RELIABILITY THEORY: HISTORY & CURRENT STATE IN BIBLIOGRAPHIES

Igor Ushakov

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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):

1. Kozlov, B.A., and I.A. Ushakov. (1966) Brief Handbook of Reliability Calculations for Electronics Equipment, (*Russian*). Sovetskoe Radio.
2. Kozlov, B.A., and I.A. Ushakov (1970). *Reliability Handbook*. Holt, Rinehart and Winston, New York
3. Kozlov, B.A., and I.A. Ushakov. (1975) Handbook of Reliability Calculations for Electronic and Automatic Equipment (*Russian*). Sovetskoe Radio
4. Kozlow, B.A., and I.A. Uschakov. (1978) Reliability Handbook for Electronic and Automatic Systems (*German*). Verlag Technik.
5. Kozlow, B.A., and I.A. Uschakov. (1979) Reliability Handbook for Engineers (*German*). Springer.
6. Ushakov, I. (ed.) (1985). Reliability of Technical Systems: Handbook. (Russian). Radio i Sviaz.
7. Ushakov, I. (ed.) (1989). Prirucka Spolehlivosti v Radioelektronice a Automatizacni technice. (*Check.*). SNTL.
8. Rook, P. (1990). Software reliability handbook. Cluver.
9. Kececioglu, D. (1991) Reliability engineering handbook. Prentice Hall.
10. Ushakov, I.A., ed. (1994) *Handbook of Reliability Engineering.* Wiley.
11. Ireson, W., C. Coombs, R. Moss (1995) Handbook of Reliability Engineering and Management. McGrow Hill.
12. Kececioglu, D. (1995) Maintainability, availability, and operational readiness engineering handbook. Prentice Hall.
13. Pecht, M., ed. (1995), *Product Reliability, Maintainability, and Supportability Handbook* CRC Press.
14. Pahm, H. (2003) Handbook on Reliability Engineering. Springer.
15. Lyu, R. (ed.). (2005) Handbook of Software Reliability Engineering. McGraw-Hill
16. Misra, K. (2008) *Handbook of Performability Engineering* . Springer.
17. Stapelberg, R. (2009) Handbook of Reliability, Availability, Maintainability and Safety in Engineering Design

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):

1. Bazovsky, I. (1961). *Reliability Theory and Practice*. Prentice Hall.
2. Lloyd, D.K., and M. Lipow (1962). *Reliability: Management, Methods, and Mathematics.* Prentice-Hall.
3. Polovko, A. M. (1964). Fundamentals of Reliability Theory.(Russian). Nauka.
4. Barlow, R.E., and F. Proschan (1965) *Mathematical Theory of Reliability.* Wiley.
5. Gnedenko, B.V., Yu.K. Belyaev and A.D. Solovyev (1965). *Mathematical Methods in Reliability Theory*. (Russian). Nauka
6. Polovko, A. M. (1968). Fundamentals of Reliability Theory. Academic Press.
7. Gnedenko, B.V., Yu.K. Belyaev and A.D. Solovyev (1969). *Mathematical Methods in Reliability Theory.* Academic Press.
8. Barlow, R.E., and F. Proschan (1975) *Statistical Theory of Reliability and Life Testing.* Holt, Rinehart and Winston
9. Barlow, R.E., and F. Proschan (1981) *Statistical Theory of Reliability and Life Testing*, 2nd ed. To Begin With.
10. Hoyland, A., M. Rausand (1994). System Reliability Theory: Models and Statistical Methods. Wiley
11. Gnedenko, B.V., and I.A. Ushakov (1995) *Probabilistic Reliability Engineering.* Wiley.
12. Barlow, R.E. (1998) Engineering Reliability, SIAM.
13. Bazovsky, I. (2004). *Reliability Theory and Practice*. Dover.
14. Zio, E. (2007). An introduction to the basics of reliability and risk analysis. World Scientific.
15. Ushakov , I.A. (2009). Theory of System Reliability.(Russian).Drofa.
16. Tobias, P.A., and D.C. Trindade (2010). Applied Reliability, 3rd edition. CRC Press

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):

1. Bolotin, V.V. (1966) Statistical Aspects in the Theory of Structural Stability in Dynamic Stability of Structures. Pergamon Press
2. Ushakov, I. (1969) Methods of Solution of Simplest Optimal Redundancy Problems under Constraints (Russian). Sovetskoe Radio.
3. Amstadter, B.L. (1971). *Reliability mathematics: Fundamentals, practices, procedures*. McGraw-Hill.
4. Buslenko, N.P., V.V. Kalashnikov, and I.N. Kovalenko (1973) *Lectures on Theory of Complex Systems* (in Russian). Sovietskoe Radio.
5. Mann, N.R., R.E. Schaefer, and N.D. Singpurwalla (1974) *Methods of Statistical Analysis of Reliability and Life Data.* Wiley.
6. Barlow, R.E., Fussell, J.B. and Singpurwalla, N.D. (1975) Reliability and Fault Tree Analysis, SIAM
7. Konenkov, Yu.K., and I.A. Ushakov (1975) Reliability of Electronic Equipment under Mechanical Stress (Russian). Sovetskoe Radio
8. Ryabinin I. (1976) Reliability of Engineering Systems. Principles and Analysis.
9. Gertbakh, I.B., (1977). *Models of Preventive Maintenance*. North-Holland.
10. Kaufmann, A., Grouchko, D., Cruon, R. (1977). *Mathematical models for the study of the reliability of systems.* Academic Press.
11. Kapur, K.C., and L.R. Lamberson (1977). *Reliability in Engineering Design*. Wiley.
12. Tillman, F.A., C.L. Hwang, and W. Kuo (1980) Optimization of System Reliability. Marcel Dekker.
13. McCormick, N. J. (1981). Reliability and Risk Analysis. Academic Press.
14. Lawless, J.F. (1982). *Statistical Models and Methods for Lifetime Data.* Wiley.
15. Martz, H. F., and R.A. Waller (1982) *Bayesian Reliability Analysis.* Wiley
16. Nelson, W. (1982), *Applied Life Data Analysis.* Wiley.
17. Pavlov, I.V. (1982) *Statistical Methods of Reliability Estimation by Tests Results.* (Russian) Moscow, Radio i Svyaz
18. Gnedenko, B.V., ed. (1983) *Aspects of Mathematical Theory of Reliability* (Russian). Authors: E.Yu. Barzilovich, Yu.K Belyaev, V.A. Kashtanov, I.N. Kovalenko, A.D. Solovyev, I.A. Ushakov. Moscow, Radio i Svyaz.
19. Cox, D.R., and D. Oakes (1984). *Analysis of Survival Data*. Chapman & Hall.
20. Osaki. S., Y.Hatoyama. (eds). (1984), Stochastic Models in Reliability Theory. Springer.
21. Birolini, A. (1985). *On the use of stochastic processes in modeling reliability problems.* Springer.
22. Melchers, R.E. (1987). *Structural reliability: Analysis and prediction*. Wiley.
23. Shooman, M. (1987), *Software Engineering: Design, Reliability, and Management*, McGraw-Hill
24. Bolotin, V. V. (1989). *Prediction of Service Life for Machines and Structures,* ASME Press.
25. Rudenko, Yu.N., and I.A. Ushakov (1989). *Reliability of Power Systems* (Russian). Nauka.
26. Nelson, W (1990), *Accelerated Testing: Statistical Models, Test Plans and Data Analysis*, Wiley.

27. Volkovich, V.L., A.F. Voloshin, V.A. Zaslavsky, and I.A. Ushakov (1992) *Models and Methods of Optimization of Complex System Reliability* (in Russian). Naukova Dumka.
28. Neufelder, A. (1993), *Ensuring Software Reliability.* Marcel Dekker
29. Leemis, L. M., (1995). *Reliability: Probabilistic Models and Statistical Methods*, Prentice-Hall.
30. Elsayed, E. A. (1996). Reliability Engineering. Addison Wesley.
31. Carter, A. (1997) Mechanical reliability and design. Wiley.
32. Ebeling, C. E., (1997), An Introduction *to Reliability and Maintainability Engineering*, McGraw-Hill
33. Kovalenko, I.N., N.Y. Kuznetsov, and P.A. Pegg. (1997) *Mathematical Theory of Reliability of Time Dependent Systems with Practical Applications.* Wiley.
34. Raizer V.D. (1998), Theory of Reliability in Structural Design, ASU Publ. House.
35. Modarres M., , M. Kaminskiy and V. Krivtsov (1999). Engineering and Risk Analysis: A Practical Guide (2nd ed.), Marcel Dekker.
36. Gertsbakh, I. (2000), Theory of Reliability with Applications to Preventive Maintenance. Springer.
37. Aven, T., U. Jensen, (1999) *Stochastic models in reliability*, Springer.
38. Ionescu, D.C. and N. Limnios.(Eds) (1999). Proceedings of the Int'l. Conf. on Mathematical Methods in Reliability Statistical and Probabilistic Models in Reliability. Birkhauser.
39. Kuo. W., M. Zuo. (2003). Optimal Reliability Modelling. Wiley.
40. Lindqvist, B., and K. Doksum. (Eds.) 2003. Proc. of the 3rd Int'l. Conf. on Mathematical Methods in Reliability. Mathematical and Statistical Methods in Reliability. World Scientific.
41. Kolowrocki, K. (2004). Reliability of Large Systems. Elsevier.
42. Nelson, Wayne B., (2004), *Accelerated Testing - Statistical Models, Test Plans, and Data Analysis.* Wiley
43. Neubeck, K. (2004) Practical Reliability Analysis. Prentice Hall.
44. Xie Min, Poh Kim-Leng, Dai Yuan-Shun (2004) *Computing System Reliability: Models and Analysis*, Kluwer.
45. Levitin, G. (2005). The Universal Generating Function in Reliability Analysis and Optimization. Springer.
46. Musa, John (2005) Software Reliability Engineering: More Reliable Software Faster and Cheaper, (2nd ed.). McGrow-Hill.
47. Nelson, W.B. (2005) A bibliography of accelerated test plans. IEEE Trans. on Reliability. Vol. 54, No.2.
48. Wilson, A., N. Limnios, S. Keller-McNulty, Y. Armijo. (Eds) (2005). Proc. of the 4th Int'l. Conf. on Mathematical Methods in Reliability. Modern Statistical and Mathematical Methods in Reliability. World Scientific.
49. Dhillon, B.S. (2006). Maintainability, Maintenance, and Reliability for Engineers. CRC Press.
50. Singpurwalla, N.D. (2006) Reliability and Risk: A Bayesian Perspective. Wiley.
51. Epstein, B., and I. Weissman (2008). Mathematical Models for Systems Reliability. CRC Press.
52. Raizer , V. (2009). Reliability of Structures: Analysis and Applications. Backbone Publishing.

