

## **FLIGHTDECK AUTOMATION PROBLEMS (FLAP) MODEL FOR SAFETY TECHNOLOGY PORTFOLIO ASSESSMENT**

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### **Abstract**

NASA's Aviation Safety Program (AvSP) develops and advances methodologies and technologies to improve air transportation safety. The Safety Analysis and Integration Team (SAIT) conducts a safety technology portfolio assessment (PA) to analyze the program content, to examine the benefits and risks of products with respect to program goals, and to support programmatic decision making. The PA process includes systematic identification of current and future safety risks as well as tracking several quantitative and qualitative metrics to ensure the program goals are addressing prominent safety risks accurately and effectively. One of the metrics within the PA process involves using quantitative aviation safety models to gauge the impact of the safety products. This paper demonstrates the role of aviation safety modeling by providing model outputs and evaluating a sample of portfolio elements using the Flightdeck Automation Problems (FLAP) model. The model enables not only ranking of the quantitative relative risk reduction impact of all portfolio elements, but also highlighting the areas with high potential impact via sensitivity and gap analyses in support of the program office. Although the model outputs are preliminary and products are notional, the process shown in this paper is essential to a comprehensive PA of NASA's safety products in the current program and future programs/projects.

### **Keywords**

Aviation safety, flightdeck automation, portfolio assessment

### **Introduction**

The Aviation Safety Program (AvSP) of NASA is a "focused" program to develop and advance methodologies and technologies (referred to as products) to improve air transportation safety. The AvSP is comprised of three research projects: Vehicle Systems Safety Technologies (VSST) Project, System-wide Safety Assurance Technologies (SSAT) Project, and Atmospheric Environment Safety Technologies (AEST) Project. These projects are focused on the AvSP's top ten technical challenges (TCs) in the areas of accident prevention and mitigation, aviation system monitoring, and modeling. As of 2013, there were 46 safety products being developed within these TCs in the AvSP technology portfolio. The safety products include innovative algorithms, tools, concepts and technologies for improving the overall safety of vehicles and systems operations in the future. To examine the benefits and risks of these products to the program goal, NASA Systems Analysis and Methods (SAM) group within the Safety Analysis and Integration Team (SAIT) of the AvSP led a portfolio assessment (PA) to support the Program Director's decision making. As part of the PA process, the SAIT employs both quantitative (modeling, programmatic and expected implementation costs) and qualitative (technical development risk, implementation risk, technical readiness level) metrics alike (Jones et al., 2010).

The paper is comprised of two sections. First, an overview of the FLIGHTDECK Automation Problems (FLAP) model, a high level systems-integrated model for examining safety issues due to automation, will be given. The FLAP model is one of a series of three aviation safety models that were developed to provide a quantitative safety metric to support the AvSP PA (Luxhøj et al., 2012). The other two models are the in-flight Loss-of-Control Accident Framework (LOCAF) model (Ancel et al., in press) and the runway safety (RUNSAFE) model (Green,

2014). The second section illustrates the modeling effort's contribution to the overall PA process using the FLAP model and a small set of sample notional products. The outcomes of the modeling effort presented in this paper are integrated into the overall technology PA process by combining other metrics of interest which provides valuable information for decision making and communication.

## **FLAP Model**

This section provides a brief outline of the FLAP model which was developed using Bayesian Belief Networks (BBNs) and modeled with the Hugin Software (Hugin Expert, 2013). A BBN is a directed acyclic graphical representation of a network which contains a set of nodes representing causal factors connected via links, designating the causal dependencies. The modeling process including the extensive literature review, modeling approach, boundary conditions, assumptions and data population is provided in detail in Ancel & Shih (2014) and Luxhøj et al. (2012). Recent studies identified vulnerabilities in pilot use of, and interaction with automation systems as well as manual flight operations related to pilot complacency and heavy reliance on automated systems (FAA, 2013a, 2013b). Consequently, the focus of the FLAP model is on the effects of increased complexity and reliance on automation systems in transport category aircraft accidents and incidents. Following subsections provide the node definitions and interactions throughout the model.

