ANALYSIS ON THE IMPORTANT INDICATORS IN BAYESIAN BELIEF NETWORK MODEL FOR RPS SOFTWARE RELIABILITY ASSESSMENT

Sang Hun Lee, Hyun Gook Kang
Department of Mechanical, Aerospace, and Nuclear Engineering
Rensselaer Polytechnic Institute
110 8th St, Troy, NY, USA
lees35@rpi.edu; kangh6@rpi.edu

Tsong-Lun Chu, Athi Varuttamaseni, and Meng Yue
Brookhaven National Laboratory
Brookhaven Avenue, Upton, NY, USA
chu@bnl.gov; avarutta@bnl.gov; yuemeng@bnl.gov

Jaehyun Cho
Korea Atomic Energy Research Institute
111, Daedeok-daero, Daejeon, Republic of Korea
chojh@kaeri.re.kr

Ming Li
U.S. Nuclear Regulatory Commission
Washington, DC, USA
Ming.Li@nrc.gov

Seung Jun Lee
School of Mechanical and Nuclear Engineering
Ulsan National Institute of Science and Technology
50, UNIST-gil, Ulsan, Republic of Korea
sjlee420@unist.ac.kr

Bayesian belief network model was developed in authors' previous research that quantifies the number of software faults based on software development life cycle (SDLC) characteristics of nuclear power plant (NPP) safety-related software. In a nuclear application, in order to effectively reduce the number of software defects in a target digital safety system, it is important to analyze the SDLC phases or related activities that are the major contributors to the final number of residual faults in the software. First, in order to identify the software development activities (attributes) as strong or weak indicators for the overall development or V&V quality of specific software development lifecycle (SDLC) phase, the indication measure of an attribute for development and V&V quality is proposed and the contribution of attributes' states to the quality nodes were analyzed. Secondly, the contribution analysis of quality nodes on the number of residual software defects is conducted considering the improvement of development and V&V quality from Medium to High quality in each SDLC phase. Furthermore, the cost of fixing detected defects passed from previous phases when the development and V&V quality is improved from Medium to High is assessed. This study is expected to provide an insight on analyzing the important SDLC phases and related software attributes to be considered when one desires to effectively optimize the SDLC for targeting fewer residual software defects in NPP digital safety-related system.

I. INTRODUCTION

The analog systems in nuclear power plants (NPPs) are approaching obsolescence; thus, existing NPPs have begun to replace current analog instrumentation and control (I&C) systems with digital-based ones, while new plant designs fully incorporating digital systems. This shift in technology necessitates the need to develop and integrate digital I&C risk models into NPP probabilistic risk assessment (PRA) models. Previous research has explored the possibility of addressing failure in digital I&C systems within the framework of current NPP PRAs, including reliability modeling of software failure in a digital I&C system [1, 2]. Especially, since software failure can significantly affect the digital safety systems [3], the reliability of the software must be quantified to guarantee the safety of a digitalized NPP.

In order to model NPP safety software failures and quantify the software failure probability, a Bayesian belief network (BBN) model was developed in the authors' previous research, which estimates the number of faults in safety-related software systems and the software failure probability. The causal relationships in the model represent those of the safety-related software where the model structure was constructed using safety-related software characteristics and product information. In particular, the model captures the causal relationships among the software development activities, the software development and verification and validation (V&V) quality, the number of residual software defects, and the software failure probability.

In a nuclear application, in order to effectively reduce the number of defects in safety-related or safety-critical software, the developed BBN model can be used to analyze which software development lifecycle (SDLC) phase is the major contributor to the number of residual faults in the software, and then identify the related development activities which determine the development and V&V quality of that SDLC phase. In the BBN model, SDLC characteristics, such as development quality, V&V quality and related software development activities (attributes), are represented using a hierarchical structure. Therefore, each SDLC phase has different contributions to the final number of residual defects in the software. Similarly, each attribute, which serves as an indirect indicator of the software development and V&V quality and is linked to quality nodes in a diverging configuration, has a different contribution to inferring the related software development and V&V quality in each SDLC phase.

