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RELIABILITY: PAST, PRESENT, FUTURE

Key-note opening lecture at the Conference "Mathematical Methods in Reliability" (MMR-2000) in Bordeaux, France, 2000

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I treasure both faces of mathematics:
the pure as a beautiful retreat from reality,
and the applied as an ardent hope for life.
I. Heller

Introduction

It is a great honor for me to present this Opening Lecture at the World Reliability Forum. I was a young man when I jumped in the white water of a vivid stream of reliability theory and application creek. Late 50-s and early 60-s were really the time of reliability "Renaissance". Since then reliability has been developed to a powerful applied mathematical discipline, with both, theoretical and applied sides. It is impossible to imagine any modern research institution or manufacturing plant without reliability laboratories or departments.

I am lucky to have been working at QUALCOMM, an exceptional telecommunication company where I have a chance to apply my expertise in entire reliability area: from availability analysis of satellite telecommunication system to quality assurance of cellular phones, from optimal spare allocation for terrestrial network to accelerated testing and warranty claim rate projection.

Everyday practical work generates new theoretical problems in need of solutions. New solutions challenge new applications. What could be better and more exciting than such kind of reliability engineering?

I hope that we all -- from manufacturing and research, from testing and data inferences, in both industry and academia -- will prove our usefulness for the next, XXI industrial age, as we did it in the past and as we are doing it in the present.

Main Directions of Modern Reliability Theory

One can distinguish several directions of modern Reliability Theory, main among them are:

1. Quality Control of mass production
2. "Pure" Reliability analysis
   - ◊ Structural models
   - ◊ Functional models
   - ◊ Maintenance models
3. Effectiveness ("Performability")
4. Survivability
5. Safety
6. Security
7. Software Reliability

First two points do not need any explanations: they are subjects of everyday engineering activity. Others would be slightly explained.

Effectiveness ("performability") analysis relates to systems for which one is not able to formulate "all or nothing" type of failure criterion. Effectiveness characterizes a system ability to perform its main functions even with partial capacity. Failures of some (or even majority of system components) lead only to gradual degradation of the system ability to perform its functions/operations. Actually, one deals with such indices like "partial availability" or "partial system down time". These type of models are used to describe multi-channel systems (e.g. telecommunication, transportation) or systems with embedded "functional redundancy" where there are optional ways to perform system tasks, though with decreased quality.

Fore systems operations of which are characterized by its current state, the effectiveness index, E, can be expressed as

$$\sum_{\forall s} \Phi_s H_s$$

where H_s is the probability of state s, and Φ_s is the conditional probability of the system successful operation. For systems whose effectiveness of operating depends on the trajectory of state changing, analogous formula can be easily written in a general form (though few examples of constructive applications are known for this case).

It is about the time to mention that actually the main idea of this approach was introduced in Kolmogorov's work [1945] where he analyzed the probability of a plane destruction by anti-aircraft fire.

Of course, one can reduce effectiveness analysis to "pure" reliability analysis by choosing an appropriate failure criterion. For instance, a system might be considered failed if the total system "capacity" (or ability to perform its operation) declines below some predetermined level.

Survivability is a special property of a system to "withstand impacts". These impacts can be unpredictable inner failures (usually due to operator errors), environmental influences (earthquakes, floods, hurricanes) or hostile human nature actions (enemy military operations or terrorist acts). 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 searching out "minimum cut". Usually survivability consideration is related to large terrestrial systems (telecommunication or power networks, transportation systems). The same type of reliability indices is applied to military objects that are subjected to statistically unpredictable impacts.

The survivability measure is usually expressed in the power of set of system units whose destruction leads to the system "death". One of possible characterization of survivability is the minimum set of such units:

$$X^* = \{\min X:\ \Phi_{\bar{X}} = 0\}$$

where X is the set of destroyed system's units ($\bar{X}$ is a supplementary set). Though there is no probabilistic consideration, nevertheless, one sometimes uses several levels of "possibilities of occurrence" of destruction of various units.

