

# BBN-BASED PORTFOLIO RISK ASSESSMENT FOR NASA TECHNOLOGY R&D OUTCOME

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## Abstract

The NASA Aeronautics Research Mission Directorate (ARMD) vision falls into six strategic thrusts that are aimed to support the challenges of the Next Generation Air Transportation System (NextGen). In order to achieve the goals of the ARMD vision, the Airspace Operations and Safety Program (AOSP) is committed to developing and delivering new technologies. To meet the dual challenges of constrained resources and timely technology delivery, program portfolio risk assessment is critical for communication and decision-making. This paper describes how Bayesian Belief Network (BBN) is applied to assess the probability of a technology meeting the expected outcome. The network takes into account the different risk factors of technology development and implementation phases. The use of BBNs allows for all technologies of projects in a program portfolio to be separately examined and compared. In addition, the technology interaction effects are modeled through the application of object-oriented BBNs. The paper discusses the development of simplified project risk BBNs and presents various risk results. The results presented include the probability of project risks not meeting success criteria, the risk drivers under uncertainty via sensitivity analysis, and what-if analysis. Finally, the paper shows how program portfolio risk can be assessed using risk results from BBNs of projects in the portfolio.

## Keywords

Portfolio risk, project risk, BBN, sensitivity analysis, object-oriented BBN, tornado diagram.

## Introduction

With NASA's overall goal of transforming aviation, NASA ARMD has the vision to benefit today's and the future's air transportation system, aviation industry, and the passengers and businesses who rely on aviation every day. The ARMD aeronautical research and development (R&D) encompasses a broad range of technologies to meet future needs of the aviation community, or the outcomes of the six Strategic Thrusts, as identified in NASA Aeronautics Strategic Implementation Plan (SIP) (NASA Aeronautics Research Mission Directorate, 2014). NASA ARMD technologies aim at increasing the capacity and improving the efficiency, safety, and environmental compatibility of the national airspace system (NAS). AOSP supports ARMD particularly through providing relevant technologies contributing to Thrusts 1, 5, and 6. The ultimate goal of AOSP is to mature its technologies from low technology readiness level (TRL) (NASA, 2012) to high TRL for a successful technology transfer and implementation on operational systems in the NAS. To achieve this goal with constrained resources, the AOSP management team provides leadership to set strategic visions, build a portfolio, allocate proper funding to technology projects or sub-projects in the portfolio, and guide the R&D execution. Consequently, portfolio assessment is a critical component of program management activities. Program portfolio management requires insight into technology (sub)projects from various perspectives, such as benefit, cost and risk. This paper focuses on portfolio assessment from a risk perspective.

It should be noted that for NASA AOSP, the risk management has been implemented at the sub-project level, project level and program level. At program level, the desire is to perform a portfolio risk assessment with a consistent and transparent analysis process across the technology projects to provide insight for key decision-making and communication. To this end, the Bayesian Belief Network (BBN) approach was chosen to model individual sub-project risks and is used in portfolio assessment. For the sake of simplicity, sub-project is simply referred to as project in BBN discussions throughout this paper. The paper explains why and how the BBN was utilized to provide a visual model of various risks and their relationships within a project and/or across projects. Various results from the project BBN analysis are presented, including probabilistic estimates of concerned risks, risk drivers from

sensitivity analysis, and exploratory results from what-if scenarios. Finally, portfolio risk is assessed using comparative results from project BBNs and the concept of benefit/cost/risk analysis. Due to the sensitivity to the program/projects, all BBN input data and results in this paper are notional.

## **Portfolio Risk Assessment of NASA Technology Projects**

For NASA AOSP technology projects and sub-projects, success is achieved when the technologies are developed and implemented on aviation operational systems. There are several types of risks to consider, including funding, schedule, technical, and safety risks. In terms of risk management, the primary goal of all (sub)projects is to reduce all types of risks to a manageable and non-problematic level. The typical way to manage risks is by using a 5x5 probability and impact matrix (NASA Office of Safety and Mission Assurance, 2008) (NASA Office of the Chief Engineer, 2008) that compares likelihood to severity; each has a 5-level scale. Likelihood ranges from extremely improbable to frequent; while severity ranges from minimal to catastrophic. The common risk analysis process is to classify concerned risks into one of the five categories for risk likelihood and severity, and mark risks into the cells on a two-dimensional grid of this 5x5 risk matrix. The matrix is generally colored as a heat map, therefore, providing a visual snapshot of the risks that a project faces at an instance of time. In addition, risks can be ranked by their risk level or risk score from the combined rating scale of probability and severity. With the 5x5 risk matrix, (sub)project management teams conduct a continuous risk assessment to gain feasibility of timely delivery and allocation of constrained resources.