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):

1. Gnedenko, B. V. , Yu. K. Belyaev, I. N. Kovalenko. (1964). Mathematical problems in Reliability Theory. Scientific Achievements in Probability Theory and Mathematical Statistics. VINITI.
2. Gnedenko, B.V., B.A. Kozlov, I.A. Ushakov. The role and place of the Reliability theory in the process of creating technical systems. In: Theory of Probability and Queuing Theory. Nauka.
3. El-Neweihi, E., F. Proschan, (1980) Multistate reliability models: a survey. In: *Multivariate Analysis V* . Ed. by P.R.Krishnaiah. North-Holland.
4. Griffith W. S. (1980) A survey of some results in multistate reliability theory, *Proc. of the 11th Annual Pittsburgh Conf. on Modeling and Simulation.*
5. Belyaev, Yu.K., B.V. Gnedenko, and I.A. Ushakov (1983) Mathematical Problems in Queuing and Reliability Theory. *Engineering Cybernetics,* Vol.21, No.6
6. Gertsbakh , I., (1984). Asymptotic methods in reliability theory: A review. Adv. Appl. Prob., 16.
7. El-Neweihi, E., F. Proschan. (1984) Degradable systems: a survey of multistate system theory. *Communication in Statistics. Theory and Methods* .Vol.13,
8. Dhillon, B., K.Ugwu (1985). Bibliography of literature on telecommunication systems reliability. Microelectronics and Reliability,
9. Vol. 25, No. 4.
10. Rukhin, A.L., and Hsieh, H.K. (1987) Survey of Soviet Work in Reliability. *Statistical Science*, Vol.2, No. 4.
11. Aven, T. (1988). Some considerations on reliability theory and its applications. Reliability Engineering & System Safety.Volume 21, Issue 3.
12. Evans, R. (1996) Real Reliability. IEEE Trans. on Reliability. Vol. 45, No.3.
13. Ushakov, I. (1996). Reliability Calculations: To Do or Not To Do? *IEEE Transaction on Reliability, Vol. 45,* No. 4.
14. Denson, W. (1998) The history of reliability prediction. IEEE Trans. on Reliability. Vol. 47, No.3.
15. Lalli, V.R. (1998) Space-system reliability: a historical perspective. IEEE Trans. on Reliability. Vol. 47, No.3.
16. Evans, R.A. (1998) Electronics reliability: a personal view. IEEE Trans. on Reliability. Vol. 47, No.3.
17. Evans, R.A. (2000) Models for reliability of repaired equipment. . IEEE Trans. on Reliability. Vol. 49, No.3.
18. Kuo, W. Prasad, V.R. (2000) An annotated overview of system-reliability optimization. IEEE Trans. on Reliability. Vol. 49, No.2.
19. Ushakov, I. (2000) Reliability: Past, Present, Future. *Proc. of the 2nd Conf. Mathematical Models in Reliability.*
20. Barlow, R.E. (2002). Mathematical Reliability Theory: From the Beginning to the Present Time. Proc. of 3rd Int'l Conf. on Mathematical Methods in Reliability.
21. Levitin G., Lisnianski A., Ushakov I., (2003) Reliability of Multi-State Systems: A Historical Overview. In Mathematical and statistical methods in reliability, Ed. by B. Lindqvist and K. Doksum (Eds.). World Scientific.

22. Kaminskiy, M.P. Krivtsov, V.V. (2005) A bibliography of accelerated test plans part II - references. IEEE Trans. on Reliability. Vol. 54, No.3.
23. Ushakov , I. (2006). D'ou venons-nous? Qui sommes-nous? Ou allons-nous? RTA Jounal, Vol.1, No.1. Gnedenko Forum.
24. Way Kuo (2007) Compatibility and Simplicity: The Fundamentals of Reliability. IEEE Trans. on Reliability. Vol. 56, No.4.
25. Shuen-Lin Jeng Jye-Chyi Lu Kaibo Wang (2007) A Review of Reliability Research on Nanotechnology. IEEE Trans. on Reliability. Vol. 56, No.3.
26. Ushakov, I. (2007). Is reliability theory still alive? RTA Jounal, Vol.2, No. 2. Gnedenko Forum.

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):

1. Erlang, A.K. (1909). The Theory of Probabilities and Telephone Conversations. Nyt Tidsskrift for Matematik B, vol. 20.
2. Cox, D., W.Smith (1954) On the superposition of renewal processes. Biometrika, vol.41, No.(1-2).
3. Ososkov, G.A. (1956). A limit theorem for flows of similar events. Theory Probab. Appl., V. 1, No. 2
4. Renyi, A. (1956). Poisson-folyamat egy jemllemzese (Hungarian). Ann. Math. Statist, V. 1, No. 4
5. Saaty, T. (1961) Elements of Queueing Theory with Applications. McGraw-Hill.
6. Cox, D.R. (1962). Renewal Theory. John Wiley, New York.

7. Grigelionis, B (1963). On convergence of sums of steps stochastic processes to a Poisson Process. Theory Probab. Appl. V.8, No.2
8. Khinchin, A. (1963). Works on the mathematical theory of queuinf systems. Nauka.
9. Gnedenko, B.V. (1964). On duplication with renewal. Engrg Cybernet. No. 5
10. Gnedenko, B.V. (1964). On spare duplication. Engrg Cybernet. No. 4
11. Gnedenko B.V., Kovalenko I.N. (1966) Introduction to Queueing Theory. (Russian). Nauka.
12. Gnedenko B.V., Kovalenko I.N., (1971) Introduction to Queueing Theory. Akademie-Verlag.
13. Cox, D.R, and V. Isham (1980). Point Processes. Chapman and Hall.
14. Gnedenko, B.V., ed. (1983) Aspects of Mathematical Theory of Reliability (Russian). Authors: E.Yu. Barzilovich, Yu.K Belyaev, V.A. Kashtanov, I.N. Kovalenko, A.D. Solovyev, I.A. Ushakov. Moscow, Radio i Svyaz.
15. Gnedenko B.V., Kovalenko I.N. (1989) Introduction to Queueing Theory. Birkhдuser,
16. Kijima, M. (1989). Some Results for Repairable Systems with General Repair. Journal of Applied Probability, No. 26.
17. Gnedenko, B.V., and I.A. Ushakov (1995) Probabilistic Reliability Engineering. Wiley.
18. Gross, Donald; Carl M. Harris (1998). Fundamentals of Queueing Theory. Wiley.
19. Genis, Ya. (2005). On reliability of renewal systems with fast repair. RTA Jounal, Vol.1, No.2. Gnedenko Forum.

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):

1. Moore, E., C. Shannon (1956) Reliable circuits using less reliable relays. J.Franklin Inst. No.9.
2. Esary, J.D., and F. Proschan (1962). The reliability of coherent systems. In: Redundancy Techniques for Computing Systems. Spartan Books, Washington, D.C.
3. Ushakov, I., Yu. Konenkov (1964). Evaluation of branching systems operational effectiveness. (Russian) In: "Cybernetics for Service to Communism". Energiya.
4. Lomonosov, M.V., and V. Polessky (1971). Upper bound for the reliability of information networks. Problems Inform. Transmission. Vol. 7
5. Lomonosov, M.V., and V. Polessky (1972). Lower bound of network reliability. Problems Inform. Transmission. Vol. 8
6. Gadasin, V.A., and I.A. Ushakov (1975). Reliability of Complex Information and Control Systems (Russian). Sovetskoe Radio.
7. Ushakov, I.A., and E.I. Litvak (1977). An upper and lower estimate of the parameters of two-terminal networks. Engrg. Cybernet. vol. 15
8. Litvak, E., I. Ushakov. (1984) Estimation of parameters of structurally complex systems. Engrg, Cybernet. vol. 22, no.4.

