RELIABILITY THEORY: HISTORY & CURRENT STATE IN BIBLIOGRAPHIES

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Introduction

Actually, this is not a review of past and recent works on reliability theory and adjoining areas. It is rather a selected bibliography with brief comments.

Of course, any such selected bibliography or review reflects knowledge, experience and even scientific taste of the author. Nevertheless, I hope that, in general, the depicted picture of recent reliability theory state is more or less objective.

Main results in Reliability Theory have been obtained in 1960-1970s. In this connection, it would be interesting to remember the speech at the closing banquet at the MMR-2004 Conference (Santa Fe, USA) made by one of the most prominent specialists on Reliability Theory – Nozer Singpurwalla, who is Professor of The George Washington University and Director of the Institute for Reliability and Risk Analysis. His speech title was: “IS RELIABILITY THEORY STILL ALIVE?”

Reliability engineering is like medicine. The difference is in the objects of application: systems in one case and human beings in another. Could you imagine that medicine could be exhausted? The same is with Reliability Theory! As Mark Twain told: “Rumors about my death are strongly exaggerated.”

Probably, the question was formulated by Nozer Singpurwalla a bit incorrectly. Of course, Reliability Theory is alive but is it still developed? That’s the question.

“History teaches the continuity of the development of science. We know that every age has its own problems, which the following age either solves or casts aside as profitless and replaces by
new ones.” This is a citation from David Hilbert’s Lecture “Mathematical Problems” delivered in 1900. Hilbert told about pure mathematics, however the same words are correct in respect to applied mathematics and, in particular, to reliability theory.

**Main Directions of Modern Reliability Theory**

Historically, reliability field was divided into three main directions:

- Quality Control of Mass Production
- Reliability Engineering
- Reliability Testing
- Pure Theoretical Studies.

Of course, there are no strict borders between those directions. Actually, reliability testing takes the beginning in quality control as well mathematical modeling in reliability engineering is rooted in pure probabilistic investigations.

Basic fundamentals of the reliability theory that moved forward reliability engineering has been actually developed in 1960-s. Not in vain we see a lot of re-published works which first editions are date by 1960-1970-s. A good example is re-publishing the book by Igor Bazovsky “Reliability Theory and Practice” in 40 years after first edition!

Latest works mostly presented some developments and customizing of existent analytical methods, though it would be incorrect do not mention several outbursts of real fundamental publications that will be discussed later.

Classical “pure” Reliability Theory consists of the following main bodies:

- Structural models
- Functional models
- Maintenance models
- Computational methods (in particular, Monte Carlo)
- Testing
- Statistical inferences
- Optimization problems in reliability

We intentionally omitted problems of Quality Control because this old engineering problem (much older than reliability analysis!) is well developed and already almost “frozen”.

It seems to us that chronological order of references will be more convenient for the reader: you can see “historical horizons” and process of reliability theory and applications development.

Everybody understands that any review of such kind bears the stamp of subjectivity and incompleteness. The author would be grateful for any comments, additions and corrections.

**Books & Reviews**

Modern market is full of different handbooks, textbooks, specialized monographs and reviews on Reliability Theory and its applications. Of course, it is practically impossible to compile a comprehensive review of all these materials. Even if one could undertake such a scientific adventure, it would be almost useless itself: it is better to have a list of publications in some thematic clusters than to read boring description of the book contents.

Keeping this in mind, we propose you very brief comments to sections and hope that the titles of books and reviews will say about their contents even more than trivial annotations.

Understanding of history of any subject is very important. It is timely to remember words from the famous anti-utopian George Orwell’s novel “Nineteen Eighty-Four”: “Who controls the past controls the future. Who controls the future controls the present”. Only knowledge of the past allows us to move forward in a right direction.
To make historical horizons more clear, we give bibliographies in chronological-alphabetical order. Moreover, we decided to give up the total list of references: bibliography will be given by chapters, i.e. dividing it onto smaller lists related to concrete topic.

**Handbooks**

It seems that handbooks in each technical area gives the best understanding of the current state of the art of this particular area because namely accumulate accurate and practically useful results for engineering practice.

One of the first Handbooks on Reliability [1] for practical engineers was published in 1966. It reflected probabilistic methods of reliability analysis and synthesis of electronic devices and systems and statistical inferences of test and field data. Later this book was multiply revised [3, 5, 6] and translated into English, German and Check [2, 4, 5, 7, 10].

Then from 1991 handbooks began to consider some practical engineering methodology of design, not only methods of reliability evaluation. Among them we would like to distinguish the first handbooks on software reliability [8, 14].

**Bibliography (in chronological-alphabetical ordering):**

Textbooks

One of the first successful textbooks in reliability was written by Igor Bazovsky [1]. This book was simple, informative and instructive. Not in vain this book has been re-published [13] in almost half a century!