Although the 5x5 risk matrix can be an effective tool at the (sub)project level by managing each risk item and providing certain risk evaluations, the relationships among risks and risk drivers under uncertainty to the (sub)project's success cannot be analyzed. Additionally, the disparity of concerned risks over risk categories across (sub)projects makes a risk matrix not appropriate for a portfolio risk assessment. Therefore, it is important to seek out an alternative risk analysis method that is able to, not only consistently analyze individual (sub)project outcome risk, but also provide useful insight from a comparative (sub)project risk analysis for a program portfolio risk assessment. The results from the portfolio risk assessment facilitate management communication and decision-making to attain a balanced portfolio investment and achieve the program goals.

## **BBN Background**

As discussed, the identified risks and their relations in and across the projects are better captured through an alternate method. A visual representation of cause and effects with multi-dependency would grasp the risks and relations well. The aspect of multi-dependency is modelled well through the BBN technique using Hugin Explorer (Hugin Expert A/S, 2016). A BBN is a probabilistic graphical model; modeling uncertainty with probabilities and representing probabilistic structure with nodes and arrows. In a BBN developed for project risk, the nodes represent the risk variables (or factors) and arrows to each node represent the dependency between the two or more risks as shown in Exhibit 1. The nodes that have no dependency from other nodes are considered leaf nodes. The nodes that are dependent on another node are considered child nodes. Finally, the nodes that the child nodes are dependent on are called parent nodes. Each node has two or more states associated with it. Depending on the node type selected, labelled, numbered, Boolean, or interval, determines the number of states available and naming convention for each state. A labelled node allows for descriptive states to be defined, whereas an interval node allows states to be specified in a continuous numerical range. Although BBN modeling of project risk using labelled nodes is the focus of this paper, BBN modeling using interval nodes is also briefly discussed to show its advantages over the labelled nodes in some aspects.

The BBN technique with labelled nodes requires probability values of each state. The probability inputs range from 0 to 1. The leaf nodes require marginal probability inputs, while all the child nodes require conditional probabilities (CPs) (Mendenhall & Sincich, 2007) dependent on the parent nodes associated with them. These probability values are typically elicited from subject matter experts (SME). The required number of probability inputs for a leaf node is dependent upon the number of states of the node. The number of CPs for a child node is determined from the number of child node states and associated parent state configurations. For example, referencing Exhibit 1, if all nodes in this network have two states and the selected child node is dependent on three parent nodes, there are 16 ( $=2^4$ ) required CPs inputs (CP table size). The required CP inputs can quickly grow beyond SMEs' cognitive capability with increasing number of input nodes and/or states. Alternatively, conditional probabilities in a child node may be filled in by requesting SMEs to provide the relative risk importance of each parent node to the child node. Once a BBN is constructed, Bayesian inference can be made using the Bayes' rule with updated knowledge and evidence, such as in the evidence sensitivity analysis.

Furthermore, BBN modeling allows different models to be developed independently and encapsulated as sub-models (or objects) to have connections to the core working model, showing interdependency between networks. In the past, NASA Aeronautics Program has used the BBN technique to show the causal factors in different domains leading towards an undesirable event in aviation safety modeling work (Ancel, Shih, Jones, Reveley & Luxhøj, 2014). The new proposed application of BBNs is to model key risks of a project in a snapshot of its timeline and to consider the project risks interdependence in project outcome risk and program portfolio assessment.