Safety is a special property of a system characterizing effective performance of its main predetermine functions (production of goods, electrical power generation, gas and oil transportation, etc.) without dangerous environmental consequences for people and nature. Safety is usually considered in probabilistic terms that are close to those used in a "pure" reliability analysis. In some sense, one considers in this case two-dimensional model. For instance, one can formulate the following optimization problem:

$$\min_{\Psi}\{C(\Psi) \mid R(\Psi) \geq R_{required}, S(\Psi) \geq S_{required}\}$$

where Ψ is the system configuration, C is the system cost, R is the system reliability index, and S is the system safety index.

Security is sometimes considered as a part of reliability-survivability problem. Indeed, many systems must not only operate reliably but also at the same time provide protection against non-sanctioned access. Many telecommunication systems dealing with military, banking or other highly confidential information are requested to be secure. It is to the point to ask: "*Quis custodiet ipsos custodes*? Because systems mentioned above are actually considered failed if security is not provided, there is an interesting nod of "two reliabilities".

Software Reliability… Now we come to the most confusing area in reliability theory and practice - the so-called software reliability. Multiple attempts to apply traditional reliability concepts to this subject are unsuccessful and lead only to some disaster. Who could explain what means "MTBF" for software? And first of all, what does it mean "failure" in this case?

The answer on these questions could be found in the answer: What do you mean under "software reliability"? Let us consider main features of reliability:

- stochastic nature of failures
- time dependence of failures
- independence of failures (or probabilistic dependence).

What one has analyzing software? Errors caused by software have no stochastic nature: they will repeat as soon as some conditions will be repeated. Errors of software, in a sense, are not "objective", they depend on type of operations, type of inputs and, at last, on type of users. Allow me to compare software errors with printing errors in the book. Assume that there are many typewriting errors in Chapter 1, and no errors at all in Chapter 2. One uses only Chapter 1 and complains that the book is very bad. Another uses only Chapter 2 and tells everybody that the book is perfect.

Errors caused by software do not depend on time in a usually understandable way: if you don't use software it cannot fail! At a pinch, in this sense software can be compared with a spare unit which can be used but nobody knows the timing of this usage.

At last, independence of errors. There is no such concept as a "sample" for software: there is a phenomenon of cloning. "Replacement" of "failed" software has no sense! You will change one Mollie for another Mollie

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with the same genes, with the same illness, with the same properties.

Problem of software quality is extremely important because more and more technical systems become "software dependent". It is about the time to say that this problem needs independent and intensive attention of applied mathematicians. However, it seems that attempts to put "hardware reliability shoes" on "software legs" is absolutely wrong and, moreover, will lead only to a logical dead end.

Attempts of using probabilistic reliability concepts to unrelated problems are not new. I remember as in the 60-s, when in the former Soviet Union there was a "fashion" to talk of reliability for everything, the State Bureau of Standard issued a standard on reliability of sausages!

Another funny case. When I was working at a top secret Soviet military-industrial enterprise, an editor of technical reports, a former KGB officer, changed the word "reliable" for "trustworthy" through all my report.

Let us don't repeat such mistakes and name an apple an apple!

History of Ideas in Reliability

Of course, the history of reliability theory did not begin recently. However, we should accept that the first waves of the modern reliability theory came from the United States in late 50-s. First time reliability experts gathered together at IEEE Reliability conferences that began to be regular since then. First proceedings of those conferences played a revolutionary role in information exchange in reliability community. With a small delay analogous forums of reliability experts gathered then in the former Soviet Union. In some sense these two countries, competing in Cold War in modern technology, became two poles of research in reliability field.

However, one can find examples of activity in reliability area before this time. We begin a brief review of history of ideas of reliability with a well know example.

In the middle of 30-s Swedish engineer and mathematician W. Weibull [1939], analyzing strength of materials, actually reduced the problem of assembly failure (he analyzed bearings) to the model of a "weakest link". He suggested a simple and convenient mathematical model for description, which is known as Weibull distribution. This well-known distribution is good because of two parameters of scale and shape it is very flexible and allows one to approximate almost any field data. Almost simultaneously and independently, outstanding Russian mathematician B. Gnedenko [1943] found three classes of limit distributions, one of which corresponded to Weibull distribution. Those fundamental results were based not on "gut feeling" or formal convenience of a "flexible" mathematical formula. They were proven and their applicability was shown. Probably, it was the first really significant result in future developed reliability theory.