The next significant and deep book, written by David Lloyd and Myron Lipow [2], was full of interesting practical problems and original solutions. It does not lose its importance even now. Soon, the first monograph on reliability [3] was published in the former Soviet Union. Scientific competition between American and Soviet reliability schools began.

However, of course a real revolution was done by two excellent books: Richard Barlow and Frank Proschan [4] and Boris Gnedenko, Yuri Belyaev and Alexander Solovyev [5]. The role of those books is difficult to overestimate. The first one introduced new concepts of monotone systems, distributions with monotone increasing and decreasing failure rates and gave deep presentation of optimal maintenance and optimal redundancy problems. The second book contained many new results on repairable redundant systems (including first results on asymptotic analysis), specific inferences of reliability data and many solutions of interesting engineering problems.

One can say that these two books have laid a fundamental of the modern theory of reliability. They are real Bibles on Reliability Theory.

Bibliography (in chronological-alphabetical ordering):


Books

Monographs on reliability are dedicated to the entire spectrum of reliability problems. Among them a number of works on various statistical aspects of reliability [5, 14, 16-17, 19, 26, 42] including Bayesian methods [15, 51]. There are books on such important engineering problem as optimal
maintenance \[8, 36, 49\] and optimal redundancy \[2, 27, 39\]. Do not leave without attention such important direction as reliability of mechanical systems \[1, 7, 24, 31, 34, 52\].

Many interesting new ideas can be found in Proceedings of Annual Reliability and Maintainability Symposium organized by IEEE.

**Bibliography (in chronological-alphabetical ordering):**

17. Pavlov, I.V. (1982) *Statistical Methods of Reliability Estimation by Tests Results.* (Russian) Moscow, Radio i Svyaz

**Reviews**

The best image of current state of various aspects of Reliability Theory can be obtained from reviews. Some review are on general state of Reliability Theory [1-2, 5, 10, 19], and some of them
cover special topics. We would like to mention reviews on a new direction in relatively – multi-state systems reliability analysis [3-4, 7, 20]. Very interesting and useful for understanding recent state and path of development of Reliability Theory one can find in such analytical papers as [12-13, 16-17, 19, 23, 26].

Bibliography (in chronological-alphabetical ordering):


Repairable Systems

Traditional mathematical tools for analyzing reliability of repairable systems are methods of the Queuing Theory. It is time to remember that this theory was originated in [1] by talented Danish mathematician, statistician and engineer Agner Erlang in the beginning of the last century.

A real burst of the Queuing Theory happened in early 1960s. One can mention that a number of problems in repairable systems reliability analysis are reduced to the queuing problems just by simple change of terms.

The next very powerful impact on repairable system analysis was done by a series of excellent works in the Renewal Theory. In the middle of 1950s Alfred Renyi [4] formulated an asymptotic theorem related to the “thinning” procedure, and approximately at the same time David Cox with Walter Smith [2] and Gennady Ososkov [3] proved an asymptotic theorem related to the superposition procedure for point stochastic processes. In the beginning of 1960-s Bronyus Grigelionis [7] generalized the theorem on point processes superposition. These theorems stated that random thinning of a point process or superposition of independent point processes asymptotically lead to the Poisson Process.

Boris Gnedenko [9, 10] was the first scientist who, in the beginning of 60-s, got asymptotical results for repairable systems reliability. He found asymptotic distributions of time to failure of such a system for the case when repair time is relatively small. This work was followed by a series of excellent works by Igor Kovalenko, Alexander Solovyev and others [14]. Now asymptotic methods in reliability take an important place in large-scale systems consisting of highly reliable units. One can find some review of strong and approximate models for highly available systems in [17].

In a sense, recent publications on the subject bring few new ideas; they are mostly “technological”: main results were obtained about 30 years ago.

Bibliography (in chronological-alphabetical ordering):


Networks & Large Scale Systems

In the middle of 1950-s the Moore-Shannon model [1] was published. It opened a new direction – asymptotic analysis of network reliability. In late 1960s John Esary and Frank Proschan developed method of reliability bounds estimation for arbitrary two-pole networks with known structure. Later this direction was developed in [4-5, 7-8, 10]. All these works were based on counting minimal paths and cuts of a network rather than on enumeration of entire number of possible network states. Next step was implementation of Graph Theory for network reliability analysis [6, 11-13].

It was a beginning of a powerful direction in reliability analysis of large scale systems.

Bibliography (in chronological-alphabetical ordering):


OPTIMAL REDUNDANCY

First papers on optimal redundancy was published in the middle of 1950-s by F. Moskowitz and J. McLean [1]. Though now this paper might seem to be a little bit naïve, its role was significant. In brief terms, the problem of optimal redundancy is in finding such a redundant (or spare) unit allocation that deliver the required reliability under minimal cost or, in the inverse case, to get maximum reliability under certain constraints on the system cost. Later, methods of solution of the problem of optimal redundancy were developed by R. Bellman [2, 4], F. Proschan [3, 7] and J. Kettelle [5].