Considering these points, this study investigates the contribution of attribute quality and development and V&V quality to the final number of software defects using the BBN model. Particularly, an indication measure is proposed to identify the relative contribution of an attribute to the development or V&V quality in each SDLC phase, and the conditional probability (belief) of the quality nodes given the observed attribute qualities is analyzed. Additionally, the contributions of development quality and V&V quality to the number of software defects are analyzed by directly inserting evidence to the quality nodes in the BBN model. Such contribution analyses and results are expected to provide insights on the efforts to focus on the activities with higher contributions in order to optimize the SDLC with respect to targeting fewer residual defects, resulting in lower software failure probability.

II. BBN MODEL STRUCTURE AND PARAMETERS

The BBN model, developed in authors' previous research, estimates the number of faults remaining in nuclear safety-related software, considering SDLC characteristics such as the quality of software development and V&V activities, and software-self characteristics, such as program size and complexity. The model, consisting of five SDLC phases (Requirements, Design, Implementation, Test, and Installation & Checkout), starts with the defects remaining in the Requirements phase and tracks the number of defects through all remaining phases.

The model for each phase estimates the number of residual software faults in that phase. As an example, a framework for estimating the number of defects remaining in the software in the Design phase is shown in Fig. 1. Here, the BBN model assumes that the development and V&V quality in each SDLC phase directly impacts the number of remaining defects in that phase. Such impacts are expressed in the model in terms of the faults that may be introduced by the development activity group, and the faults that can be detected and removed by the activity of the V&V group. It is notable that the BBN structures of other SDLC phases can be modeled in a similar manner.

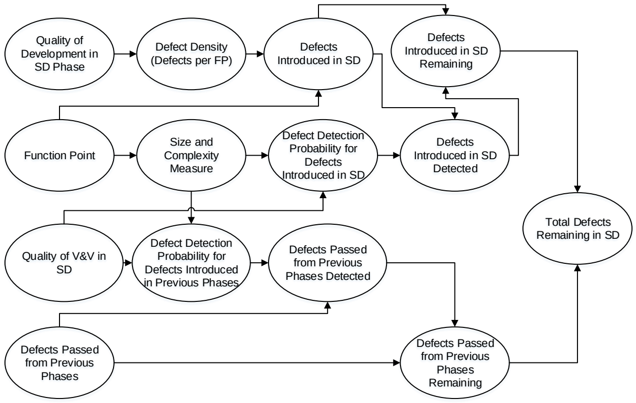

Quality of Development in SD Phase
Defect Density (Defects per FP)
Defects Introduced in SD
Defects Introduced in SD Remaining
Function Point
Size and Complexity Measure
Defect Detection Probability for Defects Introduced in SD
Defects Introduced in SD Detected
Total Defects Remaining in SD
Quality of V&V in SD
Defect Detection Probability for Defects Introduced in Previous Phases
Defects Passed from Previous Phases Detected
Defects Passed from Previous Phases
Defects Passed from Previous Phases Remaining

Fig. 1. Overview of the BBN model for the software Design phase.

II.A. Development and V&V quality nodes

As shown in Fig. 1, the BBN model of each phase is represented with two types of activities: Development and V&V activities. The important assumption is that the development and V&V quality in each SDLC phase directly impacts the number of remaining defects in that phase. As shown in Fig. 1, the model assumes that the development quality of the safety-related software is directly related to the defect density (the number of defects introduced per function point) in each SDLC phase.

In addition, the V&V quality of the software is related to the detection (and thus removal of the detected defects) probability for defects introduced in each SDLC phase and defects passed from previous phases. The quality nodes in the BBN model are qualitatively modeled with three states—*High*, *Medium*, and *Low*—with each state representing the overall quality of the activities, defined as follows:

- *High*: State corresponding to the quality of the software development by a high-maturity company rigorously following established standards, and implementing additional measures to significantly improve the quality of the software.
- *Medium*: State representing the quality of a software development in which all required activities for safety-related systems are completed.
- *Low*: State representing the quality of a software development in which required activities for safety-related systems are not completed.