After the WWII, many new ideas flooded into reliability theory. Last fifty years brought a number of new solutions and new methods in reliability theory and engineering.

In late 40-s J. von Neuman, probably, first time used Monte Carlo simulation for calculation of multi-dimensional integrals over some specific domains. Very soon, specialists for numerical modeling queuing systems, including reliability models of repairable systems applied this technique. In this connection we would like to mention N. Buslenko and his pupils [Buslenko, Kalashnikov, Kovalenko, 1973; see also in Ushakov, ed., 1994].

Proving two key theorems of the Renewal Theory made a very powerful impact on reliability theory. A. Renyi [1956] formulated the asymptotic theorem related to the "thinning" procedure, and G. Ososkov [1956] formulated the asymptotic theorem related to the superposition procedure for point stochastic processes. Later Yu. Belyaev [1962] and B. Grigelionis [1964] generalized these results. These theorems allowed one to construct flexible and practically convenient mathematical models of repairable systems. These results also can be used for simple and effective approximate models [Gnedenko and Ushakov, 1995].

In the middle of 50-s E. Moore and C. Shannon[1965] published the paper on asymptotic analysis of network reliability. They showed the so-called *S*-shape dependence of network reliability on the unit reliability. In late 60-s J. Esary and F. Proschan [1962] obtained the so-called Esary-Proschan lower and upper bounds of an arbitrary two-pole network with known structure. These bounds were expressed via complete sets of network's paths and cuts. This work ignited works by M. Lomonosov and V. Polessky [1971, 1972] dedicated to network reliability. Later the Litvak-Ushakov lower and upper bounds [Ushakov and Litvak, 1977] were obtained. These results were based on non-intersected network's paths and cuts. (In a sense, these bound are more effective for practical applications.)

D. Lloyd and M. Lipow [1962] considered an interesting problem: estimation of system reliability on the basis of unit test data. They proposed a well working heuristics. R. Mirnyi and A. Solovyev [1964] obtained first strong mathematical result in this direction. They considered the case of no failures during testing. Their model corresponds to a concept of a "weakest link". Then Yu. Belyaev {Belyaev et al.,

1967] obtained some results using Monte Carlo simulation. Many interesting analytical results were obtained by I. Pavlov [see in Gnedenko et al., 1999] and others.

First papers on optimal redundancy was published, probably, in the middle of 50-s [F. Moskowitz and J. McLean, 1956]. Though this paper might seem to be a little bit naïve now, its role was significant. Later discrete analogue of the steepest descent method [Black and Proschan, 1959] and dynamic algorithm [Bellman and Dreyfus, 1958] were suggested. J. Kettelle [1962] proposed an effective practical modification of dynamic programming algorithm for solution of this problem. This approach was a significant step of implementation of the optimal redundancy solution into practical applications. Further development of this method was done in series of works [Proschan and Bray, 1965; Ushakov, 1965, 1995; Tillman et al., 1980].

Work of D. Cox [Cox, 1962; Cox and Isham, 1980] made an outstanding impact on the reliability theory development . It opened new vision of usage point stochastic processes in reliability modeling.

B. Gnedenko [1964a, 1964b] was the first who analyzed highly available systems in the beginning of 60-s. He considered a duplicated system and showed that asymptotic distribution of time to failure of such a system is exponential and indifferent with respect to the type of repair time distribution (if repair time is relatively small). This work was followed by a series of excellent works by I. Kovalenko, A. Solovyev and others [see in Gnedenko, ed., 1983]. 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 [Gnedenko and Ushakov, 1995].

R. Barlow, C. Derman, L. Hunter, and F. Proschan were one of the first who paid a serious attention to the problem of preventive maintenance [Barlow and Hunter, 1960; C. Derman, 1963; Barlow et al., 1963]. Unfortunately, these methods (further developed into sophisticated mathematical models) still did not find real practical applications mostly due to a lack of consistent field data. It is about time to mention that this direction in reliability theory is the most "vulnerable": optimal solutions are very dependent on the type of time to failure distribution but knowledge of it needs enormous volume of field data.

R. Barlow and F. Proschan [1965] introduced classes of distributions with increasing and decreasing failure rates, IFR and DFR, respectively. Later they generalized their approaching introducing expanded classes. That step was very significant because it opened the path for analyzing units and systems reliability invariantly to specific type of failure distributions.