9. Chiou, S.N., Li, V.O.K. (1986) Reliability analysis of a communication network with multimode components. IEEE Journal of Selected Areas in Communications , Vol.SAC-4.
10. Ushakov, I., V.A. Kaustov and E.I. Litvak. (1986). The Computational Effectiveness of Reliability Estimates by the Method of Nonedge-Intersecting Chains and Cuts. Soviet Journal of Computer and System Sciences , Vol. 24, No. 4.
11. Reinshke, K., I. Ushakov. (1987), Application of Graph Theory for Reliability Analysis, (in German), Verlag Technik.
12. Reinshke, K., I. Ushakov. (1988), Application of Graph Theory for Reliability Analysis, (in Russian), Radio i Sviaz.
13. Reinshke, K., I. Ushakov. (1988), Application of Graph Theory for Reliability Analysis, (in German), Springer.Elperin, T, I. Gertsbakx, M. Lomonosov (1991) Estimation of network reliability using graphs evolution models. IEEE Trans. Reliab., No.40.
14. Ushakov, I. (1989). Reliability Analysis of Computer Systems and Networks (Russian). Mashinostroenie.
15. Lomonosov, M. (1994) On Monte Carlo estimates in Network Reliability. Probab. Engnrg. Inf. Sci., No.8.
16. Ushakov, I. (1994) Methods of Research in Telecommunications Reliability (An Overview of Research in the Former Soviet Union). RTA,
17. Altiparmak, F., B. Dengiz, A. Smith. (1997) Local search genetic algorithm for optimal design of reliable networks. IEEE Transactions on Evolutionary Computation, vol. 1, no. 3
18. Dengiz, B., F. Altiparmak, A. Smith. (1997) Efficient optimization of all-terminal reliable networks using an evolutionary approach. IEEE Transactions on Reliability, vol. 46, no. 1.
19. Wei-Jenn Ke Sheng-De Wang (1997) Reliability evaluation for distributed computing networks with imperfect nodes. IEEE Trans. on Reliability. Vol. 46, No.4.Cancela, H. El Khadiri, M. (1998) Series-parallel reductions in Monte Carlo network-reliability evaluation. IEEE Trans. on Reliability. Vol. 47, No.2.
20. Deeter, D., A. Smith (1998) Economic design of reliable networks, IIE Transactions, vol. 30.
21. Malec, H.A. (1998) Communications reliability: a historical perspective. IEEE Trans. on Reliability. Vol. 47, No.3.
22. Abo-El-Fotoh, H.M.F. Al-Sumait, L.S. (2001) A neural approach to topological optimization of communication networks, with reliability constraints. IEEE Trans. on Reliability. Vol. 50, No.4.
23. Rauzy, A. (2001) Mathematical foundations of minimal cutsets. IEEE Trans. on Reliability. Vol. 50, No.4.
24. Snow, A.P. (2001) Network reliability: the concurrent challenges of innovation, competition, and complexity. IEEE Trans. on Reliability. Vol. 50, No.1.
25. Levitin, G. (2002) Optimal reliability enhancement for multi-state transmission networks with fixed transmission time, Reliability Engineering & System Safety, vol. 76.
26. Lin, Y. (2002) Using minimal cuts to evaluate the system reliability of a stochastic-flow network with failures at nodes and arcs, Reliability Engineering & System Safety, 75.
27. Srivaree-ratana, C., A. Konak, Alice E. Smith. (2002) Estimation of all-terminal network reliability using an artificial neural network. Computers and Operations Research, vol. 29, no. 7.
28. Kroese, D.P. Kin-Ping Hui Nariai, S. (2007) Network Reliability Optimization via the Cross-Entropy Method. IEEE Trans. on Reliability. Vol. 56, No.2.
29. Fotuhi-Firuzabad, M., R. Billinton, T.S. Munian, B. Vinayagam. (2003) A novel approach to determine minimal tie-sets of complex network. IEEE Trans. on Reliability. Vol. 52, No.4.

30. Kolowrocki K. (2003) Asymptotic Approach to Reliability Analysis of Large Systems with Degrading Components, International Journal of Reliability, Quality and Safety Engineering, Vol. 10, No. 3.
31. Yi-Kuei Lin (2004) Reliability of a stochastic-flow network with unreliable branches & nodes, under budget constraints. IEEE Trans. on Reliability. Vol. 53, No.3.
32. Fang-Ming Shao Xuemin Shen Pin-Han Ho (2005) Reliability optimization of distributed access networks with constrained total cost. IEEE Trans. on Reliability. Vol. 54, No.3.
33. Marseguerra, M. Zio, E. Podofillini, L. Coit, D.W. (2005) Optimal design of reliable network systems in presence of uncertainty. IEEE Trans. on Reliability. Vol. 54, No.2.
34. Kroese, D.P. Kin-Ping Hui Nariai, S. (2007) Network Reliability Optimization via the Cross-Entropy Method. IEEE Trans. on Reliability. Vol. 56, No.2.
35. Wei-Chang Yen (2007) A Simple Heuristic Algorithm for Generating All Minimal Paths. IEEE Trans. on Reliability. Vol. 56, No.3.
36. Yi-Kuei Lin (2007) Reliability of a Flow Network Subject to Budget Constraints. IEEE Trans. on Reliability. Vol. 56, No.1.
37. Altiparmak, F., B. Dengiz, A. Smith. (2009) A general neural network model for estimating telecommunications network reliability. IEEE Transactions on Reliability, vol. 58, no. 1.
38. Altiparmak, F., B. Dengiz, A. Smith. (2009) Optimal Design of Reliable Computer Networks A Comparison of Metaheuristics. Journal of Heuristics, vol. 9, no. 6.
39. Sharafat, A.R. Ma'rouzi, O.R. . (2009). All-Terminal Network Reliability Using Recursive Truncation Algorithm. IEEE Trans. on Reliability. Vol. 58, No.2
40. Tsitsiashvili, G., and A. Losev . (2009). An asymptotic analysis of a reliability of internet type networks. RTA Jounal, Vol.4, No.3. Gnedenko Forum.

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].

The first book on optimal redundancy [8] appeared only in the end of 1960s.

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):

1. Moskowitz, F., and J. McLean (1956). Some reliability aspects of system design. IRE Trans. Vol. PGRQC-8.
2. Bellman, R.E., and S. Dreyfus (1958). Dynamic programming and reliability of multi-component devices. Opns Res., Vol. 6, No.2.
3. Black, G., and F. Proschan (1959). On optimal redundancy. Opns Res., V.7, No.5
4. Bellman, R.E., and E. Dreyfus (1962) Applied Dynamic Programming. Princeton University Press.
5. Kettelle, J.D. (1962). Least-cost allocation of reliability investment. Opns Res. Vol. 10, No. 2
6. Derman, C. (1963). Optimal replacement and maintenance under Markovian deterioration with probability bounds on failure. Management Science, V. 9, No. 3.

7. Proschan, F., and T. Bray (1965). Optimum Redundancy under Multiple Constraints. Opns. Res., Vol. 13, No. 5.
8. Ushakov, I. (1969). Methods of Solution of Simplest Optimal Redundancy Problems under Constraints (Russian). Sovetskoe Radio.
9. Ushakov, I.A., and A.V. Yasenovets (1977) Statistical methods of solving problems of optimal standby. Engineering Cybernetics, No.6
10. Ushakov, I.A., and E.I. Gordienko (1978) Solution of some optimization problems by means of statistical simulation (in Russian). Electronosche Infdormationsverarbeitung und Kybernetik, 14(11)
11. Volkovich, V.L., A.F. Voloshin, V.A. Zaslavsky, and I.A. Ushakov (1992) Models and Methods of Optimization of Complex System Reliability (in Russian). Kiev, Naukova Dumka.
12. Coit, D., A. Smith. (1996) Reliability optimization of series-parallel systems using a genetic algorithm," . IEEE Transactions on Reliability vol. 45, no. 2.
13. Coit, D., A. Smith. (1996) Solving the redundancy allocation problem using a combined neural network / genetic algorithm approach. Computers and Operations Research, vol. 23, no. 6.
14. Lisnianski, A., G. Levitin, H. Ben-Haim, D. Elmakis, (1996) Power system structure optimization subject to reliability constraints, Electric Power Systems Research, vol. 39, No.2.
15. Dengiz, B. Altiparmak, F. Smith, A.E. (1997) Efficient optimization of all-terminal reliable networks, using an evolutionary approach. IEEE Trans. on Reliability. Vol. 46, No.1.
16. Rubinstein, R.Y. Levitin, G. Lisnianski, A. Ben-Haim, H. (1997) Redundancy optimization of static series-parallel reliability models under uncertainty. IEEE Trans. on Reliability. Vol. 46, No.4.
17. Ushakov, I., S. Chakravarty, E. Gordienko. (1998) Novel Simulation Technique for Spare-Kit Optimization. Proc. of the IEEE Systems, Man, and Cybernetics Conference.
18. Prasad, V.R., Kuo, W., Kim, K.M. (1999) Optimal allocation of s-identical, multi-functional spares in a series system. IEEE Trans. on Reliability. Vol. 48, No.2.
19. Sung Chang Sup, Cho Yong Kwon (1999) Branch-and-bound redundancy optimization for a series system with multiple-choice constraints. IEEE Trans. on Reliability. Vol. 48, No.2.
20. Prasad, V.R. Kuo, W. (2000) Reliability optimization of coherent systems. IEEE Trans. on Reliability. Vol. 49, No.3.
21. Pusher, W., I. Ushakov. (2002) Calculation of nomenclature of spare parts for mobile repair station. Methods of Quality Management, №4
22. "Efficiently solving the redundancy allocation problem using tabu search," Sadan Kulturel-Konak, Alice E. Smith and David W. Coit, IIE Transactions, vol. 35, 2003, 515-526.
23. Coit, D.W. Tongdan Jin Wattanapongsakorn, N. (2004) System optimization with component reliability estimation uncertainty: a multi-criteria approach. IEEE Trans. on Reliability. Vol. 53, No.3.
24. Kuo. W., M. Zuo. (2003). Optimal Reliability Modelling. Wiley.
25. Marseguerra, M. Zio, E. Podofillini, L. (2004) Optimal reliability/availability of uncertain systems via multi-objective genetic algorithms. IEEE Trans. on Reliability. Vol. 53, No.3.
26. Ramirez-Marquez, J., D. Coit. (2004) A Heuristic for Solving the Redundancy Allocation Problem for Multistate Series-Parallel Systems. Reliability Engineering & System Safety, vol. 83, no. 3.
27. Romera, R. Valdes, J.E. Zequeira, R.I. (2004) Active-redundancy allocation in systems. IEEE Trans. on Reliability. Vol. 53, No.3.
28. Yun-Chia Liang, Smith, A.E. (2004) An ant colony optimization algorithm for the redundancy allocation problem. IEEE Trans. on Reliability. Vol. 53, No.3.
29. Yalaoui, A., Chatelet, E., Chengbin Chu (2005) A new dynamic programming method for reliability & redundancy allocation in a parallel-series system. IEEE Trans. on Reliability. Vol. 54, No.2.