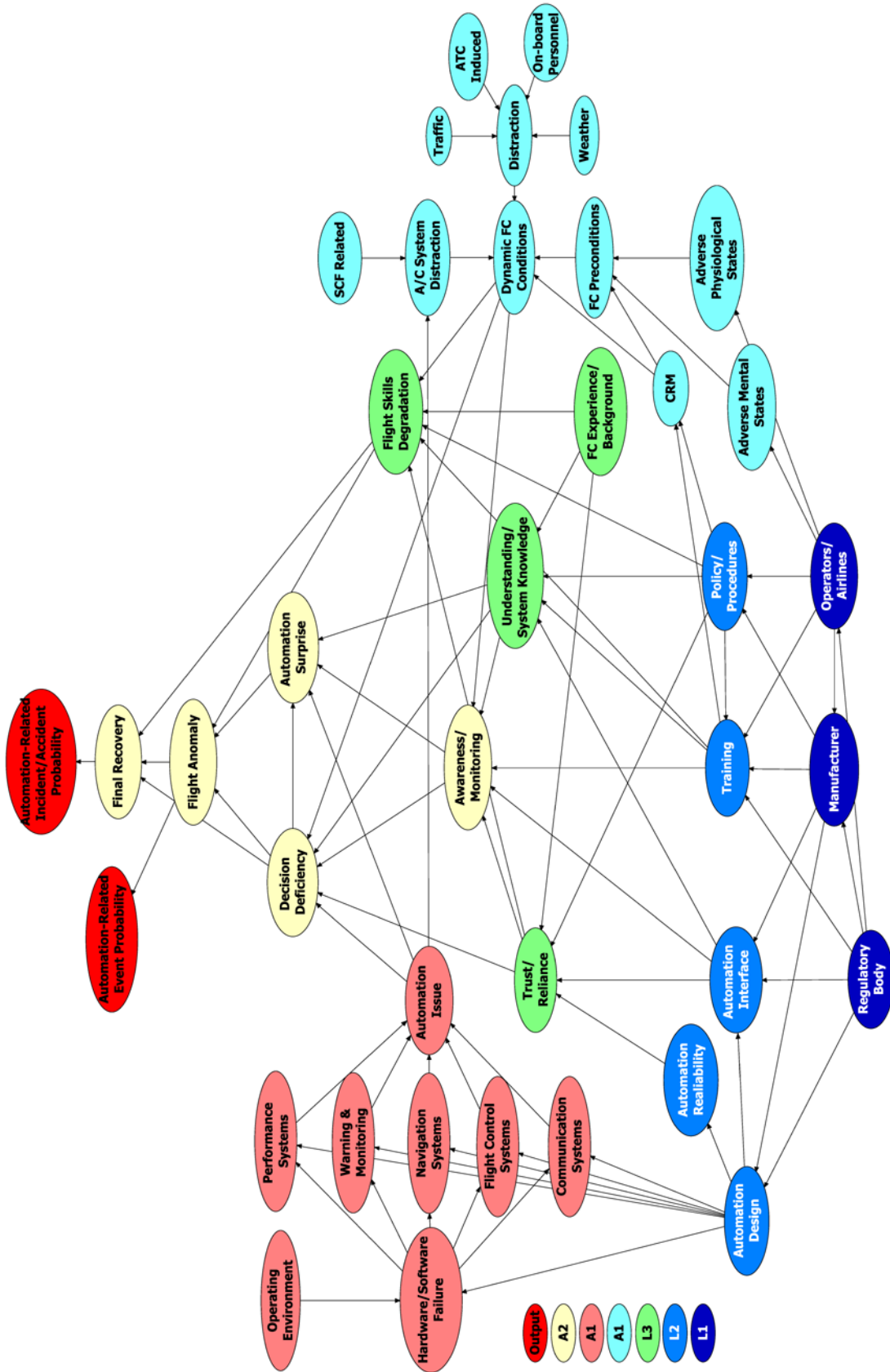
### **L1 Level: Latent Organizational Factors**