II.B. Attribute nodes

Development and V&V qualities are often hard to directly measure as they represent the overall quality of software development or V&V activities. In the model, the quality nodes are thus treated as unobservable nodes, and the impact of the quality nodes of the SDLC phases on the number of software defects is expressed in terms of (1) the faults that may be introduced by various software development activities, and (2) the faults that can be detected and removed by related software V&V activities. The quality in carrying out these activities is assessed by investigating the software developmental activities (attributes) of a safety-related system for each SDLC phase. Fig. 2 depicts the connection between a quality node and attribute nodes, here representing the overall quality of the development activities in the software Design phase.

In the BBN model, the diverging connection approach is used to model the relationship between the quality nodes and attribute nodes; that is, the quality nodes in the center have attributes connected to them in a diverging configuration, as shown in Figs. 2 and 3, wherein the attribute nodes are modeled as indicator nodes similar to the indicator nodes of Fenton et al. [4, 5]. Similar to the three states defined above for the quality nodes, the attribute nodes are modeled with the three states defined as below:

- *High*: In addition to satisfactorily carrying out the required activities, additional activities were undertaken that are expected to significantly improve the quality of the work, and enhance the software's reliability.
- *Medium*: All required (or equivalent) activities were satisfactorily carried out.
- *Low*: Some of the required activities were not carried out satisfactorily.

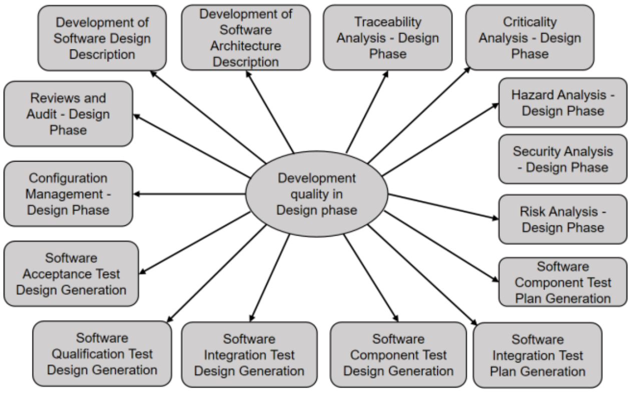

Development of Software Design Description
Development of Software Architecture Description
Traceability Analysis - Design Phase
Criticality Analysis - Design Phase
Reviews and Audit - Design Phase
Hazard Analysis - Design Phase
Security Analysis - Design Phase
Configuration Management - Design Phase
Development quality in Design phase
Risk Analysis - Design Phase
Software Acceptance Test Design Generation
Software Component Test Plan Generation
Software Qualification Test Design Generation
Software Integration Test Design Generation
Software Component Test Design Generation
Software Integration Test Plan Generation

Fig. 2. Attributes nodes for development quality in software Design phase.

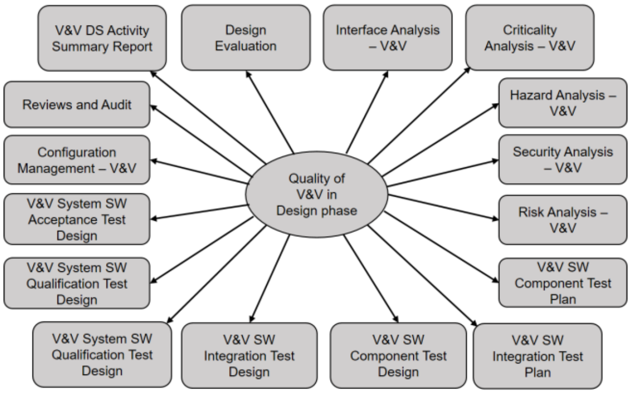

V&V DS Activity Summary Report
Design Evaluation
Interface Analysis – V&V
Criticality Analysis – V&V
Reviews and Audit
Hazard Analysis – V&V
Configuration Management – V&V
Security Analysis – V&V
Quality of V&V in Design phase
V&V System SW Acceptance Test Design
Risk Analysis – V&V
V&V System SW Qualification Test Design
V&V SW Component Test Plan
V&V System SW Qualification Test Design
V&V SW Integration Test Design
V&V SW Component Test Design
V&V SW Integration Test Plan

Fig. 3. Attributes nodes for V&V quality in software Design phase.