**Exhibit 1. Project Outcome Risk BBN.**



### **BBN Development for a Project Outcome Risk**

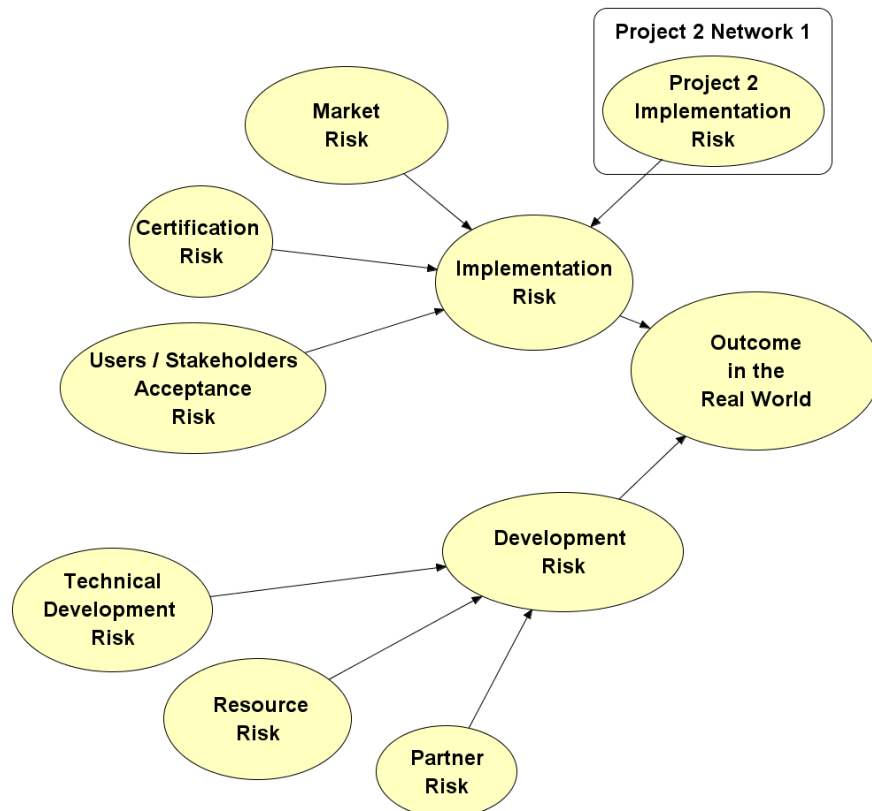
The key steps to creating a project BBN are to identify the risks that are evident in a project and to determine the relationships between these risk factors. It is common practice to keep a maximum of five dependency inputs to a risk node to ease the difficulty in assigning probabilities into the network. This does not mean to remove risks from the analysis, but develop a taxonomy that encompasses and aggregates risk variables to reduce the number of risk inputs for a simpler BBN network. For NASA AOSP’s technologies and projects, most risks largely fall into the development or implementation phase. Furthermore, the development phase can be broken into either technical development risk or technical management risk, while the implementation phase includes business risks and certification risks. These two phases of interest can contain multiple layers of risks. However, for the current portfolio assessment, a simplified project risk BBN was developed as shown in Exhibit 1. This simplified risk BBN contains only three key common project risk factors in each phase and a final node for the project risk of meeting/not meeting expected outcome in the real world.

The top-level simplified BBN in Exhibit 1 is used for each project for an initial risk assessment of a portfolio with many projects. The inputs for these networks are further simplified by assigning only two states to each risk node, a High state and Low state. The states imply that this particular risk is either at a high risk state or at a low risk state. It should be noted that these two defined states are mutually exclusive. This simplification makes it manageable for the SMEs or project leads to provide probabilities with minimal human error. When requesting SMEs to provide probability values, they are only asked to provide a High state probability value for the leaf nodes. Since the overall probability value must be equal to 1, the Low state probability value is calculated by subtracting

out the High state probability value. In the case for a child node, SMEs will provide relative risk importance values of parent nodes to the child node, which is the alternative approach to directly eliciting CPs as mentioned in the previous section. The input values to a static BBN, like Exhibit 1, are typically based on the current progress and knowledge at a point of time in the project timeline.

For a program portfolio assessment, it is important to understand how the projects influence each other throughout a portfolio. Interdependencies between projects may increase risk significantly and having a model that represents the dependencies becomes very beneficial. Exhibit 2 shows how the project interdependency can be modeled through the concept of Object-Oriented Bayesian Networks (OOBN) using the Hugin software. The node that is labeled Project 2 Network 1 is a node that encapsulates all selected risk factors from Project 2 as an object (or sub-model). Any risk node in the Project 2 BBN can be assigned as an output node and be properly linked to one or multiple risk nodes in the current network. In Exhibit 2, Project 2 Implementation Risk is connected to the current network. Although only one project dependency is shown in Exhibit 2, there can be additional encapsulated nodes depending on how many project interdependencies are present. With risk contribution from the Project 2 Implementation Risk node into the current Implementation Risk, it will require more conditional probability inputs for Implementation Risk. These project interdependent connections throughout the portfolio can be made as long as the overall network is not a cycle, since a BBN is a directed acyclic graphic model.

**Exhibit 2. BBN with Interdependency from a Second Network.**



Assessing project risk by BBN typically requires the project SMEs to provide marginal probability for the parent nodes and conditional probabilities for the child nodes. As the network becomes more complex with many input nodes and many more desired states, the determination of conditional probabilities by SMEs, even with the alternative approach of relative importance, is quickly beyond human’s cognitive capability. Therefore, a new technique is being investigated to generate probabilities with minimum inputs for determining the project risk. This alternative technique includes changing labelled nodes to interval nodes and choosing an appropriate continuous statistical distribution function. The distribution function serves as a means to generate marginal and conditional probabilities, which normally require direct inputs from SMEs. The term interval is equivalent to the term ranked, which is used elsewhere (Fenton & Neil, 2013).

In this alternative technique, a truncated normal distribution, with bounds of 0 and 1, generates the probabilities of each state of a node with given mean and variance. The interval of 0-0.5 represents the low risk state, while the interval of 0.5 -1 the high risk state. Only two intervals are chosen currently, but many intervals can be used as long as the set of intervals are continuous. For the discussed project risk, the mean value of the distribution would still be acquired from a SME. This is simply the high risk probability for all leaf nodes. For a child node, the mean value of the distribution would be calculated based on the relative risk importance and computed mean values of the parent nodes. The variance value that is required has been determined to be between 0.1 and 0.05 for leaf nodes and 0.01 for child nodes. It was found that these mean and variance values provide results with a maximum difference of 0.05 from the original probability values when comparing with those computed with direct inputs from the SMEs.