30. Coit, D.W. Konak, A. (2006). Multiple Weighted Objectives Heuristic for the Redundancy Allocation Problem. IEEE Trans. on Reliability. Vol. 55, No.3.
31. Ha, C. Kuo, W. (2006). Multi-path heuristic for redundancy allocation: the tree heuristic. IEEE Trans. on Reliability. Vol. 55, No.1.
32. Konak, A., D. Coit, A. Smith (2006)Multi-Objective Optimization Using Genetic Algorithms: A Tutorial. Reliability Engineering & System Safety, vol. 91, no. 9, September 2006.
33. Levitin, G. (2006). Genetic algorithms in reliability engineering. Guest editorial. G., Reliability Engineering & System Safety, 91(9).
34. Billionnet, A. (2008) Redundancy Allocation for Series-Parallel Systems Using Integer Linear Programming. IEEE Trans. on Reliability. Vol. 57, No.3.
35. Runqing Huang Lingling Meng Lifeng Xi Liu, C.R. (2008) Modeling and Analyzing a Joint Optimization Policy of Block-Replacement and Spare Inventory With Random-Leadtime. IEEE Trans. on Reliability. Vol. 57, No.1.

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):

1. Ushakov, I., Yu. Konenkov (1964). Evaluation of branching systems operational effectiveness. (Russian) In: “Cybernetics for Service to Communism”. Energiya.
2. Gadasin, V.A., and I.A. Ushakov (1975). Reliability of Complex Information and Control Systems (Russian). Sovetskoe Radio.
3. Rudenko, Yu.N., and I.A. Ushakov (1989). *Reliability of Power Systems* (Russian). Nauka.
4. Ushakov, I., S. Antonov, S. Chakravarty, A. Hamid,and T. Keliinoi.(1999) Spare Supply System for Globalstar, a Worldwide Telecommunication System. Proc. of the 24th International Conference on Computers and Industrial Engineering.
5. Ushakov, I., and S. Chakrvarty. (2000). Effectiveness analysis of “Globalstar” gateways. Proceedings of the 2nd Int'l. Conf. on Mathematical Methods in Reliability
6. Ushakov, I., S. Chakravarty (2002) Reliability influence on communication network capability. Methods of Quality Management, ¹7.
7. Ushakov, I., S. Chakravarty (2002) Reliability measure based on average loss of capacity. International Transaction in Operational Research, ¹9.
8. Ushakov, I., W. Puscher (2002).Territorially dispersed system of technical maintenance. *Methods of Quality Management*, No.2, 2002.
9. Ushakov, I., S. Chakravarty. (2005). Reliability measure based on average loss of capacity. *International Transaction in Operational Research,* vol.9.
10. Ushakov, I., W. Puscher (2005). Calculation of nomenclature of spare parts for mobile repair station. *Methods of Quality Management*, No.4.
11. Ushakov, I. (2006) Terrestrial maintenance system for geographically distributed clients. Eksploatacja i Niezawodnoœæ, No. 2.
12. Ni Wang, Jye-Chyi Lu, P. Kvam. (2006) Reliability Modeling in Spatially Distributed Logistics Systems. IEEE Trans. on Reliability. Vol. 55, No.3.

13. Ushakov. I. (2008). Method of optimal spare allocation for mobile repair station. RTA Jounal, Vol.3, No.3. Gnedenko Forum.

Reliability of multi-state sytems

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-alohabetical order)

1. Ushakov, I.A. (1960). Evaluation of complex systems operational effectiveness. In “Reliability of Electronic Equipment”. Sovietskoe Radio.
2. Kozlov, B., I. Ushakov. (1966). Brief Handbook of Reliability Calculations for Electronics Equipment. (Russian). Sovetskoe Radio.
3. Ushakov, I. (1967). Effectiveness of functioning complex systems. In “Reliability of Complex Technical Systems”. Sovietskoe Radio.
4. Kozlov, B., I. Ushakov (1970). Reliability Handbook. Holt, Rinehart and Winston.
5. Murchland, J. (1975) Fundamental concepts and relations for reliability analysis of multi-state systems. In *Reliability and Fault Tree Analysis.* Ed. by R. Barlow, J. Fussell, N. Singpurwalla. SIAM.
6. Kozlov, B., I. Ushakov (1975). Handbook of Reliability Calculations for Electronic and Automatic Equipment.(Russian). Sovetskoe Radio.
7. Barlow, R. E. , A. S. Wu. (1978) Coherent systems with multi-state components, *Mathematics of Operations Research*, vol. 3.
8. El-Neweihi, E., and F. Proschan. (1978) Multistate coherent systems. J. Appl. Prob. Vol.15.
9. Caldarola, L. (1980) Coherent systems with multistate components, *Nucl. Eng. Design*, vol 58.
10. Griffith, W., (1980) Multistate reliability models, *J. Applied Probability*, vol. 17,

11. Fardis, M. N. , C. A. Cornell, (1981) Analysis of coherent multistate systems, *IEEE Transactions on Reliability*, vol 30.
12. Block, H., T. Savits. (1982) A Decomposition of Multistate monotone system, *J. Applied Probability*, vol 19.
13. Fardis, M.N. , C.A. Cornell, (1982), Multistate reliability analysis. *Nuclear Engineering and Design*, Vol.60.
14. Hudson, J. C. , K. C. Kapur, (1982) Reliability Theory for Multistate Systems with Multistate Components, *Microelectronics and Reliability*, vol. 22, No. 1.
15. Hudson, J. C. , K. C. Kapur. (1983) Reliability analysis of multistate systems with multistate components, *Transactions of Institute of Industrial Engineers*, vol 15, No. 2.
16. Ohi, F., T. Nishida, (1983) Generalized multistate coherent systems. *Journal of Japan Statistical Society*, Vol.13.
17. Ebrahimi, N. (1984) Multistate reliability models, *Naval Res. Logistics*, vol 31, ,
18. Ohi,F., T. Nishida, (1984), Multistate systems in reliability theory. In: *Stochastic Models in Reliability Theory* . Ed. by S.Osaki & Y.Hatoyama. Springer.
19. Ohio, F., T. Nishida, (1984), On multistate coherent systems, *IEEE Transactions on Reliability*, vol. 33.
20. Aven, T. (1985). Reliability evaluation of multi-state systems with multi-state components. IEEE Transactions on Reliability, Vol. 34, No.5.
21. Hudson, J. & Kapur, K. (1985). Reliability bounds for multi-state systems with multi-state components. Operations Research, Vol.33, No.1
22. Reinshke, K. (1985) Systems consisting of multi-state units. In *Reliability of technical systems: Handbook*, (Russian). Ed. by I. Ushakov. Radio i Sviaz.
23. Ushakov, I. *Reliability of technical systems: Handbook*, (Russian). Radio i Sviaz.
24. Xue Jianan, (1985) New approach for multistate system analysis. Reliability Engineering , Vol.10,
25. Xue Jianan, (1985) On multistate system analysis. *IEEE Transactions on Reliability*, Vol.34, No.4.
26. Natvig, B., S. Sormo, A. Holen, G. Hogasen, (1986), Multistate reliability theory - a case study. *Advances in Applied Probability* , Vol.18,
27. El-Neweihi, E., F. Proschan, J. Sethuraman, (1988), Optimal allocation of multistate components. In: *Handbook of Statistics, Vol.7: Quality Control and Reliability.* Edited by P.R.Krishnaiah, C.R.Rao. North-Holland.
28. Andrzejczak, K. (1992) Structure analysis of multistate coherent systems. *Optimization.* Vol.25, No.2-3.
29. Aven, T. (1993) On performance measures for multistate monotone systems, *Reliability Engineering and System Safety*, vol.41.
30. Ushakov, I. (Ed.) (1994) Handbook of Reliability Engineering. Wiley.
31. Yu, K., I. Koren, Y. Guo, (1994) Generalized Multistate Monotone Coherent Systems, *IEEE Transactions on Reliability*, vol. 43, No. 2.
32. Gnedenko, B., I. Ushakov. (1995). Probabilistic Reliability Engineering. Wiley.
33. Xue, J. & Yang, K. (1995). Dynamic reliability analysis of coherent multi-state systems. IEEE Transactions on Reliability , 44.
34. Grabski, F., K. Kolowrocki, (1999) Asymptotic reliability of multistate systems with semi-Markov states of components. In Safety and reliability ed. by Schueller and Kafka. Balkema.
35. Rykov, V., B. Dimitrov B., (2002). On multi-state reliability systems. Information Processes, Vol.2, No.2.
36. Dimitrov, B., V. Rykov, P. Stanchev. (2002). On multi-state reliability systems, In *Proc. of 3rd Int. Conf. on Mathematical Methods in Reliability.*