III. CONTRIBUTION ANALYSIS OF BBN MODEL PARAMETERS

III.A. Contribution Analysis of Attributes on SDLC Quality States

In the BBN model, the development quality in each phase determines the defect density, while the V&V quality determines the probability of detecting those defects. Both quality nodes in each phase are indirectly indicated by the attributes which describe the related specific software development and V&V activities. Among the various attributes linking the development or V&V quality in a diverging configuration, each attribute has different contributions, or amount of influence, on the quality node. Therefore, in order to optimize the SDLC (target fewer defects in the software), it is important to identify the attributes that are strong indicators of the state of the software development and V&V quality nodes.

III.A.1. Indication Measure

In this study, in order to identify the attributes as strong or weak indicators for development quality or V&V quality, an indication measure is proposed. Based on the same principle for checking the linearity of data points in two-dimensional space [6], the indication measure (*I*) of an attribute for development quality and V&V quality is proposed to identify how well the attribute indicates the development or V&V quality, where *I* is defined as:

$$\begin{aligned}\Delta = {} & (P(A_M \mid Q_H) + P(A_L \mid Q_H))Q_H + \\ & (P(A_H \mid Q_M) + P(A_L \mid Q_M))Q_M + \\ & (P(A_H \mid Q_L) + P(A_M \mid Q_L))Q_L \end{aligned} \qquad (1)$$

$$\begin{aligned} I = 1 - \Delta = {} & P(A_H \mid Q_H)Q_H \\ & + P(A_M \mid Q_M)Q_M + P(A_L \mid Q_L)Q_L \end{aligned} \qquad (2)$$

where $P(A_i \mid Q_j)$ is the conditional probability of i attribute state for j development or V&V quality state. Both attribute and quality nodes are defined by states *High*, *Medium*, and *Low*. $P(Q_j)$ is the probability of a k development or V&V quality state, where the state of k is also defined as *High*, *Medium*, and *Low*. Based on Eqs. (1) and (2), the attributes which are strong indicators of development and V&V quality can be identified among the various attributes defined in each SDLC phase. Since indicating performance is a matter of interest, the prior probability of a development or V&V quality to be High, Medium, or Low is considered to be one third.

Table I shows the conditional probabilities of attribute quality *High*, *Medium*, and *Low* for a given same development quality in the Requirements phase with corresponding indication measure (*I*). Here, it can be seen that the "System/Software Qualification Test Plan Generation" attribute showed the highest indication measure for the development quality and V&V quality in the Requirements phase, meaning it represent the strongest indicators for the Development quality node in the Requirements phase. It is notable that the indication measure of each attribute nodes and the strongest indicators regarding Development and V&V quality in other SDLC phases can be derived in the same manner.

Such attributes having high indication measures can be used by software development or V&V teams to analyze which software developmental and V&V activities (attributes) are most strongly correlated with software quality, and optimize the software developmental process to achieve better development or V&V quality in each SDLC phase accordingly.

TABLE I. Attribute conditional probabilities and attribute indication measure(*I*) for Development quality in Requirements phase

Attribute	Development Quality Level			*I*
	High	Medium	Low	
System/Software Qualification Test Plan Generation	0.72	0.65	0.71	0.6910
Development of Software Requirements Specifications	0.72	0.66	0.68	0.6857
Development of a Concept Documentation	0.68	0.64	0.66	0.6587
System/Software Acceptance Test Plan Generation	0.67	0.66	0.65	0.6580
Traceability Analysis - Requirements Phase	0.57	0.66	0.71	0.6440
Security Analysis - Requirements Phase	0.64	0.64	0.63	0.6343
Software Development Planning	0.63	0.64	0.63	0.6337

III.A.2. Conditional Probability of Quality Nodes given the Evidence on Attribute Nodes