First papers and books described only traditional methods of optimization – dynamic programming and steepest descent method. Later some interesting approaches have been developed: Branch-and-Bound [19], Monte Carlo simulation [8-10, 17], genetic algorithm [32-33], evolutionary approach [15], “Ant colony method” [28] and others.

Bibliography (in chronological-alphabetical ordering):


Terrestrial Systems and Their Supply

First works on terrestrial systems concern such geographically dispersed telecommunication systems [3, 5-7, 9], energy systems [3] and military command system [1]. Afterwards papers on terrestrial supply systems appeared. Actually, the last ones were a generalization of optimal redundancy problems where supply system had a hierarchical structure and delivery of spare units took some fixed time from local stock to objects, from regional stocks to the local ones and from central stock to the regional ones [4, 8, 10-11, 13].

Bibliography (in chronological-alphabetical ordering):


**Reliability of multi-state systems**

First of all, we would like to mention a comprehensive bibliography “Reliability Analysis and Optimization of Multi-state Systems” compiled by A. Lisnianski, G. Levitin and E. Korczak. This bibliography can be found at http://iew3.technion.ac.il/~levitin/MSS.html.

The main results on this theme can be found in the monograph by Anatoly Lisnianski and Gregory Levitin [41].

**Multi-state systems reliability analysis**

First work on multi-state systems with binary units [1] considered a situation when failures of system’s units could lead to partial ability to perform required operations. As the reliability measure the author introduced mean operational effectiveness of the system. Later this idea was developed in [2-4, 6, 24, 30, 32]. Then in [7] a binary system with multi-state units was analyzed.

The most recent works on the theme relates to analysis of multi-state systems consisting of multi-state units. Papers on the subject appeared relatively rear until real burst in the beginning of 1980s.

The interest to this kind of systems is understandable: binary description of possible states of units and systems is far from reality. However, one should realize that such detailed description of a system needs more detailed statistical information that is not always accessible. Thus, a number of recent pure mathematical approaches present “games of keen brain”, rather than working engineering tool. Nevertheless, there are many really constructive works in the area mostly belonged to the “scientific tandem” Levitin-Lisnianski.

**Bibliography (in chronological-alphabetical order)**


**Universal Generating Function**

This relatively new technique for multi-system analysis started after series of papers appeared in the late 1980s [1-5]. This new formalism actually based on a simple idea: a standard generating function deals with summation of powers of arguments and a generalized generating functions allows to perform, for instance, taking minimum or maximum or others operations.

We would like to distinguish [15] where all recent results are summarized and systemized.

**Bibliography (in chronological-alphabetical ordering):**

Continuous multi-state systems

In first works on multi-state systems, there were considered systems with discreet states. Later works on continuous and even fuzzy multi-state systems appears. It is, probably, time to mention that these works (by now) have a pure academic interest.

Bibliography (in chronological-alphabetical ordering):


Reliability optimization of multi-state systems

It was naturally that after developing methods of multi-state systems analysis, the methods of optimal synthesis of such systems were developed. A general methodology of optimal redundancy was kept though there are some specific due to new properties of multi-state systems.

Bibliography (in chronological-alphabetical ordering):


Reliability of Wearing Systems

In the end of 30-s Swedish engineer and mathematician Waloddi Weibull, analyzing ball bearing longevity, actually reduced the problem of assembly failure (he analyzed bearings) to the model of a “weakest link” [1, 4]. He suggested for description of the problem a simple and convenient mathematical model, which became known as Weibull distribution. Almost simultaneously and independently, outstanding Russian mathematician Boris Gnedenko found three classes of limit distributions [2-3], one of which corresponded to the Weibull distribution.

In the middle of 1960-s Richard Barlow and Frank Proschan [5-7] introduced classes of distributions with increasing and decreasing failure rates (IFR and DFR, respectively). That step was very significant because it opened the path for analyzing units and systems reliability invariantly to specific type of failure distributions.

Bibliography (in chronological-alphabetical ordering):

2. Gnedenko, B.V. (1941) Limit theorems for maximum order statistic (in Russian). Reports of the Academy of Sciences the USSR, vol.32, No.1


**Software Reliability**

Now we come to the most confusing area in reliability theory and practice – the so-called software reliability. This term is rooted in software engineering though it very much contradicts to traditional understanding of the term “reliability” in hardware engineering. It leads to erroneous attempts of applying probabilistic reliability concepts to this subject that led only to some disaster.