37. Ushakov, I. , G. Levitin, A. Lisnianski, (2002) Multi-state system reliability: from theory to practice. Poc. of 3rd Int'l Conf. on Mathematical Methods in Reliability
38. Kuo W., Zuo M.J., (2003). Multi-state system models. In: *Optimal reliability modelling*. Wiley
39. Levitin G., Lisnianski A., Ushakov I., (2003) Reliability of Multi-State Systems: A Historical Overview. In *Mathematical and statistical methods in reliability*, Ed. by B. Lindqvist and K. Doksum (Eds.). World Scientific.
40. Levitin, G. , and A. Lisnianski, (2003) Multi-state System Reliability Analysis and Optimization. In Handbook of Reliability Engineering, Ed. by H. Pham, Springer.
41. Lisnianski , A., G. Levitin, (2003) Multi-State System Reliability. Assessment, Optimization, Applications. World Scientific.Ding, Y., A. Lisnianski, I. Frenkel. (2006) Multi-state System Reliability Assessment by Using State Reduction Techniques. Communications in Dependability and Quality Management. Vol. 9, No. 3.
42. Kapur, K. (2006) Multi-state reliability: models and applications. Eksploatacja i Niezawodnoœæ, No. 2, 2006
43. Zaitseva, E., V. Levashenko, K. Matiaško (2006) Failure analysis of series and parallel multi-state system . Eksploatacja i Niezawodnoœæ, No. 2, 2006
44. Levitin, G. (2007). Block diagram method for analyzing multi-state systems with uncovered failures. *Reliability Engineering & System Safety*, 92(6).
45. Ramirez-Marquez, J. E., G. Levitin, (2008) Algorithm for estimating reliability confidence bounds of multi-state systems, *Reliability Engineering & System Safety*, 93(8).
46. Wei-Chang Yeh (2008). A Fast Algorithm for Searching All Multi-State Minimal Cuts. IEEE Trans. on Reliability. Vol. 57, No.4.
47. Zhigang Tian Yam, R.C.M. Zuo, M.J. Hong-Zhong Huang (2008) Reliability Bounds for Multi-State k-out-of-n Systems. IEEE Trans. on Reliability. Vol. 57, No.1.
48. Kolowrocki, K. (2009). Reliability and risk analysis of multi-state systems with degrading components. RTA Jounal, Vol.4, No.1. Gnedenko Forum.

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):

1. Ushakov, I. (1986). A Universal Generating Function. *Soviet Journal of Computer and System Sciences*, Vol. 24, No. 5.
2. Ushakov, I., (1987). Optimal Standby Problem and a Universal Generating Function. *Soviet Journal of Computer and System Sciences*, Vol. 25, No. 4.
3. Ushakov, I., (1987). Solution of Multi-Criteria Discrete Optimization Problems Using a Universal Generating Function. *Soviet Journal of Computer and System Sciences* Vol. 25, No. 5.
4. Ushakov, I. (1998). An object oriented approach to generalized generating function. *Proc. of the ECCO-XI Conference.*
5. Ushakov, I., (1998). Reliability Analysis of Multi-State Systems by Means of a Modified Generating Function. *Journal of Information Processes and Cybernetics*, Vol.24, No.3.

6. Levitin, G. (1999) A universal generating function approach for analysis of multi-state systems with dependent elements. *Reliability Engineering & System Safety,* vol. 84, No.3.
7. Levitin, G., A. Lisnianski, (1999) Importance and sensitivity analysis of multi-state systems using universal generating functions method, *Reliability Engineering & System Safety*, vol. 65.
8. Levitin, G., A. Lisnianski, H. Ben-Haim, D. Elmakis, (2000) Genetic algorithm and universal generating function technique for solving problems of power system reliability optimization, *Proc. of, Int. Conf. on Electric Utility Deregulation and Restructuring and Power Technologie*.
9. Lisnianski, A. , G. Levitin. (2000) Universal generating function application to multi-state system reliability analysis & optimization. Proc. of 2nd Int'l Conf. on Mathematical Methods in Reliability.
10. Ushakov, I . (2000). The Method of Generating Sequences. *European Journal of Operational Research*, Vol. 125/2.
11. Levitin G., Lisnianski A., (2003). Multi-state system reliability analysis and optimization (universal generating function and genetic algorithm approach). In: *Handbook of Reliability Engineering*, H. Pham (Ed.). Springer.
12. Levitin, G.. (2004) A universal generating function approach for the analysis of multi-state systems with dependent elements, *Reliability Engineering and System Safety,* 84/3.
13. Linianski, A. (2004) Application of Semi-Markov Processes and Universal Generating Function Technique for Multi-state System Reliability Evaluation. Proc. of the 4th Int'l Conf. on Mathematical Methods in Reliability.
14. Lisnianski, A. (2004) Combined Universal Generating Function and Semi-Markov Process Technique for Multi-state System Reliability Evaluation. Proc. of 4th Int'l Conf. on Mathematical Methods in Reliability.
15. Levitin, G. (2005). *The Universal Generating Function in Reliability Analysis and Optimisation*. Springer.
16. Ding, Y., A. Lisnianski. (2008). Fuzzy universal generating functions for multi-state system reliability assessment. Fuzzy Sets and Systems, 159 (3.
17. Ushakov, I. and S. Chakravarty (2008) Object oriented commonalities in universal generating function for reliability and in C++ . RTA Jounal, Vol.3, No.2. Gnedenko Forum.
18. Wei-Chang Yeh (2008) The Extension of Universal Generating Function Method to Search for All One-to-Many Minimal Paths of Acyclic Multi-State-Arc Flow-Conservation Networks. IEEE Trans. on Reliability. Vol. 57, No.1.

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):

1. Baxter, L. A. (1984) Continuum structures. I. *Journal of Applied Probability*, vol. 21.
2. Block, H. W. , Savits, T. H. (1984) Continuous multi-state structure functions. *Operations Research*, vol. 32.
3. Baxter, L. A. (1986) Continuum structures II. *Mathematical Proceedings of the Cambridge Philosophical Society*, No. 99.
4. Montero, J., Tejada, J. and Yanez, J. (1990) Structural properties of continuum systems. *European Journal of Operational Research*, 45.

5. Rakowsky, U. (1995) Continuous Multistate Coherent Systems in Reliability Engineering (in German). *Automatisierungstechnik*, Vol. 43, No. 4.
6. Yang, K. and Xue, J. (1996) Continuous state reliability analysis. In: *Proc. of the Annual Reliability and Maintainability Symposium.*
7. Cutello, V., Montero, J., Yanez, J., (1996) Structure functions with fuzzy states. *Fuzzy Sets Systems*, No. 83.
8. Lisnianski, A. (2001) Estimation of Boundary Points for Continuum-state System Reliability Measures. Reliability Engineering and System Safety, 74, vol. 1.
9. Lisnianski, A. (2002) Continuous-state system reliability models as an extension of multi-state models. Proc. of 3rd Int'l Conf. on Mathematical Methods in Reliability.
10. Finkelstein, M. (2004) Simple Continuous State Systems of Continuous State Components, Proc. 4th Int'l Conf. on Mathematical Methods in Reliability.
11. Ding, Y. Zuo, M.J. Lisnianski, A. Tian, Z. (2008) Fuzzy Multi-State Systems: General Definitions, and Performance Assessment. IEEE Trans. on Reliability. Vol. 57, No.4.
12. Liu, Y., H-Z. Huang, G. Levitin (2008). Reliability and performance assessment for fuzzy multi-state elements, *Journal of Risk and Reliability*, 222(4).

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):

1. Levitin, G. (1998) Optimal allocation of multi-state elements in linear consecutively-connected systems with delays, *Int. Journal of Reliability, Quality and Safety Engineering*, vol. 9,.
2. Levitin, G. Lisnianski, A. Ben-Haim, H. Elmakis, D. (1998). Redundancy optimization for series-parallel multi-state systems. *IEEE Transactions on Reliability* vol. 47, No. 2.
3. Levitin, G., and A. Lisnianski. (1999). Joint Redundancy and Maintenance Optimization for Multi-state Series-parallel systems. Reliability Engineering and System Safety, vol. 64, No.1.
4. Levitin, G. (2000) Multistate series-parallel system expansion-scheduling subject to availability constraints. IEEE Trans. on Reliability. Vol. 49, No.2.
5. Levitin, G. , A. Lisnianski (2000). Optimal Replacement Scheduling in Multi-state Series-parallel Systems. Quality and Reliability Engineering International.
6. Levitin, G., A. Lisnianski. (2000) Optimization of imperfect preventive maintenance for multi-state systems. Reliability Engineering and System Safety, 67.
7. Lisnianski, A., G. Levitin, H. Ben Haim (2000). Structure optimization of multi-state system with time redundancy. *Reliability Engineering & System Safety,* vol. 67.
8. Levitin, G. (2001) Redundancy optimization for multi-state system with fixed resource-requirements and unreliable sources, *IEEE Transactions on Reliability*, vol. 50.
9. Levitin, G. A. Lisnianski. (2001). A new approach to solving problems of multi-state system reliability optimization. *Quality and Reliability Engineering International*, vol. 17, No. 2.
10. Levitin,G., and A. Lisnianski. (2001). Structure Optimization of Multi-state System with two Failure modes. Reliability Engineering and System Safety, vol. 72.
11. Levitin, G. (2002) Redundancy optimization for multi-state system with fixed resource requirements and unreliable sources. *IEEE Transactions on Reliability* vol. 50.

