed system design and mechanism of improved RCM process as integrated with CMMS. The proposed solution is integrated with design and operational systems, consolidates some successful maintainability approaches to formulate an effective solution for optimized plant maintenance and develops tasks reliability-based preventive maintenance (RBPM) to sustain the product (system) reliability optimization approach proposed in this paper.

4. CONCLUSION AND PERSPECTIVES

The contributions of this work are highlighted in section 3. In particular, the applications of different optimization frameworks are put into the broader context of achieving system effectiveness in different process design situations, on inherent or achievable reliability. Integrating maintainability, availability and safety at the conceptual design stage has not been the aim of the task, but as all those parameters are not disjoint, some guidelines are for the purpose are found implicitly in this paper. Further recommendations for future work shall outline in details the integration in process design of these last parameters including an outline for the future development of a prototype of a process-engineering tool to manage maintenance strategies from the early process design stages.

REFERENCES


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