The bottom three nodes include the L1 level organizational latent factors such as the *Regulatory Body*, *Manufacturer*, and *Operators/Airlines* (Exhibit 1). The *Regulatory Body* node represents deficiencies within the regulatory process in both aircraft certification and flight standards of commercial transport operations (FAA, 2013). The *Regulatory Body* node is linked to five other nodes: *Manufacturer*, *Training*, *Operators/Airlines*, *Automation Design*, and *Automation Interface*. The *Manufacturer* node represents large aircraft manufacturers as well as those companies which manufacture automation systems or avionic equipment. The node covers deficiencies in automation design philosophy and approach, over-automation, and standardization and also cultural diversity that could eventually lead to human factors issues (FAA, 1996). The *Manufacturer* node influences characteristics of *Automation Design*, *Automation Interface*, and also affects *Training* and *Policy/Procedures* nodes (FAA, 1996). The *Operators/Airlines* node delineates the organizational aspects of corporate airlines as causal or contributing factors in automation accidents/incidents. The organizational deficiencies can trickle down and materialize as *Training* (Parasuraman & Riley, 1997) or *Policy/Procedure* (FAA, 1996, p. 65) issues. Also, lack of adequate supervision and management guidance can result in *Adverse Physiological or Mental States* in flightcrews. Finally, links between the *Operator/Airlines* and *Manufacturer* nodes represent unrealistic airline expectations or requirements imposed on the manufacturers, driven by economic motivation and operational efficiency.

### **L2 Level: Latent Underlying Factors**

The second latent layer includes underlying factors affecting both automation systems and airline operations. These factors are *Training*, *Policy/Procedures*, *Automation Design*, *Automation Reliability*, and *Automation Interface*. The *Training* node includes deficiencies associated with inadequate training, generally associated with the common practice of "on-the-job" training (Orlady, Orlady, & Lauber, 1999; Sarter, Woods, & Billings, 1997). This node is connected to *Flight Skills Degradation* (designates the basic stick & rudder training), *Awareness/Monitoring*, *Understanding/System Knowledge*, and *Crew Resource Management (CRM)* nodes, representing respective training constituents. The *Policy/Procedures* node covers deficiencies associated with inappropriate flightcrew guidance. For instance, procedures inconsistent with manufacturer recommendations, or incorrect modification of procedures for economic or fuel saving reasons are examples of issues covered in this node (FAA, 1996, 2013). The *Policy/Procedures* node is connected to the *Flight Skills Degradation*, *Trust/Reliance*, *Understanding/System Knowledge*, *Training*, and *CRM* nodes, representing cases of inadequate operator guidance on automation usage and aircraft control. The *Automation Design* node encompasses issues within the automation system design process including system, hardware, and software designs from preliminary phase to flight hardware including assumptions, requirements, testing/debugging, implementation, verification and validation, quality assurance, etc. The *Automation Design* node is connected to all the downstream nodes in the automation related A1 level nodes since improper planning and execution of automation requirements can result in failures and unexpected behavior throughout the system. The *Automation Reliability* node primarily affects the flightcrew's perception where highly reliable automation systems inherently increase reliance on automation. However, deficiencies found in automation design could potentially result in a higher number of failures, which in turn, affects the perceived system reliability by pilots (FAA, 1996), therefore connecting the *Automation Reliability* node to the *Trust/Reliance* node.

Exhibit 1. FLAP Model



The final node in this level is the *Automation Interface*. The automation interface deficiencies are linked to degraded flightcrew situational awareness, pilot saturation and/or confusion (FAA, 1996). This node contains issues related to determination of the characteristics of visual, auditory, and tactile alerting systems as well as alert categorization issues (Ancel & Shih, 2014; Veitengruber, 1978). The *Automation Interface* node is linked to three causal factors; *Trust/Reliance*, *Awareness/Monitoring* (Sarter et al., 1997), and *Understanding/System Knowledge* (FAA, 2013) as shown in Exhibit 1.