12. Levitin, G. , and A. Lisnianski, (2003) Multi-state System Reliability Analysis and Optimization. In Handbook of Reliability Engineering, Ed. by H. Pham, Springer.
13. Levitin, G. (2003) Optimal allocation of multistate elements in a linear consecutively-connected system. IEEE Trans. on Reliability. Vol. 52, No.2.
14. Levitin, G. (2003) Optimal allocation of multi-state elements in linear consecutively-connected systems with vulnerable nodes. *European Journal of Operational Research*, vol. 150.
15. Nourelfath, M, and N. Nahas, (2004) Ant Colony Optimization to Redundancy Allocation for Multi-state Systems. Proc. of 4th Int'l Conf. on Mathematical Methods in Reliability.
16. Ramirez-Marquez J.E., Coit D.W., (2004) A heuristic for solving the redundancy allocation problem for multi-state series-parallel systems, *Reliability Engineering & System Safety,* , vol. 83.
17. Tian Z., Zuo M., Huang H. (2005) Reliability-redundancy allocation for multi-state series-parallel systems. In *Advances in Safety and Reliability, ed. by* Kolowrocki . Taylor & Francis Group.
18. Levitin, G. (2008) Optimal structure of multi-state systems with uncovered failures. *IEEE Transactions on Reliability*, vol. 57, No.1.
19. Levitin, G., S. Amari. (2008). Multi-state systems with multi-fault coverage. *Reliability Engineering & System Safety,* 93.
20. Levitin, G., S. Amari. (2008) Multi-state systems with static performance dependent fault coverage. *Journal of Risk and Reliability*, 222(O2).
21. Zhigang Tian Zuo, M.J. Hongzhong Huang(2008) Reliability-Redundancy Allocation for Multi-State Series-Parallel Systems. IEEE Trans. on Reliability. Vol. 57, No.2.
22. Tian Zh., G. Levitin, M. Zuo. (2009). A joint reliability-redundancy optimization approach for multi-state series-parallel systems, *Reliability Engineering & System Safety,* 94 (10).

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.

<u>Bibliography (in chronological-alphabetical ordering):</u>

1. Weibull, W. (1939). A statistical theory of the strength of materials. *Ing.Vetenskaps Akad. Handl*., No. 151.
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
3. Gnedenko, B.V. (1943) Sur la Distribution Limite du Terme Maximum d'Une Serie Aleatorie. *Ann. Math.,* vol.44, No.3
4. Weibull, W. (1951) A statistical distribution function of wide applicability. *J. Appl. Mech.* Vol.18, No.3.
5. Barlow, R.E., and F. Proschan (1965) *Mathematical Theory of Reliability.* Wiley.

6. Barlow, R.E., and F. Proschan (1975) *Statistical Theory of Reliability and Life Testing*. Holt, Rinehart and Winston
7. Barlow, R.E., and F. Proschan (1981) *Statistical Theory of Reliability and Life Testing*, 2nd ed. To Begin With.
8. Raizer V.D. (2004), Theory of Reliability in Structural Design, J.Appl.Mech.Rev.,Vol 57,no1,
9. Pulcini, G. Guida, M. (2009).Reliability Analysis of Mechanical Systems With Bounded and Bathtub Shaped Intensity Function. IEEE Trans. on Reliability. Vol. 58, No.3
10. Raizer, V. (2009). Reliability assessment due to wear. RTA Jounal, Vol.4, No.1. Gnedenko Forum.

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):

1. Musa, J. (1975) A Theory of Software Reliability and Its Application. IEEE Trans. Software Eng. Vol.1, No.3.
2. Hamilton, P. A., J.D. Musa (1978). "Measuring Reliability of Computation Center Software," Proc. 3rd International Conference on Software Engineering.
3. Drake, H. D., D. E. Wolting. (1987). Reliability theory applied to software testing. Hewlett-Packard Journal, vol. 38, No.4.
4. Shooman, M. (1987), *Software Engineering: Design, Reliability, and Management*, McGraw-Hill
5. Musa, J. : Software reliability measurement.(1980) Journal of Systems and Software, No. 1.
6. Musa, J. , A. Ackerman (1989) Quantifying Software Validation: When to Stop Testing? IEEE Software Vol.6, No,3.
7. Iannino, A., J. Musa (1990) Software Reliability. Advances in Computers, No. 30.
8. Cai, K.-Y., C.-Y. Wen, M.-L. Zhang. (1991) A critical review on software reliability modeling. Reliability Engineering & System Safety.Vol. 32, No. 3.
9. Jones, W. D. (1991). "Reliability Models for Very Large Software Systems in Industry," Proc. Int'l Symposium on Software Reliability Engineering.
10. Bennett, J., M. Denoncourt, J.D. Healy (1992). "Software Reliability Prediction for Telecommunication Systems," Proc. 2nd Bellcore/Purdue Symposium on Issues in Software Reliability Estimation.
11. Neufelder, A. (1993), *Ensuring Software Reliability.* Marcel Dekker.

12. Kropfl, D. and Ehrlich, W. (1995). "Telecommunications Network Operating Systems: Experiences in Software Reliability Engineering," Proc. 1995 Int'l Symposium on Software Reliability Engineering.
13. Singpurwalla, N.D. (1995). The failure rate of software: does it exist? IEEE Transactions on Reliability. Vol.44, No. 3.
14. Chillarege, R. (1996) What Is Software Failure? . IEEE Trans. on Reliability. Vol. 45,
15. Musa, J. (1996) : Software-Reliability-Engineered Testing. IEEE Computer, vol. 29, No.11.
16. Musa, J. , W. Ehrlich (1996) Advances in Software Reliability Engineering. Advances in Computers, No. 42.
17. Everett, W. Keene, S., Jr. Nikora, A. (1998) Applying software reliability engineering in the 1990s. IEEE Trans. on Reliability. Vol. 47, No.3.
18. Musa, J. (1998) Software Reliability Engineering McGraw-Hill.
19. Smidts, C. Stutzke, M. Stoddard, R.W. (1998) Software reliability modeling: an approach to early reliability prediction. IEEE Trans. on Reliability. Vol. 47, No.3.
20. Evans, R.A. (2000) The unreliability of real-life software . IEEE Trans. on Reliability. Vol. 49, No.3.
21. Goseva-Popstojanova, K. Trivedi, K.S. (2000) Failure correlation in software reliability models. IEEE Trans. on Reliability. Vol. 49, No.2.
22. Musa, J. (2004) Software Reliability Engineering: More Reliable Software Faster and Cheaper (2nd ed.) AuthorHouse.
23. Musa, J. (2005) Teaching SRE to Software Practitioners. ISSRE, No.4
24. Jeske, D.R., X. Zhang Pham, L. (2005) Adjusting software failure rates that are estimated from test data. IEEE Trans. on Reliability. Vol. 54, No.1.
25. Musa, John (2005) Software Reliability Engineering: More Reliable Software Faster and Cheaper, 2nd. Edition, McGrow-Hill.
26. Musa, J., A. Laurie A. Williams (2005). How Should Software Reliability Engineering Be Taught? ISSRE No. 3
27. Costa, E.O., de Souza, G.A. Pozo, A.T.R. Vergilio, S.R. (2007) Exploring Genetic Programming and Boosting Techniques to Model Software Reliability. IEEE Trans. on Reliability. Vol. 56, No.3.
28. Chin-Yu Huang Wei-Chih Huang (2008) Software Reliability Analysis and Measurement Using Finite and Infinite Server Queueing Models. IEEE Trans. on Reliability. Vol. 57, No.1.
29. Costa, E.O. Pozo, A. Vergilio, S.R. (2010).A Genetic Programming Approach for Software Reliability Modeling. IEEE Trans. on Reliability. Vol. 59, No.1.
30. Pfleeger, S., J. Atlee (2010)Software Engineering: Theory and Practice. (4th ed.) Pearson Higher Education.