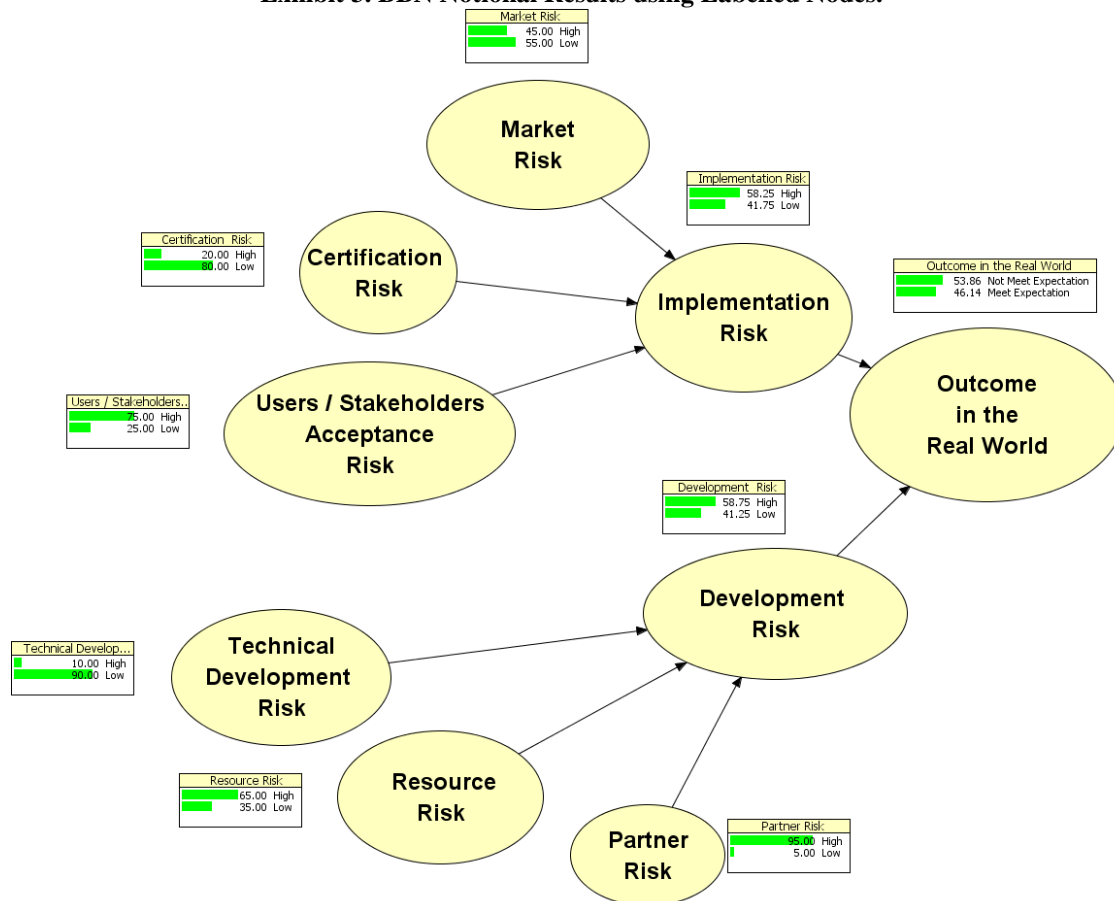
### BBN Risk Assessment Results

After the development of the risk BBN for each project, a set of analyses was performed to provide notional results of the risks. The projects risks can be represented both individually and together over the portfolio.

#### Single Project Risk Assessment Results

The notional results for a project risk are shown in Exhibit 3. For leaf nodes, the box next to each node displays the state probability inputs. The box next to the child nodes represent the computed probability values of each state. These probabilities indicate how likely each risk factor is to occur at each state. However, to understand how risks are dependent on variability and uncertainty in the project, a sensitivity analysis would be required. An evidence sensitivity analysis was performed on the project Outcome Risk node to show how sensitive the results of this Outcome Risk is to variations of each of the other risk factors in the current network. The sensitivity analysis results from Hugin are output to a tornado diagram as depicted in Exhibit 4.