### **L3 Level: Latent Flightcrew Factors**

The third level of latent causal factors consists of *Flightcrew (FC) Experience/Background*, *Trust/Reliance*, *Flight Skill Degradation*, and *Understanding/System Knowledge* nodes. The *FC Experience/Background* node distinguishes the varying flightcrew personal factors including experience level (seasoned vs. young pilots), training background (military vs. civil aviation), and operational environment. The *Flightcrew Experience/Background* node is linked to *Flight Skills Degradation*, *Understanding/System Knowledge*, and flightcrew *Trust/Reliance* nodes (Parasuraman & Riley, 1997; Sarter et al., 1997). The *Trust/Reliance* node includes flightcrew complacency and inappropriate confidence level assigned to autoflight systems. The *Trust/Reliance* node is a parent causal node for three nodes; namely, *Awareness/Monitoring* (Sarter et al., 1997), *Flight Skills Degradation*, and *Decision Deficiency* (Parasuraman & Riley, 1997). The *Flight Skills Degradation* node contains erosion of manual flight skills (e.g. basic stick-and-rudder capabilities, instrument scan, etc.) due to continuous operation of autoflight systems and lack of practice (FAA, 2013a; Or lady et al., 1999). The *Flight Skills Degradation* node is connected to both the *Flight Anomaly* and *Final Recovery* nodes to represent the cases where degraded skills can cause flight anomalies or unsuccessful flight recovery. The *Understanding/System Knowledge* node refers to issues related to flightcrew knowledge of aircraft systems or presence of gaps in their mental model of the system (e.g. autoflight modes, flight management computer, system couplings). This node is connected to the *Decision Deficiency* node since issues with pilot *Understanding/System Knowledge* is one of the primary sources of errors captured in the *Decision Deficiency* node. Pilot understanding is also linked to *Automation Surprise* and flightcrew *System Awareness/Monitoring* nodes (FAA, 1996).

### **A1 Level: Active Factors/Automation Triggers**

The first active layer includes the *Operating Environment* node, the *Hardware/Software Failure* node, five automation function nodes, and the *Automation Issue* node. The *Operating Environment* node provides external causes that potentially affect the operation of hardware/software (HW/SW) either by disrupting sensor outputs or by damaging aircraft systems directly. The *HW/SW Failure* node includes all glitches and malfunctions of the systems that were not anticipated by the designers, including malfunctions of antennas, sensors, etc. that provide information to the automation systems downstream nodes. The *Performance Systems* node includes issues associated with the performance function of the flight management system (FMS) (e.g., weight and balance, fuel weight, take off reference data, etc.) (Walter, 2001). The *Warning & Monitoring Systems* include automated warning systems such as aircraft configuration, monitoring of aircraft systems and presence of environmental threats due to both faulty design and HW/SW failure (Or lady et al., 1999). The *Navigation Systems* node covers the components and systems used in navigation including all precision approach system components. The *Flight Control Systems* node encompasses all the systems involved in automatic flight within the FMS and implementation of inputs via flight control surfaces. Finally, the *Communication Systems* node includes data link and surveillance systems. Systems like the Aircraft Communications Addressing and Reporting System, telemetry, communication radios, satellite links, telemetry, and ADS-B/C are included in this node (Walter, 2001). The *Automation Issue* node provides the probability of an automation system exhibiting malfunction or failure, stemming from any of the five functional systems described above. Besides failures, inconsistent or unexpected automation system behavior itself can also be the root of flightcrew confusion or decision deficiency and it is represented within the *Automation Issue* node. Unexpected automation behavior which is captured in the *Automation Issue* node is linked to *Automation Surprise* and *A/C System Distraction* nodes (Sarter et al., 1997).

### **A1 Level: Active Factors/Flightcrew Triggers**

This level considers external and internal sources of distraction as well as psychological and physiological aspects of FC performance, in an approach similar to Reason's model of accident causation. The flightcrew triggers level is divided into two sections: FC active factors prior to the flight, and FC active factors during the flight.

**Flightcrew Active Factors – Pre-Flight.** The causal factors in this section help determine the FC readiness before the flight takes place. The *Adverse Physiological States* node includes physical fatigue/lack of sleep, medical illness,

and physiological incapacitation in general. The node is connected to the *FC Preconditions* node and *Dynamic FC Conditions* node, which then connects to the *Awareness/Monitoring* node that is greatly affected by the presence of physiological issues. The *Adverse Mental States* node includes complacency, distraction, *get-home-itis*, misplaced motivation, mental tiredness, distraction, confusion, depression, and/or alcoholism. The *Crew Resource Management (CRM)* node includes deficiencies such as communication skills and coordination that take place among the flightcrew as well as between other entities before, during, and after the flight (Ancel & Shih, 2012). The *CRM* node is linked to both *FC Preconditions* and *Dynamic FC Conditions*, indicating issues associated with the pre-flight briefing as well as in-flight communication and coordination, respectively. The *Flightcrew Preconditions* node is an aggregation node that considers flightcrew adverse physiological and mental states as well as CRM deficiencies and determines the fitness of the flightcrew for the upcoming flight. This node is linked to the *Dynamic Flightcrew Conditions* node, providing a baseline which is then updated by considering the presence of distractions throughout the flight.