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):

1. Epstein, B., M. Sobel (1953) Life Testing. *J. of the Amer.Stat. Assoc.,* vol. 48
2. Epstein, B., M. Sobel. (1955) Sequential life testing in exponential case. *Ann. Math. Statist.,* v.26, No.1.
3. Epstein, B. (1960) Estimation from life test data. *Technometrics,* vol.2, No. 4,
4. Epstein, B. (1960) Statistical life test acceptance procedures. *Technometrics,* vol.2, No. 4.
5. Epstein, B. (1960) Testing for the validity of the assumption that the underlying distribution of life is exponential. *Technometrics,* vol.2, No. 1
6. Zelen, M., and M.C. Dannemiller (1961) The robustness of life testing procedures derived from the exponential distribution. Technometrics, Vol. 3,
7. Lloyd, D.K., and M. Lipow (1962) Reliability Management, Methods and Mathematics. Prentice Hall.
8. Mirny, R., A. Solovyev (1964) Estimation of system reliability on the basis of its units tests. (Russian) In: "*Cybernetics in Service for Communism",* v.2, Moscow, Energiya
9. Cohen, A.C. (1963) Progressively censored samples in life testing. Technometrics, v.5, No. 3
10. Cohen, A.C. (1965) Maximum likelihood in the Weibull distribution based on complete and on censored samples. Technometrics, vol.7, No.4.
11. Barlow, R.E., and S. Gupta (1966) Distribution-free life testing sampling plans. Technometrics, vol.8, No.4
12. Barlow, R., and F. Proschan (1967) Exponential life test procedures when the distribution has monotone failure rate. *J. of the Amer. Stat. Assoc.,* vol. 62.
13. Nelson, W. (1969) Hazard plotting for incomplete failure data. J. Qual. Technol.,v.1
14. Pavlov, I.V. (1974) System reliability estimation on the basis of aging units tests. Sov. J. Comput. Syst. Science, No.3
15. Ushakov, I.A. (1980) Reliability estimation based on truncated tests. *Sov. J. on Comput. and Syst. Science*, No.5.
16. Nelson, W. (1982), *Applied Life Data Analysis*, Wiley.
17. Pavlov, I.V. (1982) Statistical Methods of Reliability Estimation by Tests Results. (Russian). Radio i Svyaz
18. Ushakov, I.A., M.V. Kozlov, and M.V. Topolsky (1982) Point estimates of reliability indexes on the basis of truncated samples (in Russian). Reliability and Quality Control, No.10
19. Belyaev, Yu.K. (1985) Multiplicative estimates of the probability of failure free operation. *Sov. J. on Comput. and Syst. Science*, No. 4
20. Cox, D. R., and Oaks, D. (1984). The Analysis of Survival Data, Chapman & Hall, London, New York.
21. Pavlov, I.V., and I.A. Ushakov (1984) Unbiased estimator of distribution function based on multiple censored sample. *Theor. of Probab. and Its Appl.*, v.29, No.3,
22. Zamyatin, A.A. (1986) Statistical inferences for renewable system with multiple failures. Sov. J. on Comput. and Syst. Science , No.3
23. Crowder, M. J., Kimber A. C., Smith, R. L., and Sweeting, T. J. (1991) Statistical Analysis of Reliability Data, Chapman & Hall.
24. Ushakov, I., S. Wise. (2000) Estimation of component reliability by system testing. *Methods of Quality Management*, №8.

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):

1. Gugushvili, D. F., Zgenti, L.D., and Namiecheyshvili, O. M. (1975). Accelerated reliability tests, *Engineering Cybernetics*, No.3
2. Kaminskiy, M. (1987). Accelerated life test planning and data analysis, (Russian). Electronica.
3. Nelson, W (1990), Accelerated Testing: Statistical Models, Test Plans and Data Analysis, Wiley.
4. Kaminskiy, M., and L. Kristalinsky (1992). Reliability prediction of capacitors on the basis of accelerated life test data, (in Russian) *Electronica*
5. Owen, W.J. Padgett, W.J. (2000) A Birnbaum-Saunders accelerated life model. IEEE Trans. on Reliability. Vol. 49, No.2.
6. Gerville-Réache, L., M. Nikulin (2006) On statistical modeling in accelerated life testing. Eksploatacja i Niezawodnoœæ, No. 2.
7. Pascual, F. (2008) Accelerated Life Test Planning With Independent Weibull Competing Risks. IEEE Trans. on Reliability. Vol. 57, No.3.

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):

1. Madansky, A. (1965) Approximate confidence limits for the reliability of series and parallel systems. Technometrics, November, 1965.
2. Belyaev, Yu. (1966) Construction of the lower confidence limit for the system reliability on the basis of testing its components (Russian). In "Reliability of Complex Systems". Sovetskoe radio.
3. Belyaev, Yu.K. (1966) Confidence limits for functions of several variables (Russian). Proc, of the Soviet Ac. of Sc., vol. 169, No.4
4. Johns, M., G. Lieberman (1966) An exact asymptotycally efficient confidence bound for reliability in the case of the Weibull distribution. *Technometrics,* vol.8, No.1
5. Belyaev, Yu., T. Dugina, and E. Chepurin (1967) Computation of the lower confidence limit for the complex system reliability. *Engineering Cybernetics*, No.2 & 3.
6. Engelman, L., H. Roach, and G. Shick (1967) Computer program for exact confidence bounds. *J. of Industr. Engng.,* v.18, No. 8

7. Schick, G.J. (1967) A comparison of some old and new methods in establishing confidence intervals of serially connected systems. J. of Industr. Engng, v.18, No.8
8. Belyaev, Yu.K. (1968) On simple methods of confidence limit construction. Engineering Cybernetics, No.5
9. Belyaev, Yu.K. (1968) On simple methods of confidence limit construction. Engineering Cybernetics, No.5.
10. Myhre,J., and S.C. Saunders (1968) Comparison of two methods of obtaining approximate confidence intervals for system reliability. Technometrics, vol.10,
11. Easterling, R.G. (1972) Approximate confidence limits for the system reliability. J.Amer.Statist. Assoc., v.67
12. Pavlov, I.V. (1973) Confidence limits for system reliability on the basis of its components testing. *Eng. Cybernetics*, No.1
13. Krol', I.A. (1974) Using the confidence set method for interval estimation of reliability indices. Eng. Cybernetics (USA), No.1
14. Mann, N.R. (1974) Approximate optimum confidence bounds on series and series-parallel system reliability for systems with binomial subsystem data. *IEEE Trans. Reliability*, vol. R-23
15. Mann, N.R., and F.E.Grubbs (1974) Approximately optimum confidence bounds for system reliability based on component test plan. *Technometrics,* vol.16
16. Mann, N.R., R.E. Schaefer, and N.D. Singpurwalla (1974) *Methods of Statistical Analysis of Reliability and Life Data.* Wiley.
17. Sudakov, R.S. (1974) About interval estimation of reliability of series system. (Russian) *Engng. Cyber.*, No.3
18. Winterbottom, A (1974) Lower confidence limits for series system reliability from binomial subsystem data. J. Amer. Statist. Assoc., vol. 69
19. Krol', I.A. (1975) Interval reliability estimation for "continuous" and instant failures. Eng. Cybernetics, No.5
20. Pavlov, I.V. (1977) Interval estimation for functions of several unknown variables. Sov. J. Comput. Syst. Science, No.3 and 5
21. Pavlov, I.V. (1977) Monotone confidence limits for the class of distributions with increasing failure rate. Sov. J. Comput. Syst. Science, No.6
22. Pavlov, I.V. (1980) Fiducial approach for estimation of complex system reliability by results of its component testing. Sov. J. Comput. Syst. Science, No.4
23. Farkhad-Zade, E.M. (1979) About difference of limit values of confidence and fiducial intervals for reliability parameters of systems. (Russian) Engng. Cyber. No.4
24. Groysberg, L.B. (1980) On fiducial approach for reliability estimation. Sov. J. Comput. Syst. Science, No.4
25. Pavlov, I.V. (1981) On correctness of the fiducial approach for construction of confidence limits for complex system reliability indices. Sov. J. Comput. Syst. Science, No.5
26. Pavlov, I.V. (1981) On fiducial approach for construction of confidence limits for functions of several unknown parameters. Proc, of the Soviet Ac. of Sc., vol. 258, No.6
27. Lawless, J.F. (1982). *Statistical Models and Methods for Lifetime Data.* Wiley.
28. Pavlov, I.V. (1982) On construction of sequential confidence intervals and sets. Sov. J. on Comput. and Syst. Science, No. 3
29. Pavlov, I.V. (1983) Sequential confidence sets. Reports of the Academy of Sc. of the USSR, v.270, No.2
30. Martz, H.F., and I.S. Duran (1985) A comparison of three methods for calculating lower confidence limit s on system reliability using binomial component data. IEEE Transaction of Reliability, v. R-34, No.2
31. Pavlov, I.V. (1992) Computation of the confidence limits for series systems (Russian). Reliability and Quality Control, No.5

32. Pavlov, I.V. (1995) Confidence limits of reliability indexes for censored samples (in Russian). *Reliability and Quality Control*, No.7
33. Coit, D.W. (1997) System-reliability confidence-intervals for complex-systems with estimated component-reliability. IEEE Trans. on Reliability. Vol. 46, No.4.
34. Dostal, R., L. Iannuzzelli (1977) Confidence limits for system reliability when testing takes place at the component level. In: "*The Theory and Applications of Reliability* ", v.2, ed. by C.P. Tsakos and I.N. Shimi. Academic Press

Bayesian Metods

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):

