Special section on “Applications of probabilistic graphical models in dependability, diagnosis and prognosis”

Philippe Weber, Luigi Portinale

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Editorial

Special section on: Applications of Probabilistic Graphical Models in Dependability, Diagnosis and Prognosis

In order to manage and to maintain in operating condition industrial artefacts during the lifecycle, engineers usually produce models for the prediction or the prognosis of functioning or dysfunctioning states of the system. These models are extracted from knowledge of the systems and depend on the objective of the model. In dependability analysis, models may serve to several aims:

- To assess the impact of maintenance activities on the ability to maintain operational conditions and to aid decisions during maintenance.
- To assess the impact of control and pilotage activities on wear, degradations (faults) or failures prognosis of all or part of the system; thus, they satisfy the main goals as service quality or low-risk situations for users, staff, environment, etc.
- To assess the efficiency of means to warrant an acceptable level of risk, whatever the operational constraints and environmental perturbations.

There are several domains of the application of dependability. These domains can be associated with different aspects of the system behavior such as management modes, governance, human factors, extreme events or rare events and their consequence over society, maintenance, control and supervision or risk reductions of socio-technical systems, etc.

Nevertheless, most engineers have neither the tools nor the methods to effectively understand the whole set of information (knowledge and evidence) according to the operational constraints and disturbances that condition the functioning of complex socio-technical systems. The phenomena encountered are so complex as a result of their heterogeneity and the number of nested mechanisms of different natures that it is often quite difficult to reach the required objectives or levels of performance. Moreover, there is usually no exact analytical model able to describe the whole phenomenon encountered. It is also impossible to know exactly all the states of the system and to observe all the component states at each point in time, in order to determine the optimal decision. The engineers should bear in mind that all models are biased and partial. As a result, engineers need new methods to solve these modeling problems.

Nowadays, it is necessary to model systems and components with a finite but unbounded set of states or performance levels i.e. systems with multiple states. In addition, the component behaviors are conditioned by the operational constraints and environmental disturbances of the system. In such cases, dependability assessment becomes difficult because it should take into account the combining effects of dependent failures due to constraints, disturbances and the intrinsic multi-state nature of system components. All of this results in an increasing number of scenarios to model and evaluate. The consequence is a cumbersome activity for the analyst, often enforcing bias and partiality.

However, quantitative assessment is necessary to warrant the viability of systems and their performance regarding risk, dependability or control. It is thus necessary to handle an uncertain representation of the system in order to describe its working and/or faulty behavior. This imperfect perception goes toward a probabilistic view of system states. The main difficulties are the integration of a huge quantity of information to model industrial or socio-technical systems subject to a large set of interactions with their environment. In order to contribute to solving this modeling problem, this section focuses on the use of graph theoretical and probabilistic approaches based on Probabilistic Graphical Models (PGM), in maintenance, in risk analysis and management, and in control theory as well.

Why use Probabilistic Graphical Models (PGM)?

Probabilistic Graphical Models like Bayesian Networks, Evidential Network, Decision Networks or Markov Random Fields have been proposed in the field of Artificial Intelligence as a probabilistic framework for reasoning under uncertain knowledge. The robustness and flexibility of this class of modeling formalism are demonstrated by the wide spectrum of real-world problems in which they have been successfully applied. In particular, they have gathered a lot of attention and have provided a set of relevant solutions in industrial fault detection, identification and recovery and in dependability analysis. Moreover, PGM are emerging research directions in Fault Diagnosis, Safety-critical systems, Fault-Tolerant Control and Prognosis.

PGM and Bayesian Networks in particular, have definitely become reference formalism in dependability modeling and assessment. The graphical structure, together with the compact representation of the joint distribution of the system variables of interest, provide the reliability engineer with a powerful tool both at the modeling and at the analytical level [1], [2], [3].

The dependency structure induced by the graph component of the formalism, allows the modeler to make explicit a set of reasonable independence assumptions that may lead to a huge simplification at the computational level, as well as with respect to the problem of probability elicitation, without compromising the suitability of the produced model to the actual real-world application.

Indeed, standard dependability models usually fit into two categories:

- Combinatorial models (as Fault trees or Reliability Block Diagrams): they determine the occurrence of undesired events through a combinatorial composition of sub-events; this class of models is very easy to analyze, but it cannot model situations involving complex dependencies among system components and sub-systems.
- State-space models (as Markov Chains or Petri Nets): they allow one to model complex interactions among system parts, but they may incur in the well-known "state-explosion" problem; this usually means that the analysis has to be performed by considering the whole cross-product of the system's variables, producing a potentially huge number of states.

Bayesian networks and related models, allow for an efficient factorization of the set of system states, without the need for an explicit representation of the whole joint distribution; moreover, an additional advantage is the availability of inference algorithms for the analysis of any a-posteriori situation of interest (i.e., evidence can be gathered by a monitoring system and fed into a dependability framework for fault detection and identification). Finally, when time is explicitly taken into account, models like Dynamic Bayesian Networks result in a factored representation of a Markov Chain, providing a framework with the modeling advantages of state-space models, without the cons at the analysis level.

Review Committee and selection

The present special section in *Reliability Engineering & System Safety - Journal - Elsevier*, from some of the most relevant researchers and practitioners in the field, provides a presentation and analysis of the probabilistic graphical model approach to dependability, with a view to the different facets involved in real-world dependability applications, meaning system reliability, maintenance and risk evaluation. This definitely supports and promotes Bayesian Networks and Probabilistic Graphical Models as some of the most relevant and important formalism in modern dependability analysis.