One of the most influenced reliability experts Nozer Singpurwalla [13] gave a good answer by his question ☹: “The failure rate of software: does it exist?”.

It is time to mention that one of the most brilliant specialists in software reliability engineering John Musa [1-2, 5-7, 15-16, 18, 22-23, 25-26] meant “reliability” in rather common sense. With the same success one can say about reliability of a person or reliability of an idea.

However, this discussion needs special time and place. One thing is clear: software reliability specialists should distinguish their reliability from hardware reliability, develop their own non-probabilistic and non-time dependent mathematical tools.

Let us just present recent works on software reliability without further discussion.

**Bibliography (in chronological-alphabetical ordering):**


23. Musa, J. (2005) Teaching SRE to Software Practitioners. ISSRE, No.4

STATISTICS

General methods

Above we mentioned various probabilistic approaches. However, Reliability Theory cannot be a real engineering tool without statistical methods. In this connection we have to mention names of two pioneers in statistical reliability – Benjamin Epstein and Mark Sobel [2-3, 6-8].

In the beginning of 1960 David Lloyd and Myron Lipow [7] find a heuristic solution for an interesting problem: estimation of system reliability on the basis of unit test data. Two years later Roald Mirny and Alexander Solovyev obtained first strong mathematical result in this direction (for no failure tests). Later Igor Pavlov got solution for a general problem [17].
Of course, during the period of time from then to now there were many improvements in methods of statistical estimate of systems reliability that the reader could see from the bibliography below.

**Bibliography (in chronological-alphabetical ordering):**

Accelerated Testing

Since testing in normal conditions (room temperature, no power overloading, no vibration, etc.) takes a too long time and requires usually a huge number of units, engineers invented method of accelerating tests. The problem arose how to extrapolate the results of such accelerated tests to a normal working conditions. There were developed several effective methods of getting needed data from results of accelerated tests. Among them the fundamental work by Wayne Nelson [3] has to be mentioned in the first place.

Bibliography (in chronological-alphabetical ordering):


Confidence Limits

In mathematical statistics from the very beginning there was developed method of confidence bounds. Actually, confidence bounds give us an understanding of the measure of possible deviation of “real” value from statistical estimate obtained on the basis of limited number of observations.

Specific of reliability problems led to developing new effective methods.

Bibliography (in chronological-alphabetical ordering):


**Bayesian Methods**

Last years a number of interesting publications appeared in Bayesian methods in reliability. Let us name Richard Barlow, Henry Martz and Nozer Singpurwalla whose numerous works made this branch of mathematical statistics a real working engineering tool. One can expect useful applications of these methods for aggregating field data and projecting reliability of new objects (especially, unique ones).

**Bibliography (in chronological-alphabetical ordering):**

Monte Carlo Simulation

In late 40-s John von Neuman invented the Monte Carlo simulation method for calculation of multi-dimensional integrals over some specific domains. (Actually, it was idea very close to Georges Buffon’s Needle method.) Later it was developed into powerful calculation method with using modern computers.

Monte Carlo simulation is very effectively applied for various calculation problems for reliability evaluation. However, it should be noticed that there are few works where Monte Carlo is used for some optimization problems [3-4, 7].

Bibliography (in chronological-alphabetical ordering):


AREAS CLOSE TO RELIABILITY

Survivability

Survivability deals with random (mostly independent) unit failures that can appear during systems operation. However, sometimes we meet situations where we can only guess about possible impacts. These impacts can be unpredictable inner failures (usually due to operator errors) or environmental influences (earthquakes, floods, hurricanes). In this case one assumes that the impacts are directed to the most critical components of the system.

Survivability analysis is usually performed in minimax terms and reduced to “bottleneck analysis”, or “minimum cut” searching. Usually survivability consideration is related to large terrestrial systems (telecommunication or power networks, transportation systems).

One of the first works on survivability was written by famous Russian naval architect academician Alexei Krylov [1]. From later works, one can distinguish [2-3] where concrete survivability analysis has been done for all-country power system.
Bibliography (in chronological-alphabetical ordering):


**Counter-terrorism protection**

Last decade is going under sign of inhuman terrorist attacks by Islamic terrorists. These hostile attacks directed mostly to ordinary people by terrorists who mimic as normal peaceful persons. It makes protection against such terrorist attacks very difficult. In this case one cannot consider probabilistic models: the impact is not random. Moreover, terrorists choose most vulnerable objects in sense of weak protection or huge loss in case of successful attack. In this case, the problem is close to the situations arising in the Game Theory. In this case the problem of minimizing of maximum possible damage arose [1-6].

Dealing with human enemies makes very important such actions as creating false targets [7, 10, 14, 19], preventive hits, misinformation of enemy, etc. In other words, this problem has its own specific.

Bibliography (in chronological-alphabetical ordering):