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Architecting Very Large, Complex Bayesian Network Simulations for Practical Airworthiness Risk Assessment Applications

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Abstract

While constructing practical Bayesian Networks (BN) of large, complex systems that are computationally tractable continues to be a significant challenge within the expanding BN modeling and simulation field, this paper advances methods that are changing the BN modeling paradigm from simplifying these models to reducing them by employing parent divorcing and generalized BN model development methods. We illustrate real world implementation of these concepts by reducing a large, complex cyber-physical risk assessment BN model into smaller, manageable ones able to be efficiently simulated, while identifying a newly structured approach toward appropriately weighting the integrating factors to be validated at the higher level. We apply d-connectedness techniques to maintain backpropagation and overall model integrity present in the larger, complex BN model, and use cause consequence and definitional/synthesis idioms to construct an Airworthiness BN risk assessment model, based on MIL-HDBK-516C, by implementing series and parallel networks of smaller models that simulate separately. Richer simulation results are enabled by extending the degree of model complexity able to be created and efficiently simulated within the practical capabilities of an existing commercial tool.

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Keywords: Bayesian Networks; BNs; Bayes; modeling; d-connected; d-separated; parent divorcing; computationally tractable simulation; Airworthiness; cyber-physical systems

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1. Introduction

This paper discusses factor identification and management for developing a large Bayesian Network (BN) model to support airworthiness risk assessment. Aircraft systems are increasing in complexity and the Department of Defense MIL-HDBK-516C Airworthiness Certification Criteria [1] is the guideline used to address risk prior to issuing flight clearance. Further complicating the problem is that there is considerable human expert judgment that is required spanning interrelated disciplines and system domains that include, but are not limited to: flight technologies, structures, propulsion, avionics, weapons systems, human systems, and safety. The cyber-physical nature of these systems means there are many dependencies across the domains. This process is still manually intensive, but technologies like BNs [2, 3] provide a means for linking these cross-cutting factors from the different domains to provide both a systematic and comprehensive risk identification process in predicting the overall risk of issuing a flight clearance.

Nomenclature

ACC	Airworthiness Certification Criteria	MS	Microsoft
AHP	Analytic Hierarchy Process	NAVAIR	Naval Air Systems Command
AIJ	Aggregate Individual Judgments	N Level	Node Level
AIP	Aggregate Individual Priorities	NPT	Node Probability Table
BN	Bayesian Network	NS<x>	Natural Synthetic Nodes, level depicted by x
CPT	Conditional Probability Table	<x>	Root Input Nodes, level depicted by x
DAG	Directed Acyclic Graph	PDF	Portable Document Format
FRR	Flight Readiness Review	SME	Subject Matter Expert
HLA	High Level Architecture	VBA	Visual Basic for Applications

1.1. Problem

There are several steps involved in developing BN models, including identifying factors to be represented as nodes, creating causal relationships between factors in a way that manages efficient simulation, and applying appropriate factor weightings [4]. A key challenge for this research is due to the complexity for constructing a BN with a large number of factors that must be considered for making an airworthiness decision. A BN model derived from the latest ACC guidelines generates over 1000 nodes, rendering a single model computationally intractable.

1.2. Objectives

There are a number of research objectives addressed in this paper. First, the paper discusses methods that can be used to structure a computationally tractable BN model set [5]. Secondly, additional factors are introduced to the structuring method in a way that supports decision making. Thirdly, the paper discusses the approach used to identify or develop an approach to appropriately "weight" the BN nodes derived from the identified factors of the ACC. Fourthly, and last, the paper identifies an approach for advancing state-of-the-art frameworks, modeling methods, or analysis methods for risk and decision making models.

1.3. Approach

The research discussed herein builds on prior research [5] and uses appropriate idioms [6] and d-connectedness principles as identified to structure a computationally tractable BN model set that supports Airworthiness decision making. A SME is guiding the assignment of weightings of the major nodes as our research efforts capture the rationale as to why the SME believes the weightings are valid, over which value ranges they may move, and why [7]. The factors are abstracted to support the structuring method. In addition to the SME, the authors use literature and professional judgment grounded in industry experience to explore and verify appropriate factors [8].