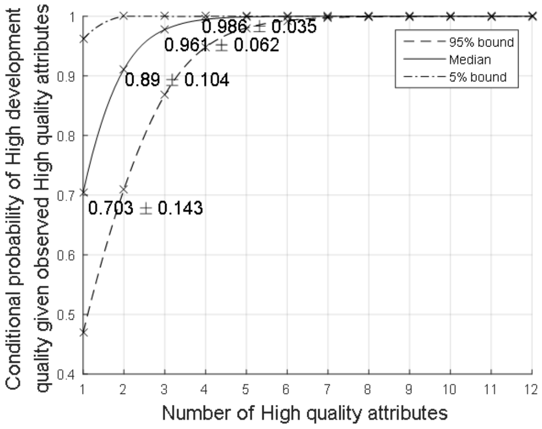
The BBN model assumes that the attribute nodes provide indirect indications for the quality nodes based on a diverging configuration. In other words, the probability of a Development or V&V Quality node having a specific quality (*High*, *Medium*, or *Low*) is evaluated based on observations of the attribute qualities by Bayesian inference. Assuming that the attributes linked to same quality node are independent, when *k* number of independent attribute qualities are evaluated, the belief in *High* development or V&V quality given evidence on attribute qualities can be defined as:

$$\begin{aligned} & P(Q_H \mid A_1^{j_1}, A_2^{j_2}, \ldots, A_k^{j_k}) \\ & = \frac{\prod_{i=1}^{k} \{P(A_i^{j_i} \mid Q_H)\} P(Q_H)}{\sum_{m=H,M,L} [\prod_{i=1}^{k} \{P(A_i^{j_i} \mid Q_m)\} P(Q_m)]} \end{aligned} \qquad (3)$$

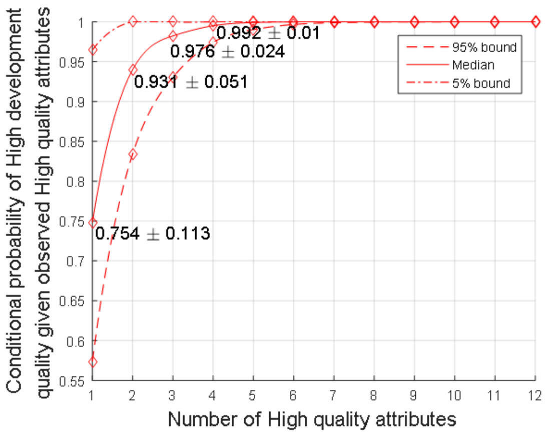
where the quality of i attribute is denoted as $A_i^{j_i}$, and $P(A_i^{j_i} \mid Q_m)$ is the conditional probability of the quality of attributes for given development quality or V&V quality, where expert opinion was used in this study to construct the. Based on Eq. (3), as a case study, the belief in High development quality in the Requirements phase was analyzed. Here, $P(Q_m)$ is the initial belief in the quality nodes to be *High*, *Medium*, or *Low* when no evidence is yet introduced, thus considered to be one third. The proposed method can also be applied to derive the belief in development or V&V quality in other SDLC phases.

Figure 4 shows the degree of belief in *High* development quality in the Requirements phase when the qualities of attributes in that phase were consistently observed as *High*. In this study, to account for the uncertainty associated with the estimates different experts provided, the NPTs that are tables of random variables whose probabilistic distributions were estimated via expert elicitation were used, leading to an uncertainty bound on the belief in High development quality given observed attribute qualities.

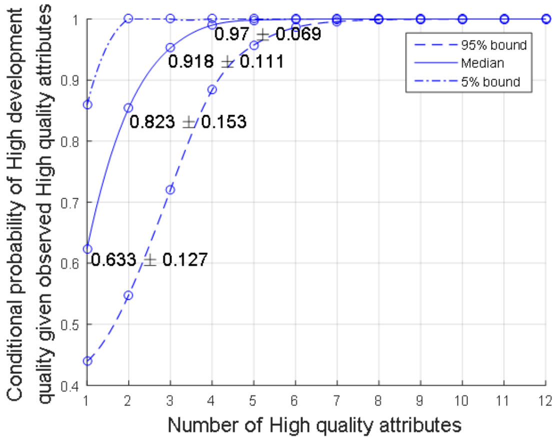
As shown in Fig. 4, the mean belief in High development quality in the Requirements phase increases while the uncertainty bound for the belief in development quality decreases as the amount of evidence (the number of attributes observed to have *High* quality) increases. In addition, the result showed that more than 6 attributes of *High* quality must be observed to have 5% low bound of the belief in *High* development quality in the Requirements phase to be over 0.99 when randomly observing High attribute quality (Fig. 4-(a)). On the other hand, at least 5 and 7 attributes of *High* quality must be observed to have 5% low bound of the belief in *High* development quality to be over 0.99, when the attributes with high indication measures (Fig. 4-(b)) and with low indication measures (Fig. 4-(c)) are sequentially observed.