This special section follows an invited session (of 10 papers) on the applications of PGM in dependability, diagnosis and prognosis, organized at the 9th IFAC International Symposium on Fault Detection, Supervision and Safety for Technical Processes (SAFEPROCESS 2015) that took place in Paris in September 2015. Some of the papers present in the special section are indeed extended versions of papers presented at SAFEPROCESS 2015.

Ten papers were submitted to the journal special section: Applications of Probabilistic Graphical Models in Dependability, Diagnosis and Prognosis. These papers have been peer-reviewed (by at least three reviewers each) by a specific section review committee (see below). This committee has given very deep analysis of each contribution. The guest editors have appreciated the work of the review committee and warmly thank all expert scientists in the field of PGM and dependability that compose the review committee.

Andrea Bobbio, Università del Piemonte Orientale (Italy)
Ibsen Chivatá Cárdenas, University of Twente (The Netherlands)
Sanjay Kumar Chaturvedi, Indian Institute of Technology Kharagpur (India)
Helge Langseth, Norwegian University of Science and Technology, (Norway)
Philippe Leray, Université de Nantes (France)
Martin Neil, University of London (UK)
Rong Pan, Arizona State University (USA)
Luigi Portinale, Università del Piemonte Orientale (Italy)
John L. Quigley, University of Strathclyde, Glasgow (UK)
Christophe Simon, Université de Lorraine (France)
Philippe Weber, Université de Lorraine, CNRS, (France).

Selected Papers

After this deep reviewing, five papers were finally selected for publication in this special section of Reliability Engineering & System Safety. These papers' original contributions address several topics: reliability, maintenance, failure diagnosis and control. All these applications illustrate the applicability and flexibility of MGP.

The first application concern reliability computation, the contribution proposed by Codetta-Raiteri and Portinale [4] is mainly focused on Generalized Continuous Time Bayesian Networks (GCTBN) as a dependability formalism to analyse complex systems. The authors resort to two specific case studies from the literature solved by GCTBN models. An analysis of results and advantages with respect to other formalism are discussed. From the modeling point of view, GTCBN allow the introduction of general probabilistic dependencies and conditional dependencies in state transition rates of system components. From the analysis point of view, any task ascribable to a posteriori probability computation can be implemented, among which the computation of system unreliability, importance indices, system monitoring, prognosis and diagnosis.

Moreover Simon and Bicking [5] propose a contribution for reliability computation. This paper presents a method to assess system reliability in the presence of epistemic and aleatory uncertainty. This hybrid method uses belief functions to model and manipulate uncertainty. P-boxes are used to represent basic uncertainties and evidential network to model the system reliability. These choices allow a flexible modeling of uncertainty, while limiting the computational cost of inferences. In particular, they offer convenient ways of integrating expert opinions and many kinds of uncertainty sources. It also can model complex systems.

The contribution proposed by Özgür-Ünlüakin and Bilgiç [6] is an interesting approach in decision-making for maintenance. The authors propose a method to define an optimal maintenance decisions for a multi-component system under partial observations in a finite horizon. The components deteriorate in time and their states are hidden to the decision maker. Nevertheless, it is possible to observe signals about the system status and to replace components in each period. The aim is to find a cost-effective replacement plan for the components in a given time horizon. The problem is formulated as a partially observable Markov decision process (POMDP). States and actions are aggregated in order to reduce the problem space and obtain an optimal aggregated policy, which is disaggregated by dynamic Bayesian networks (DBN). The procedure is statistically compared to an approximate POMDP solver that uses the full state space information. Cases where aggregation performs relatively better are isolated and it is shown that k-out-of-n systems belong to this class.

The contribution proposed by Abu-Samah et al. [7] is an application in diagnosis of failure in complex systems. In this paper, a methodology is presented to extract failure signatures for real-time failure diagnosis, using Bayesian Network models. The presented methodology allows extraction, selection and validation of failure signatures with objective to execute preventive maintenance actions avoiding failures. Moreover, proposed methodology uses event driven contextual information from product, process, equipment and maintenance data sources, instead of relying only on sensor data.

Finally, an application of control with the objective to limit the control effect on failure and unavailability of the system is proposed by Salazar et al. [8]. This work presents a Model Predictive Control (MPC) framework taking into account the usage of the actuators to preserve system reliability while maximizing control performance. Two approaches are proposed to preserve system reliability: a global approach that integrates in the control algorithm a representation of system reliability, and a local approach that integrates a representation of component reliability. The trade-off between the system reliability and the control performance should be taken into account. A methodology for MPC parameterization is proposed to handle this trade-off. System and component reliability are computed based on Dynamic Bayesian Network. The effectiveness and benefits of the proposed control framework are discussed through its application to an over-actuated system.

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Guest Editors

Philippe Weber
Université de Lorraine, Centre de Recherche en Automatique de Nancy (CRAN),
FST - B.P. 70239 54506 Vandoeuvre-lès-Nancy, France
philippe.weber@univ-lorraine.fr

Luigi Portinale
DiSIT, Computer Science Institute,
University of Piemonte Orientale, Alessandria, Italy
luigi.portinale@uniupo.it