1. Schwarz, G. (1962) Asymptotic shapes of Bayes sequential testing regions. *Ann. Math. Statist.*, v.33, No.2.
2. Cole, P.V.Z. (1975) A Bayesian reliability assessment of complex system for binomial sampling. *IEEE Transactions on Reliability*, v.24.
3. Smith, D.R., and M.D. Springer (1976) Bayesian limits for the reliability of pass/fail parallel units. *IEEE Trans. Reliability*, vol. R-25
4. Mastran, D.V. and N.D. Singpurwalla (1978) A Bayesian estimation of the reliability of coherent structures. *Operations Research*, v. 26
5. Martz, H. F., and R.A. Waller (1982) Bayesian Reliability Analysis. Wiley
6. Natvig, B. and H. Eide (1987) Bayesian estimation of system reliability. *Scandinavian Journal of Statistics*, v. 14
7. Martz, H.F., R.A. Waller and E.T. Fickas (1988) Bayesian reliability analysis of series systems of binomial subsystems and components. Technometrics, v.30
8. Martz, H.F., and R.A. Waller (1990) Bayesian reliability analysis of complex series/parallel systems of binomial subsystems and components. Technometrics, v.32.
9. Akman, O. Longcheen Huwang (1997) Bayes computation for reliability estimation. IEEE Trans. on Reliability. Vol. 46, No.1.
10. Hollander, M., J. Sethuraman and G. Ye. (2002).Bayesian Methods for Repair Models". Proc. of the 3rd International Conference on Mathematical Methods in Reliability. Communications.
11. Aven, T., A. Hjorteland (2003) A Predictive Bayesian Approach to Multistate Reliability Analysis, *International Journal of Reliability, Quality and Safety Engineering*, Vol. 10, No. 3.
12. Kaminskiy, M.P., V.V. Krivtsov (2005) A simple procedure for Bayesian estimation of the Weibull distribution. IEEE Trans. on Reliability. Vol. 54, No.4.
13. D'Apice, C., R. Manzo and S. Shorgin (2006). Some bayesian queueing and reliability models. RTA Jounal, Vol.1, #2. Gnedenko Forum.
14. Singpurwalla, N.D. (2006) Reliability and Risk: A Bayesian Perspective. NY. Wiley.
15. Ancha Xu, Yincai Tang. Ancha Xu, Yincai Tang . (2009). Bayesian Analysis of Pareto Reliability With Dependent Masked Data. IEEE Trans. on Reliability. Vol. 58, No.4
16. Polpo, A. Pereira, C.A.B. . (2009).Reliability Nonparametric Bayesian Estimation in Parallel Systems. IEEE Trans. on Reliability. Vol. 58, No.2

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):

1. Levy, L.L, & Moore, A.H. (1967). A Monte Carlo technique for obtaining system reliability confidence limits from component test data. *Transactions on Reliability, Vol.16, No.2*.
2. Buslenko, N.P., V.V. Kalashnikov, and I.N. Kovalenko (1973) *Lectures on Theory of Complex Systems* (in Russian). Sovietskoe Radio.
3. Ushakov, I.A., and A.V. Yasenovets (1977) Statistical methods of solving problems of optimal standby. Engineering Cybernetics, No.6
4. Ushakov, I.A., and E.I. Gordienko (1978) Solution of some optimization problems by means of statistical simulation (in Russian). Electronosche Infdormationsverarbeitung und Kybernetik, vol.14, No.11.
5. Kumamoto, H., Tanaka, K., Inoue, K., Henley, E. (1980). State-transition Monte Carlo for evaluating large repairable systems. *IEEE Transactions on Reliability,vol.29, No.5*.
6. Ushakov, I.A., and E.A. Aliguliev (1989) Optimization of data-transmitting network parameters using the method of statistical modeling. Soviet Journal of Computer and Systems Sciences, No. 1
7. Ushakov, I., S. Chakravarty, E. Gordienko. (1998) Novel Simulation Technique for Spare-Kit Optimization. Proc. of the IEEE Systems, Man, and Cybernetics Conference.
8. Lieber, D. Nemirovskii, A. Rubinstein, R.Y. (1999) A fast Monte Carlo method for evaluating reliability indexes. IEEE Trans. on Reliability. Vol. 48, No.3.
9. Nicola, V.F. Shahabuddin, P. Nakayama, M.K. (2001) Techniques for fast simulation of models of highly dependable systems. IEEE Trans. on Reliability. Vol. 50, No.4.

AREAS CLOSE TO RELIABILITY

Survivability

Reliability 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):

1. Krylov, A.N. (1942) The Ship Theory. Part 1: Ship Stability. Voenmorizdat
2. Kozlov, M., Yu. Malashenko, V. Rogozhin, I. Ushakov, T. Ushakova. (1986) Survivability modeling energy systems: Methodology, model, implementation. CC RAN.
3. Rudenko, Yu.N., and I.A. Ushakov (1989). Reliability of Power Systems (Russian). Nauka.
4. Levitin, G., A. Lisnianski. (2000) Survivability Maximization for Vulnerable Multi-State Systems with Bridge Topology. Reliability Engineering and System Safety, 70.
5. Stekolnikov, Yu (2002) System Survivability (Russian). Politekhnika
6. Levitin, G. (2003). Maximizing survivability of vulnerable weighted voting systems. *Reliability Engineering & System Safety*, vol. 83.
7. Levitin, G., A. Lisnianski. (2003) Optimal separation of elements in vulnerable multi-state systems, *Reliability Engineering & System Safety,* vol. 73.
8. Levitin, G., A. Lisnianski. (2003) *Optimizing* survivability of vulnerable series-parallel multi-state systems, G. *Reliability Engineering & System Safety,* vol. 79.
9. Levitin, G, Y. Dai, M. Xie, K. L. Poh. (2003). Optimizing survivability of multi-state systems with multi-level protection by multi-processor genetic algorithm, *Reliability Engineering & System Safety*, vol. 82.
10. Abdullah Konak, A., A. Smith. (2004) Capacitated network design considering survivability: An evolutionary approach. Journal of Engineering Optimization, vol. 36, no. 2.
11. Levitin, G. (2004) Protection survivability importance in systems with multilevel protection. *Quality and Reliability Engineering International*, No. 20.
12. Korczak E., G. Levitin, H. Ben Haim. (2005) Survivability of series-parallel systems with multilevel protection, *Reliability Engineering & System Safety*, vol.90/1.
13. Korczak, E, G. Levitin . (2007) Survivability of systems under multiple factor impact, , *Reliability Engineering & System Safety*, 92(2).
14. Van Gelder, P. (2008) Methods for risk analysis in disaster reduction. RTA Jounal, Vol.3, No.2. Gnedenko Forum.
15. Raizer, V. (2009) Natural disasters and structural survivability . RTA Jounal, Vol.4, No3. Gnedenko Forum.

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):

1. Ushakov, I., (2005). Cost-effective approach to counter-terrorism. Int'l Journal *Communication in Dependability and Quality Management. V*ol.8, No.3.
2. Ushakov, I., (2006). Counter-terrorism: Protection Resources Allocation. RTA, Gnedenko Forum. vol.1, No 2, 3, 4.

3. Bochkov, A., and I. Ushakov (2007). Sensitivity analysis of optimal counter-terrorism resources allocation under subjective expert estimates. RTA Jounal, Vol.2, No. 2. Gnedenko Forum.
4. Ushakov, I. (2007). Counter-terrorism: Protection Resources Allocation. Part III. Fictional "Case Study". RTA Jounal, Vol.2, No.2. Gnedenko Forum.
5. Levitin, G. (2007). Optimal defense strategy against intentional attacks. IEEE Transactions on Reliability, 56(1).
6. Levitin, G., H. Ben Haim. (2008). Importance of protections against intentional attacks. *Reliability Engineering & System Safety*, 93 (4).
7. Hausken, K., G. Levitin. (2009). False targets efficiency in defense strategy. European Journal of Operational Research 194.
8. Hausken, K., G. Levitin. (2009). Minmax defense strategy for complex multi-state systems. Reliability Engineering & System Safety 94.
9. Hausken, K., G. Levitin. (2009) Parallel systems with different types of defense resource expenditure under two sequential attacks, *Journal of Risk and Reliability*, 223 Part O, 71-85 (2009).
10. Hausken, K., G. Levitin. (2009). Protection vs. false targets in series systems. Reliability Engineering & System Safety 94.
11. Hausken, K., G. Levitin. (2009) Protection vs. separation in parallel non-homogeneous systems. The International Journal of Reliability and Quality Performance, 1.
12. Levitin, G. (2009) Optimal distribution of constrained resources in bi-contest detection-impact game, International Journal of Performability Engineering, 5(1).
13. Levitin, G. (2009) Optimizing Defense Strategies for Complex Multi-state Systems. In Game Theoretic Risk Analysis of Security Threats, ed. by Bier, V.M. and Azaiez, N. International Series in Operations Research & Management Science, Springer.
14. Levitin, G. (2009) False targets in defense strategies against intentional attacks. G. *International Journal of Performability Engineering*, 5(5).
15. Levitin, G. (2009) System survivability and defense against external impacts. Guest editorial. G. *International Journal of Performability Engineering,* 5(1).
16. Levitin, G., H. Ben Haim, (2009). Minmax defense strategy for complex multi-state systems.. *Reliability Engineering & System Safety* 94.
17. Levitin, G., K. Hausken. (2009). False targets vs. redundancy in homogeneous parallel systems, Reliability Engineering & System Safety 94.
18. Levitin, G., K. Hausken. (2009). Redundancy vs. protection vs. false targets for systems under attack.*IEEE Transactions on Reliability* 58 (1).
19. Levitin, G., K. Hausken (2009). False targets efficiency in defense strategy. *European Journal of Operational Research* 194.
20. Levitin, G., K. Hausken. (2009) Intelligence and impact contests in systems with fake targets. Defense and Security Analysis. Vol. 25, No.2.
21. Levitin, G., K. Hausken. (2009) Redundancy vs. protection in defending parallel systems against unintentional and intentional impacts. IEEE Transactions on Reliability 58(4).
22. Levitin, G., K. Hausken. (2009). Parallel systems under two sequential attacks. *Reliability Engineering & System Safety,* 94**.**
23. Hausken, K., G. Levitin, (2010). Two sequential attacks of a parallel system when defense and attack resources are expendable. International Journal of Performability Engineering 6(4
24. Levitin, G., K. Hausken. (2010). Defense and attack of systems with variable attacker system structure detection probability. Journal of the Operational Research Society 61.