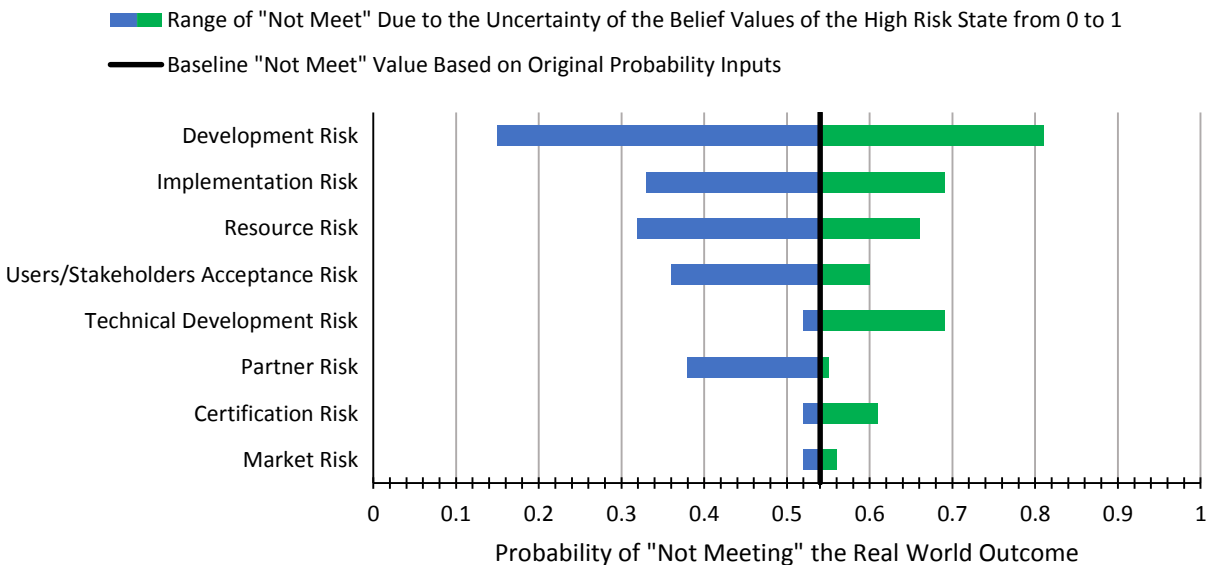
Exhibit 3. BBN Notional Results using Labelled Nodes.



Each of the bars on the tornado diagram is a simulated probability range for the project Outcome Risk, Not Meet state while varying one other risk node at a time. The extreme low value for a bar comes from applying evidence to the specified node with a probability value of 0 on the High state, reducing the amount of risk in the network and ultimately the Outcome Risk node. Similarly, the extreme high value of a bar is a result of a probability value of 1 on the High state. All of the values in between the two extremes are possible by providing a High probability value between 0 and 1 for the specified node. These ranges of values are deemed the uncertainty range determined by the belief value of the High risk state. The extreme values deviate from the baseline value of the Outcome Risk node, which originates from a Project Network with no evidence. The baseline probability value for Project 1 not meeting the Outcome is 0.54 and is shown by the black vertical line in Exhibit 4.