Last years a number of interesting publications appeared in Bayesian methods in reliability. Let us name R. Barlow, H. Martz, V. Savchuk, and N. Singpurwalla whose numerous works we have no chance to refer here only because of a lack of a room. One can expect useful applications of these methods for aggregating field data and projecting reliability of new objects (especially, unique ones).

* * *

These few names do not reflect contributions of many brilliant reliability experts during last five decades. The author tried only to mention the main ideas of modern reliability theory and brief history of their development. Everybody understands that any review of such kind bears the stamp of subjectivity and incompleteness.

In the White Water of Publications Stream

Since the beginning of "Reliability Renaissance", an alarming thing has happened: more and more publications have been appearing… A real avalanche of hundreds of new books and thousands of new papers on reliability… Is it good or it is bad? Did our professional life become easier with this immense ocean of publications? It seems to me that the situation reminds the following: somebody would like to have a drink of water and instead was thrown into the middle of deep and boundless pool.

Let us remember the history of the most significant publications in reliability.

One of the first successful books in reliability was I. Bazovsky [1961]. This book was simple, informative and instructive. The next significant and deep book, written by D. Lloyd and M. Lipow [1962], was full of number of interesting practical problems and original solutions.

A real revolution was done by two excellent books by B. Gnedenko, Yu. Belyaev and A. Solovyev [1969], published in Russian in 1965, and by R.Barlow and F. Proschan [1965]. Their role is difficult to overestimate. The first 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. The second book 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. One can say that these two books have laid a fundamental of the modern theory of reliability.

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As development of the first book [Gnedenko, ed., 1983] was published. The second one followed by [Barlow and Proschan, 1975; Barlow, 1998]

In 1966 Reliability Handbook was published in Russia and then translated in the USA [Kozlov and Ushakov, 1970]. This book had several revised editions in Russia, Germany and Czechoslovakia. The last updated American edition was published recently [Ushakov, ed., 1994].

The flow of publications on reliability has been growing exponentially. However, some books distinctly and brightly shined: [Mann, Schafer and Singpurwalla, 1974; Kapur and Lamberson, 1977; Gertbakh, 1977; Tillman, Ching-Lai, and Kuo, 1980; Nelson, 1982; Lawless, 1982; Kovalenko, Kuznetsov, and Pegg, 1998;]. Book written by W. Nelson [1982] probably needs a special mentioning. Several books (for instance, Bolotin, 1971; Rudenko and Ushakov, 1989; Cherkesov, 1974; and others) might be mentioned as oriented to special areas of application.

However to find a new worthwhile book in the real flood of new publications begins more and more difficult…

It seems that there is no appropriate selection for publication. We are hopeless in any fight with publishers who just make money. We should organize some public Reliability Forum with honest and severe evaluation of publications. Otherwise, future generation of reliability community will loose its professional level. One might shout: "S.O.S.! Save Our Science!"

Everybody writes poems (at least in the youth). It does not mean that all written poems should be published! Could you imagine that this has happened? How you could find then what is really good? You could trust some old and well-known authors but how you could find a new brilliant work?

Problems Expecting Solutions

"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.

The last century was very productive for reliability theory: many new ideas, many constructive results, many useful practical applications. Sometimes you can hear voices that reliability theory has been exhausted… The best answer for such complains is those Hilbert's words above.

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? As Mark Twain told: "Rumors about my death are strongly exaggerated."

Actually, there are many important problems, which are awaiting solutions. Let me listed some of them.

- **"Software reliability".** Does not matter how we call this. The problem remains. To construct a constructive theory of analysis of software quality and its behavior in time outside of "traditional" reliability theory scope is an exciting new problem!

- **Unique system analysis.** We met a number of examples where a single copy of a system is designed: space ships, huge damps, nuclear research equipment, etc. All these objects are to be extremely reliable. At the same time we very often have no prototype or any previous experience. How to evaluate their reliability? In what terms? What is the "confidence" of such evaluation?

- **Global terrestrial systems.** More and more modern systems are large scale, which spread over huge territories. They are, for instance, telecommunication networks, gas and oil pipelines, power systems, defense systems, etc. These systems are waiting for appropriate methods of analysis.