**Flightcrew Active Factors – In-flight.** This section provides the model with the updated FC conditions that are present during the flight by considering several sources of distractions. These distractions are divided into two categories; aircraft system related distractions and general distractions. The *Aircraft (A/C) Systems Related Distractions* node provides the probability of flightcrew to be distracted by the presence of a) *Automation Issues* and b) *System Component Failure SCF*. Distractions stemming from troubleshooting autoflight system anomalies/behavior as well as reprogramming the FMS are captured in this node. The *Distractions* node takes into consideration all other major sources of mental disturbance that potentially result in fixation or absorption. The causal factors considered are fourfold; *Traffic, ATC, On-board Personnel, and Weather*. The presence of traffic, frequent changes in the flight trajectory, cabin crew interference, presence of icing, fog/visibility issues, wind, etc. were identified as sources of distraction (CAST, 2008). The only output of the A1 Level is the *Dynamic FC Conditions* node which is connected to *Flight Skills Degradation, Decision Deficiency, and Awareness/Monitoring* nodes.

#### **A2 Level: Active Factors/Mishap**

The A2 active failure level includes nodes associated with flightcrew *System Awareness/Monitoring, Decision Deficiency, and Automation Surprise* which lead to *Flight Anomaly, and Final Recovery*. The *Awareness/Monitoring* node comprises insufficient system awareness, defined as the inability of a supervisor to track and anticipate the behavior of a) the automation system variables and controls, b) aircraft state and flight parameters, and c) operating environment (Sarter et al., 1997). This node is linked to the *Decision Deficiency* and *Automation Surprises* nodes (Sarter et al., 1997). The *Decision Deficiency* node includes all cognitive errors made by the flightcrew such as mode selection/confusion error, FMS programming, checklist/procedural errors, misdiagnosis of faults, etc. The *Decision Deficiency* node influences three nodes; *Automation Surprise, Flight Anomaly, and Final Recovery*. The *Automation Surprise* node defines cases where the operator is surprised by the automation systems, unable to comprehend its current behavior or estimate future occurrences. The presence of automation surprises is one of the prominent causal factors for the *Flight Anomaly* node, in which the flightcrew recognizes that the aircraft is outside its flight envelope or air traffic control (ATC) interventions. The *Flight Anomaly* node designates any departure from the intended flight plan or safe flight envelope that qualifies as an incident (e.g. deviation in altitude, speed, position, etc.) which may potentially develop into stall, loss-of-control, over-speed, loss of separation, controlled flight into terrain, etc. The *Final Recovery* node refers to the ability of the flightcrew to recover from an abnormal flight condition defined in the *Flight Anomaly* node. Given that the model simulates an accident and incident environment, the *Final Recovery* node plays a decisive role in whether the incident turns into an accident (Ancel & Shih, 2014).

