Opinion

Reliability in the 21st century

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This article discusses some current trends in statistical reliability research, many of which have arisen from developments in computational methods. It highlights areas of both methodology and application, where the author believes that there are excellent prospects for interesting and fruitful research in the future, in terms of both methodology and new applications. © 2009 John Wiley & Sons, Inc. *WIREs Comp Stat* 2009 1 338–341

In this opinion article, I will identify trends in statistical reliability that have become apparent to me since the start of the 21st century and that I think will continue. These trends occur within the context of a more interconnected and complex global economy and culture. Clearly this context presents major risks to our well-being and survival, at personal, local, national, and international scales, and hence reliability, in its broadest sense, has something to contribute to understanding and managing them. These risks are familiar to most readers of this volume and are discussed in numerous places, and I will not attempt even to list them in this short article. Instead, I will focus on some aspects of our world where I believe that statistical reliability can make an impact.

The focus is of course biased by my own interests and experiences, which have tended to concentrate in the last decade on probability models and Bayesian methods for reliability problems in software and telecommunications. Like a lot of statistical research, advances in computer processor speed and storage have facilitated most of these trends, and I believe that they will continue to do so.

NETWORKS

Networks are becoming pervasive, more complicated and increasingly critical components of modern society. The complexity of networks in, for example, telecommunications and energy supply, the increasing emphasis on high availability by network component manufacturers, owners, users and regulators, and the uncertainties surrounding the factors that affect reliability and availability, imply that statistical network reliability should continue to develop as a very fruitful field of research.

Network reliability has been studied for many years in the reliability literature, as well as in operations research and computer science.[1] Two problems have dominated statistical network reliability: computing the reliability of a network in terms of the reliabilities of links and nodes, and fault tolerance. The former problem is, like many in graph theory, often computationally infeasible as the network size grows, and there is much work on finding feasible approximations or sub-classes of networks where the reliability can be computed.[2] The latter is particularly important for networks that require high availability, and so has seen much work in the computer science literature.[3]

There are two key challenges for statistical modelling of network reliability that I believe are not addressed well by any approach currently. The first challenge is that the underlying causes of failure in complicated networks are not just because of the wear out of components but also software errors and what I term procedural errors. Procedural errors include human error, and also errors in the procedures that software or humans are instructed to follow. For example, an important factor in the increase in complexity of networks is not physical but rather because of changes in the regulatory environment, such as the fragmentation of ownership to encourage competition, that have introduced new vulnerabilities to the network that might cause failure. While reliability theory has a lot to say about wear out, and quite a lot to say about software bugs, it has rather less to say about procedural errors, which do not appear to be amenable to description by standard reliability models. The challenge is to develop mathematical reliability methods that can be used to model the occurrence of procedural failures, and ideally can identify vulnerabilities in those procedures

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in a practical manner. The most relevant methods in classical reliability theory that I have come across are in existing network vulnerability criteria,[4] and to a lesser extent fault tree and failure mode and effects analysis. Psychology and social science may play a role here as well, in such areas as risk perception and management.

The second challenge becomes clear if we consider the several well-known examples of widespread electricity supply or wireless telephone service failure in the last decade. The causes of these large-scale outages, that affected millions of people over a timescale of several hours, were a coincidental chain of failures of hardware and software, allied with procedural vulnerabilities that interacted in unfortunate ways to cause the total failure of large parts of the network. Critically, *dependence* between hardware, software, and human network components was necessary for the problem to arise. So, the second challenge is how to model adequately the interaction between these different types of failure modes. Any satisfactory model should be able to predict that large-scale outages could occur; something that is predicted to be very rare under the assumption of independence. Models for interactions between hardware and software have already been proposed.[5,6] Lindley and Singpurwalla[7] discuss cascading failures and a modelling approach based on probabilistic causality. Bayesian network or other causal modeling approaches offer alternative possibilities here.

DEPENDENCE

The challenge of modelling dependence in the reliability context extends beyond networks. Indeed, one can view the history of statistical reliability modelling over the last 50 years as successive attempts to move away from the independence assumption, always known to be unsatisfactory but imposed because it was the only way to develop tractable inference and prediction tools.

Initial models that allowed for dependence between failure times relied on assumptions that yielded joint probability distributions that could be calculated easily.[8] Methods such as copulas and hierarchical models have provided ways of incorporating dependence between components and subsystems while keeping the model tractable for simulation and inference. However, viable models for the performance of complex networks will need to model dependence structure, as discussed earlier, and that in order to be realistic these models will be computationally demanding for both fitting to data and prediction. This is true for other models where dependence is important, such as stochastic process and stochastic differential equation (SDE) models.

Thankfully, the computer industry has been able to maintain exponential growth in computing speed and storage for many years. It appears that this trend will continue. Such growth is vital to maintain the increase in the scope of models of dependence that we can practically use.

RELIABILITY MODELLING OF PHYSICAL SYSTEMS

Most reliability methods and most current uses of them are still in the domain of the reliability and availability of physical systems, and I expect this to continue. Furthermore, there is still a lot of potential for interesting modelling and applications that will extend the state of the art.