(a)



(b)



(c)

Fig. 4. Conditional probability of High development quality in Requirements phase as a function of the number of High quality attributes

III.B. Contribution Analysis

The BBN model assumes that the number of defects remaining in each phase is a function of development and V&V quality in each phase. In other words, software development and V&V quality determines the number of defects inserted per function point (defect density), and the detection probability for defects introduced in both current and previous phases, respectively. To analyze the effect of development and V&V quality on the number of defects remaining at the final SDLC phase, a contribution analysis for development and V&V quality is conducted by directly inserting evidence into the quality nodes in the BBN model. In the analysis, *High* development and V&V quality in each phase is considered as a case study, with the results of the model compared to the case of a typical digital protection system having 50 function points with *Medium* development and V&V quality in all SDLC phases.

As shown in Table II, *High* development quality and *High* V&V quality in the early SDLC phases decrease the number of initial defects and reduce defects in following SDLC phases. According to the results, the number of detected defects passed from the previous phase at the last phase (Installation-and-Checkout) decreases when the development and V&V quality of previous phases are *High*, because less defects are passed from the previous SDLC phases. Notably, *High* V&V quality in the Test phase results in the highest reduction in the number of detected defects in the last phase.

TABLE II. Number of detected defects passed from previous SDLC phases

Phase	Condition	Number of detected defects passed from previous phase							
		Design		Implementation		Test		Installation /Checkout	
		Mean	△Mean	Mean	△Mean	Mean	△Mean	Mean	△Mean
Requirements	Development Quality = High	1.46	-21.56%	5.05	-3.87%	9.50	-1.19%	6.57	-1.11%
	V&V Quality = High	1.18	-36.56%	4.83	-7.94%	9.37	-2.49%	6.57	-1.01%
Design	Development Quality = High	-	-	4.30	-18.17%	8.87	-7.71%	6.43	-3.21%
	V&V Quality = High	2.28	22.58%	3.55	-32.40%	8.24	-14.29%	6.30	-5.14%
Implementation	Development Quality = High	-	-	-	-	8.47	-11.85%	6.22	-6.39%
	V&V Quality = High	-	-	6.79	29.31%	6.23	-35.16%	5.61	-15.53%
Test	Development Quality = High	-	-	-	-	10.81	12.49%	3.69	-44.43%
	V&V Quality = High	-	-	-	-	11.90	23.83%	3.25	-51.08%
Installation/ Checkout	Development Quality = High	-	-	-	-	-	-	-	-
	V&V Quality = High	-	-	-	-	-	-	8.64	30.12%

Although the recursive process in the SDLC is not explicitly considered in the BBN model, in practical applications if a significant defect made in the Design phase is found in the Installation-and-Checkout phase, the software development process should be restarted again from the Design phase. Therefore, the cost of fixing a detected defect depends on the phase in which the defect is found, where defects detected in later phases cost more to fix because of the recursive process in the SDLC. Assuming the cost to fix one detected defect passed from previous phases in the Design, Implementation, Test, and Installation & Checkout phase is C, 2C, 3C, and 4C, respectively, the total cost required for the recursive fixing process when the development quality or V&V quality in each SDLC phase changes from *Medium* to *High* is calculated. The total cost is estimated by Eq. (4), with estimated costs listed in Table III for each phase. The results show that enhancement of development or V&V quality in all SDLC phases, except the Installation-and-Checkout phase, reduces the recursive fixing cost by reducing the defects introduced in each SDLC phase. Particularly, *High* V&V quality in the Implementation phase entails the highest reduction in total cost to fix detected defects.

$$\begin{aligned}\text{The total cost of fixing detected defects} =\ & \Delta\ \text{Mean in the Design phase} \times C \\ & + \Delta\ \text{Mean in the Implementation phase} \times 2C \\ & + \Delta\ \text{Mean in the Test phase} \times 3C \\ & + \Delta\ \text{Mean in the Installation/Checkout phase} \times 4C \quad (4)\end{aligned}$$