- **Communication networks.** Standard analysis of network reliability is reduced to connectivity analysis. However, real networks have capacity of their links and are described by flow exchange matrices. To find a simple and applicable method of reliability evaluation of such networks is an important task.

- **Monte Carlo simulation.** Monte Carlo simulation, being a very effective computer tool for solution of different complex problems, remains an art… Probably, simple user-friendly macro language should be designed for description reliability of complex reliability models.

- **Developing systems.** The reliability modeling of developing systems is another challenge. How to use current information obtained from the field for control of the system development? How to take into account that with time the system not only changes its structure but also embeds new or modified equipment?

- **Spare stock system.** To find an optimal spare stock for a single system is a well-known problem of discrete optimization. However, if one consider a

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hierarchical structure of local, regional and central stocks with large number of various types of spares and various supply policies, the problem becomes outside of traditional reliability or inventory control methods.

- **Time redundancy.** Time redundancy is relatively new direction in reliability theory. It considers a "functional redundancy": a system has a spare time to restart its function in the case of failure or repeat some its operations during admissible time. Not too many works are dedicated to this problem. Probably, there are not still good practical results of this complex issue. To get convenient engineering methods of analysis of systems with time redundancy is an important task.

- **"Continuous" models.** Some large systems have complex structures. To analyze them with standard "discrete" methods is a hard task. There are some attempts to consider such systems as "continuous" ones. However, these methods still are not elaborated to practical level.

- **Units with several states.** Some systems consist of units with several states, not only "up" and "down". Existing attempts of reliability evaluation of such systems by now have mostly theoretical interest: there are no simple constructive results, which can be used in everyday engineering practice.

- **Realistic accelerated testing.** Traditional and commonly used accelerated life models, based on a linear time scale transformation assumption (except D. Cox [Cox and Oakes, 1972] "proportional hazard model", which is based on essentially nonlinear time transformation). Accelerated testing is very often the only way of projection of new production reliability. To construct realistic accelerated testing (especially for assemblies of different components) is a very important practical problem.

- **Aggregation of filed data.** Reliability field data are the core of any reliability analysis. For systems in the field, these data are the basis for realistic estimation of achieved reliability level. For new designed systems they are used for realistic evaluation of the reliability level. Field data are usualy collected during long time, for different climatic conditions, for different system configurations, etc. The problem is how to aggregate as much reliability information as possible, keeping control over consistence and likelihood of these data?

- **Methodology of failure analysis.** First of all, it refers to micro-components and their assemblies. The problem is in variety of assemblies ("cards") of micro-components. Each configuration of a card presents a unique environment for a component. How they influence on each other? How they stand different environments?

- **Warranty claim rate projection.** For many industrial companies manufacturing mass production distributed among consumers, the problem of evaluating of possible future expenses for repair and/or replacement is crucial. To make a consistent projection of return based on some *a priori* information with permanent updating with current field data is a very important problem.

Conclusion

We should arrange some kind of information system with regular reviews of books on reliability. Probably, to have an expertise committee of some 50 people who will send their evaluations of the book and the books will be ordered in accordance with these average marks. There should be a regular review of the state in particular areas. We should help ourselves!
Reliability International Community numbers tens of countries: Bulgaria, China, Denmark, France, Germany, India, Israel, Italy, Japan, Russia, Spain, Sweden, Ukraine, United States of America, United Kingdom, and others… (Named in alphabetical order.)
We need International Society on Reliability for coordination our activity, for better exchange of ideas, methods, results. Taking into account the role, which Academician Boris Gnedenko played in the development of reliability theory, it would be not out of place to name this Society after Gnedenko.
We need some International journal on reliability theory and applications. It seems that this journal should publish only exceptional (or invited) papers. Of course, it does not mean that the journal should be an "elite" journal. However, I think that this journal should publish only papers on serious problems, be dedicated to surveys of various reliability branches, reviews of new books with their honest estimation (probably, with expert estimation by 10 point scale).
We have an excellent place for the Reliability Society Headquarter – this beautiful city of Bordeaux. We have an excellent Universite Victor Segalen as a host. In my turn, I agree to establish an affiliate in another beautiful city – San Diego.
It would be a good start for reliability in the new century (and even new millenium! ☺).

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