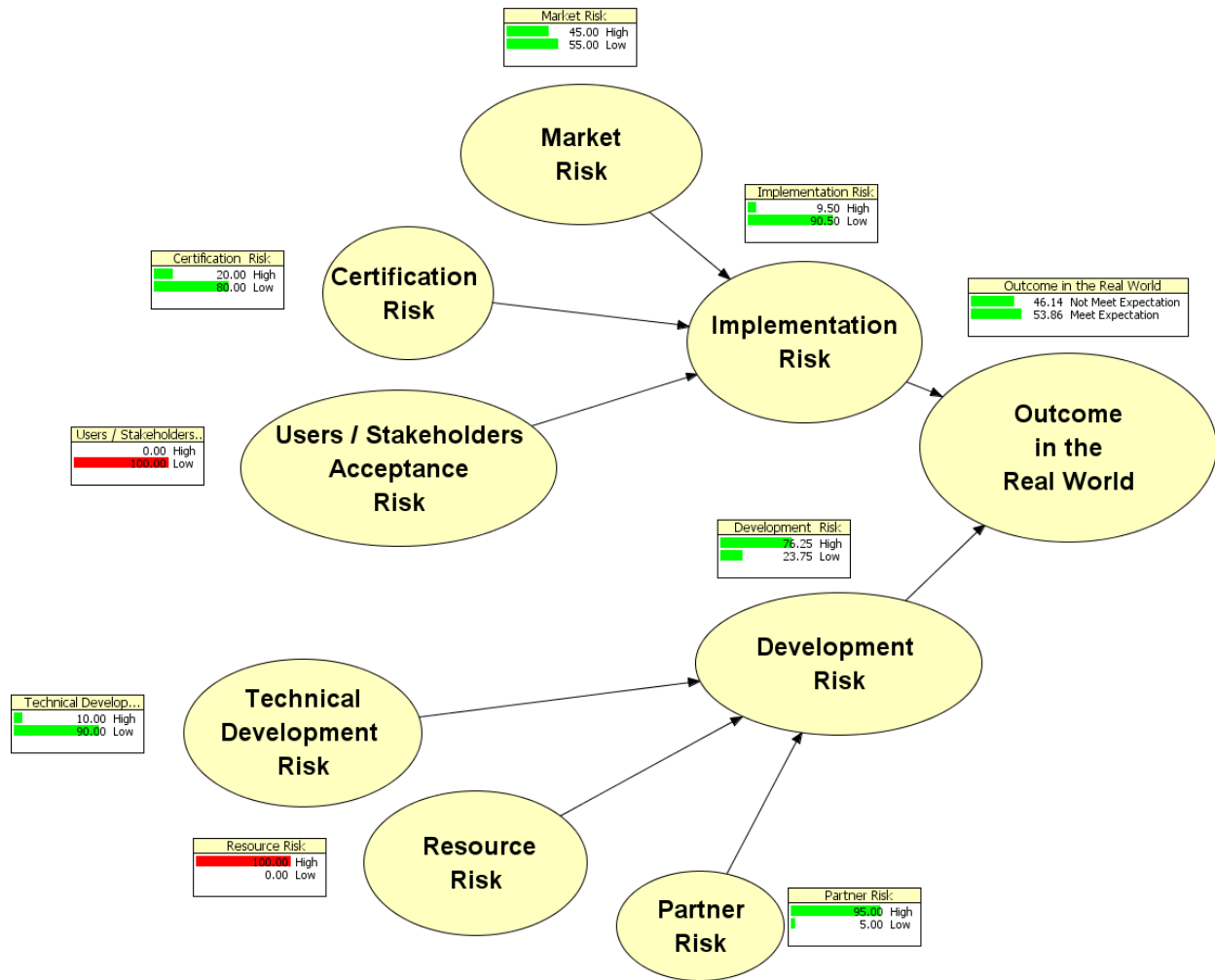
In the tornado diagram, the risks are in order of the level of influence on the inspected node. The larger the range of values the node/risk spans, the more influence it has on the node of interest. These results will allow the program/projects staff to focus their efforts to mitigate the risk with the greatest influence in order to have the greatest impact on the inspected node. Referring to Exhibit 4, the goal is to lower the probability of the Outcome Risk not meeting expectations. The blue part for each risk shows the possible beneficial outcome as the probability of Outcome Risk not meeting expectations decreases from the baseline probability value. In contrast, the green part of the tornado diagram shows the possibility of the probability of not meeting expectations increasing. The greatest payoff for a project risk mitigation would come from focusing on risk drivers that have the longer blue bars. For example, the choice of mitigating Partner Risk rather than Technical Development Risk would be logical because there is a greater opportunity for a beneficial outcome, assuming all other risks remain the same. This would then be the logical way to allocate efforts, even though Technical Development Risk has more overall influence than Partner Risk.