TABLE III. Cost of fixing detected defects in each phase when development quality or V&V quality changes from *Medium* to *High*

Phase	Condition	Cost
Requirements	Development Quality = High	-1.41 C
	V&V Quality = High	-2.52 C
Design	Development Quality = High	-4.96 C
	V&V Quality = High	-8.45 C
Implementation	Development Quality = High	-5.1 C
	V&V Quality = High	-11.18 C
Test	Development Quality = High	-8.2 C
	V&V Quality = High	-6.69 C
Installation/Check out	Development Quality = High	-
	V&V Quality = High	8.0 C

IV. CONCLUSIONS

With the goal to incorporate software failures into digital I&C PRA models, a BBN model was developed in authors' previous research that estimates the number of defects in nuclear safety-related software and the resulting probability of software failure on demand. The model captures SDLC characteristics as well as information from the nuclear safety-related software, and establishes quantitative causal relationships between the attributes, the development and V&V quality, and the number of remaining defects in each SDLC phase. As the developed BBN model assumes that the quality of each SDLC phase directly impacts the number of remaining defects, the development and V&V qualities in each SDLC phase have different contributions to the number of residual defects in the software. In addition, the attributes are employed to provide indirect indications when evaluating the development and V&V quality, which represent the overall quality of various related developmental and V&V activities. Linked to quality nodes in a diverging configuration, each attribute therefore has a different contribution on evaluating the development and V&V quality of each SDLC phase. This study thus performed contribution analyses for the attributes and development and V&V quality.

The indication measure was proposed for the attribute contribution analysis in order to identify which attributes are strong or weak indicators for the development and V&V quality in each SDLC phase. A case study was presented where, based on the indication measure, the relative contributions of each attribute to the quality nodes in the Requirements phase were analyzed. As a result, the attributes having a high conditional probability of attribute quality for the same development or V&V quality were derived, revealing the strongest indicators for the quality nodes. Such attributes having high indication measures can provide a means to optimize software development activities, by identifying which attributes defined in each quality node in the SDLC phases are the strongest contributors to the inference of software development and V&V quality.

Since the development and V&V quality is Bayesian-inferred, based on the observed attribute qualities connected to the quality nodes, the contribution of the attribute quality on the belief in the quality node was analyzed. Based on expert opinion–derived NPTs for the conditional probability of each attribute quality given development or V&V quality, the belief in High development quality given various evidence on attribute quality at Requirements phase was assessed as a case study. The number of observed attributes having the same or different quality states required to have a certain belief in the development quality state was derived, and the expected value as well as the uncertainty bound of the belief according to the number of attributes was examined. This approach provides an insight into the analysis of how many attributes having High quality must be observed among the observed attributes for achieving a desired confidence level on software development or V&V quality for software quality assurance in practical applications.

For the development and V&V quality contribution analysis, the effect of the number of residual defects in the software when the development and V&V quality is improved from Medium to High was analyzed as a case study by directly inserting evidence to the development quality or V&V quality. Results demonstrated that the development and V&V quality in early phases had a relatively weak influence on the final number of defects, since the defects introduced in early phases could be detected throughout the cycle in later SDLC phases. On the other hand, development and V&V quality in the later phases had a much greater effect on the final number of defects in the software. Furthermore, the cost of fixing a detected defect passed from previous phases when the development and V&V quality is improved from Medium to High was assessed. The result showed that enhancement in development and V&V quality in each of the first four SDLC phases reduces the recursive fixing cost by reducing the defects introduced in each SDLC phase, with High V&V Quality in the Implementation phase displaying the largest reduction in the total cost to fix the detected defects.

This study is expected to provide a better understanding of the important attributes and the development and V&V quality in each SDLC phase to be considered when one desires to effectively target fewer residual defects in NPP safety-related software using the BBN model. That is, the proposed approach can provide a measure to align efforts on nuclear safety-related software development or V&V activities to enhance software reliability. This is achieved by focusing on the development or V&V qualities with a significant effect on the final defects remaining in the software, along with related software development activities which have high indication measures or are strong indicators of the development or V&V quality in each SDLC phase.

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