I want to emphasize here the advances in modelling that respect the specific attributes of the physical system under consideration through the use of stochastic processes, often themselves solutions to SDEs. Much of the engineering theory of systems of all sorts is described through differential equations and so, in the presence of uncertainty about the system, an SDE has an obvious appeal. Methods to both simulate the solution to SDEs, and conduct statistical inference, is an active area of research.[9,10] Typically, reliability applications concentrate on first hitting times of the process to thresholds that signify degraded performance or failure; the derived failure time distribution has then been obtained through a (presumably) appropriate physical model. This is particularly appealing for systems where appealing to large-sample theory of extremes or averages is not realistic.

It is only because of advances in computing speed are such models able to be practically implemented.

NEW APPLICATIONS

The notion of risk, in the context of finance, predates reliability.[11] There is an increasing recognition that reliability concepts, such as the hazard rate, may have uses in quantifying risk in finance.[12] In his recent book, Singpurwalla argues strongly that the two ideas of risk and reliability are deeply related.[13]

There are clearly many other applications where the notions of risk and reliability are relevant, and I point out three. The first is anti-terrorism measures, and here I have come across some evidence of the use of quantitative reliability methods, such as risk assessment to make the trade off between cost and prevention. The second is climate change. I have not come across much work that studies, from the perspective of reliability and risk, similar issues such as the trade off between the costs of lowering anthropogenic carbon emissions against the benefits from decreased climate change, although such studies have certainly been done from other perspectives. For both applications, these trade offs seem to be widespread. The use of reliability methods—statistical modelling and quantification of the consequences of failure—are surely powerful tools to help to address these problems, particularly in areas where the notions of probability and risk are well known.[14]

A third application is perhaps more conventional and also my most speculative, as it comes from some exposure to the problem quite recently—statistical methods for the reliability of integrated circuits. There is a very well developed literature in this area, particularly as pertains to optimal testing, but statistical methods are not used.[15] This field combines very large samples (many gates on the chip) and complex dependencies (from common environment to the way that gates are connected). It seems to me that the problem provides the possibility for some asymptotic theory, has many computational challenges, and arises in a high-value industry with a history of research-led product development.

A WISH LIST

Finally, I will write a few lines on what I would like to happen to reliability theory in the 21st century, but for which at the moment I do not see a strong trend towards.

The first is, speaking as a proponent of Bayesian statistical inference, a wider use of prior distribution elicitation methods.[16] Typical problems in reliability come with a vast amount of information from experts who can greatly aid the analysis, if properly quantified. While Bayesian inference methods are becoming better known and accessible, and there have been some efforts in elicitation for reliability,[17,18] its use is not widespread even when a Bayesian approach is adopted for data fitting and prediction. This seems a great pity—all of that useful (and cheap to obtain) information is not utilized. I think the reasons are clear for this: that the process of elicitation can be done is not well known, if it is known that it can be done then it seems difficult to do and there is little expertize available to advise, and there is no clear idea of the benefits of doing it. Nevertheless, there is some cause for optimism here. Reliability and safety engineering are already very familiar with the process of using domain knowledge to quantify what is known about a system—to construct a reliability block diagram, for example. Prior elicitation could be viewed as simply applying that principle to another aspect of the system.

More generally, the subjective approach to reliability, such as is advocated in an earlier article with the same name as this one,[19] has much to recommend it as the complexity of the reliability questions that we face increases. Its principal advantage is that, as systems become more complex, data are increasingly unlikely to be available on all aspects of them and so we must resort to other sources of data, such as expert opinion, to produce reliability estimates. The subjective approach, quantification of expert opinion through probability and updating of reliability from data through Bayes law, offers a logically consistent approach that is also practical in many situations—thanks to the development of appropriate computational techniques and the processing power to implement them.

I also mention here the statistical software reliability. Statistical methods have still not made the impact in the software engineering industry that classical reliability methods have made in the physical engineering fields, in spite of a large body of work.[20] In my opinion, this is partly because of the lack of freely available data on which academics can test models, a lack of the acceptance that uncertainty is a fundamental property of software performance (at least not to the extent that this is accepted about the failure of physical systems) and the view that reliability only comes about by the necessary evil of testing, rather than something that forms part of the initial design and management of the software project. A change in point of view by the industry about one of the last two is probably a necessary condition for statistical methods to be widely used.

CONCLUSION

There are many fascinating and valuable topics for research in statistical reliability, some of which I have highlighted here. These will play a role in the evolution of the subject in the 21st century.

Throughout this short article, I have emphasized the role that computation has and will play in reliability. It has revolutionized the way in which statistical modelling, inference, prediction, and decision making are done, by allowing us to practically implement far more complicated and realistic models. For the foreseeable future, computing power and memory capacity look to continue their exponential growth. It will continue to be the means by which we can implement better solutions to risk and reliability problems in the 21st century.

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