**Exhibit 4. BBN Sensitivity Results in a Tornado Diagram.**



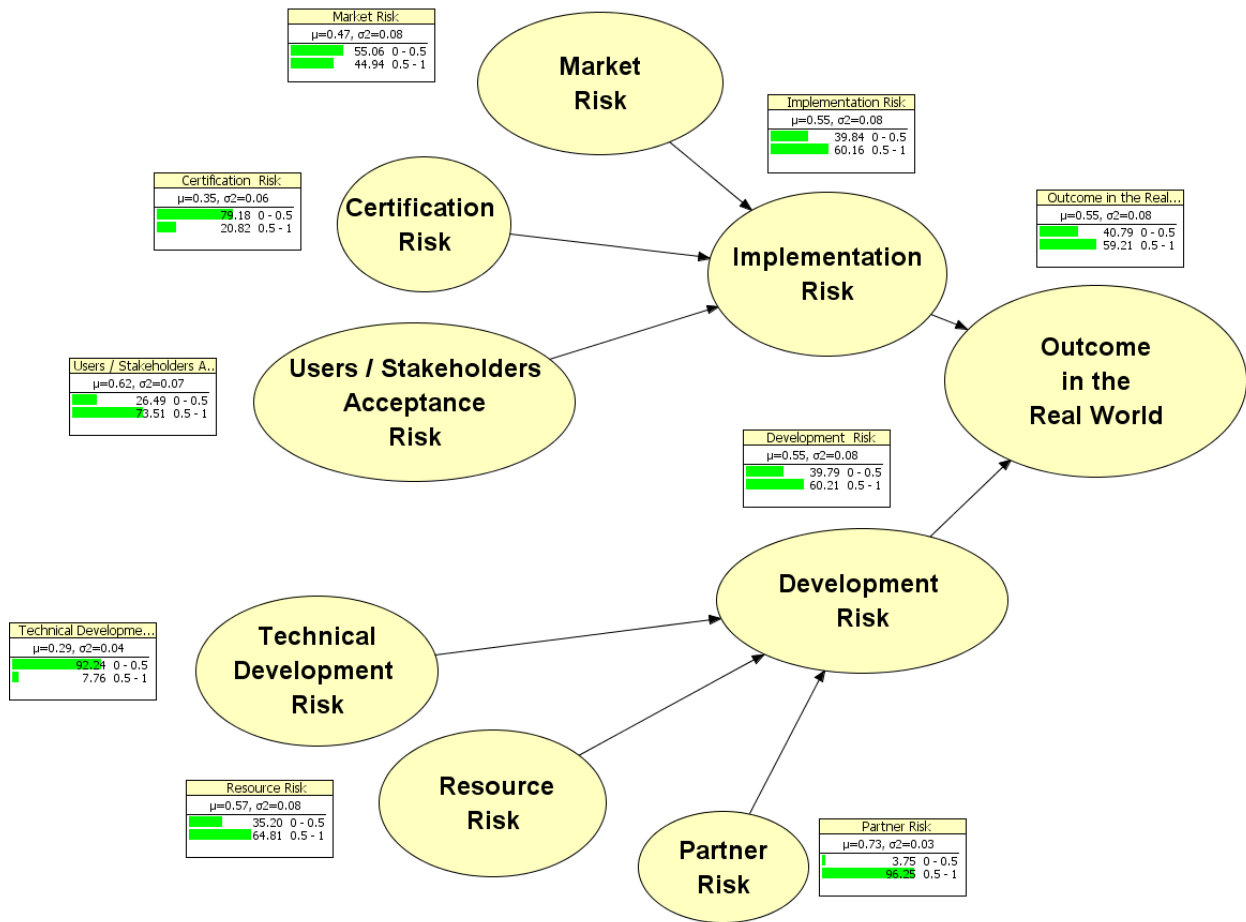
Another useful insight to project risk assessment comes from a what-if analysis. If new information is discovered or assumed after the network is established, the user can apply evidence on a node to create a what-if scenario. The risk probabilities of the entire network are then re-computed to show the impact of a certain updated belief value on all other risk factors in the network. The what-if can apply to both child and parent nodes. If a child node receives evidence, the probabilities will both forward and backward propagate. The what-if analysis is important to a project as the project eliminates risks, which will reduce the overall risk in the network. Multiple evidences can be asserted in the network at the same time to show new findings as illustrated in Exhibit 5. The difference of the original and updated probabilities can be found by comparing Exhibit 3 and Exhibit 5.

**Exhibit 5. BBN What/If Analysis.**



Finally, a preliminary run of the project risk BBN with interval nodes was conducted. The results are displayed in Exhibit 6. The comparison of Exhibit 3 and Exhibit 6 shows that the new technique of using interval nodes and truncated Normal Distribution can generate similar results. In addition, there are mean and variance values computed and displayed along with the probabilities of each of the states. It should be noted that these “new” mean and variance values are not equal to the original input, but are the mean and variance for the truncated normal distribution function with a very limited number of states (2) used. By adding additional states to each node, the “new” mean and variance will approach the input values, but the state intervals may be more difficult to interpret into descriptive words. At this moment the range allows for the verbal statement to be “Low” for the 0-0.5 range and “High” for the 0.5-1 range.

**Exhibit 6. BBN Notional Results using Interval Nodes.**

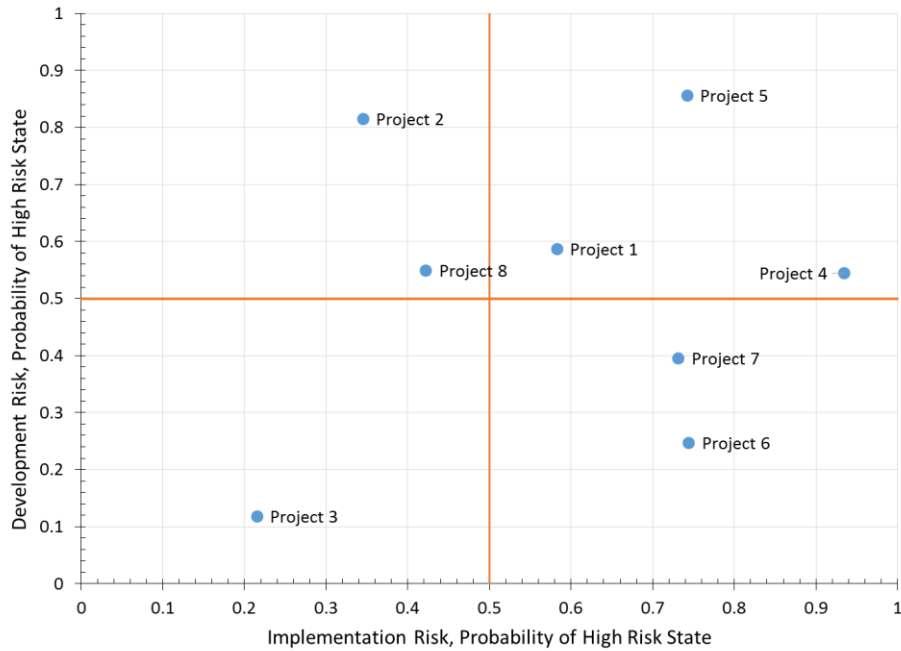


**Portfolio Risk Assessment Results**

At the program level, the risks of all projects in the portfolio should be investigated at the same time for comparison. Exhibit 7 provides this comparison through the use of a quad chart. In this case, the Implementation and Development Risks are plotted for an arbitrary set of 8 projects in the portfolio with notional numerical values. The idea is to have all projects in the portfolio fall into the bottom left quadrant, where both the probability of Implementation Risk and of Development Risk are low. The project risk BBN indicates when these two risks are minimized, a low probability for the Outcome in the Real World, Not Meet Expectations state is expected. In other words, there is a high probability that the project will be successful, meeting its expected outcome. Furthermore, the varied results in this quad chart provide a clear graphic on where all projects are in terms of their implementation and development risks. This will guide the management of the portfolio where attention is needed.

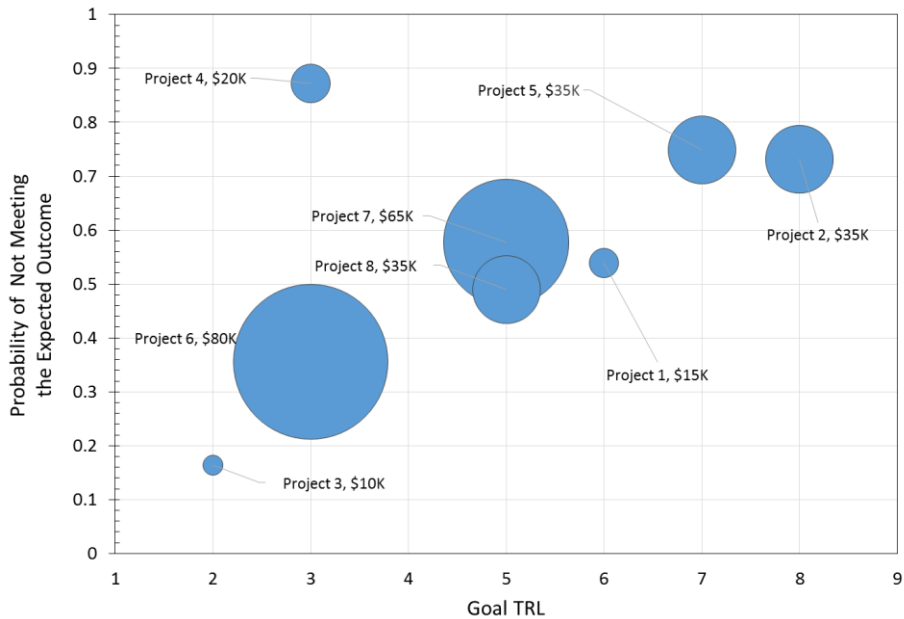


**Exhibit 7. Portfolio Quad Comparison Chart.**



As mentioned earlier, portfolio management considers various aspects of the project, such as benefit, cost and risk. As a preliminary effort for the program portfolio evaluation, the notional relationships between projects in 3 numeric-data dimensions of benefit, cost, and risk are plotted in a bubble chart. The bubble chart as presented in Exhibit 8 integrates the project risk BBN results, goal TRL or expected technology maturity, and cost or funding into one visual. A bubble chart can stimulate good communication and discussion. With constrained resources, program management must examine and compare these three key aspects across projects in the portfolio to attain a balanced portfolio and achieve the program goals.

**Exhibit 8. Portfolio Assessment from Various Perspectives.**



## Conclusions

This paper shows a BBN application for assessing NASA technology portfolio risks using labelled nodes with the option of making the BBN object-oriented representing interdependency between projects. With the current taxonomy and method, the BBN was limited to 9 identified risks with two states each. This simplification allows for the SMEs to grasp the BBN contents and provide marginal and conditional probabilities. A different type of BBN with interval nodes was also discussed. This technique simplifies the data collection phase by reducing the inputs needed from SMEs through the use of truncated normal distributions, which generate the marginal and conditional probabilities. The use of a sensitivity analysis, what-if analysis, quad comparison chart, and bubble chart can provide insights to the program office on the risk drivers and projects risk distribution, therefore, developing sound strategic and tactical risk management plans. The visualization of the risks provided from these analyses and charts stimulate important conversations between leadership and technology SMEs. Expanding the current, simplified BBN with more risk factors at finer granularity will allow for a better portfolio assessment in the future.

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