#### **FLAP Model Preliminary Results**

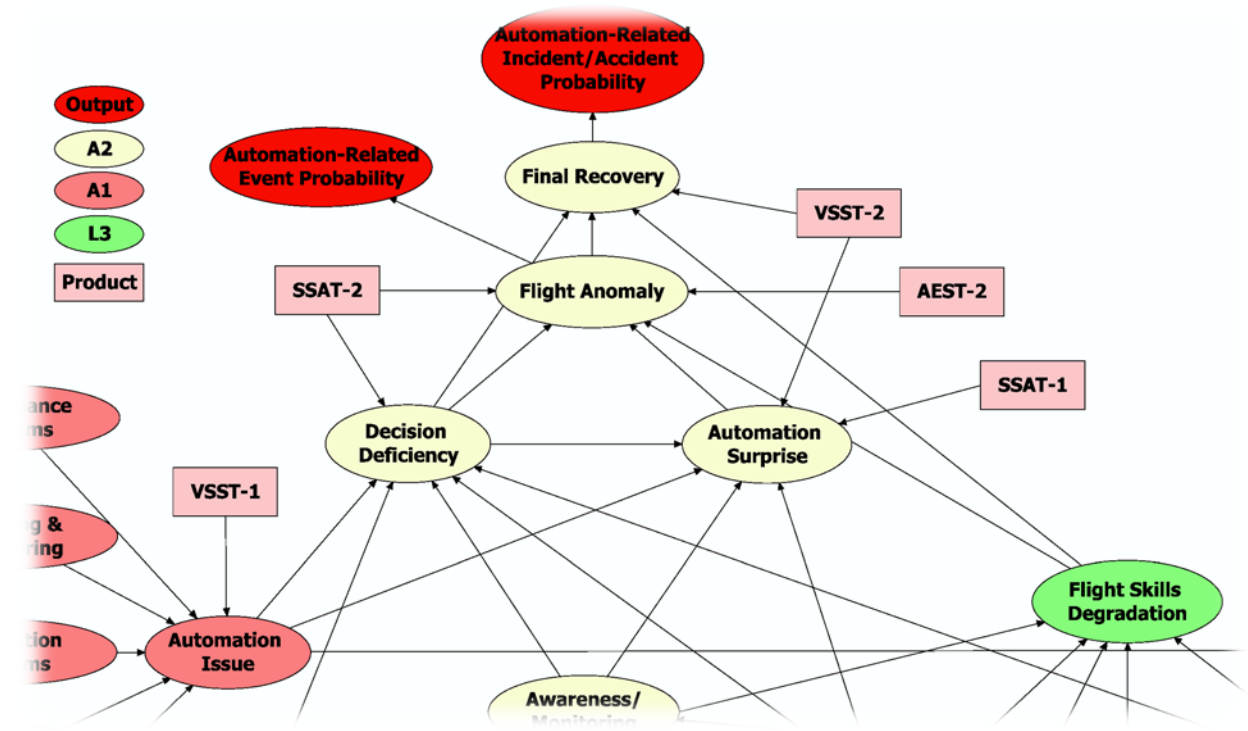
As shown in Exhibit 1, the model output nodes are *Automation-Related Event Probability* and *Automation-Related Incident/Accident Probability*. The *Automation-Related Event Probability* node reflects the ratio of automation-related events among all accidents and incidents. The uncalibrated preliminary results of the FLAP model indicate that around 78% of all U.S. based accidents and incidents in today's commercial aircraft are related to pilots' automation usage. The remaining 22% of these events are not tied to automation. The other output node, *Automation-Related Incident/Accident Probability*, provides the accident to incident ratio using the *Final Recovery* node. The preliminary results indicate that that around 2.7% of all automation related events would result in an accident, and the remaining 97.3% of them will be considered as incidents.

Besides the output nodes, all other causal factors nodes can all be accessed individually. The preliminary results show that around 80% of all events involve flightcrew *Decision Deficiencies*, whereas 72% of the cases were tied to failure in situational awareness (*Awareness/Monitoring* node). The *Flight Skills Degradation* node plays a role in around 70% of all the cases and the *Automation Issue* node which includes malfunctions and unexpected automation behavior is present in 50% of the cases. It is important to note that these values do not represent the final values of the modeling effort, nor are they intended to be used in flightdeck automation, policy or decision making processes. The next section provides an overview on how the model data is employed.

### AvSP Product Insertion Process

The technology PA is initiated with the insertion of methodologies and technologies (or products) developed within the AvSP projects onto the baseline FLAP model. The product placements and assessments are performed by subject matter experts (SMEs). First, the SMEs review all provided documentation and descriptions regarding the products. Next, they consider the products' primary and secondary mitigation effects and link the products to the affected causal factor nodes. Finally, the SMEs provide updated conditional probabilities for each node considering the products' impact on the risk reduction. Following the product insertion process, the location of the products and the model construct are verified by product developers and external expert panels to ensure proper placement, as part of the verification process. The rectangular nodes shown in Exhibit 2 represent notional products and the arrows designate the affected nodes only within the top part of the model. The five products shown in the exhibit are used as examples in the upcoming sections to demonstrate the PA process.

Exhibit 2. Notional Product Insertion



### Technology Portfolio Assessment Process

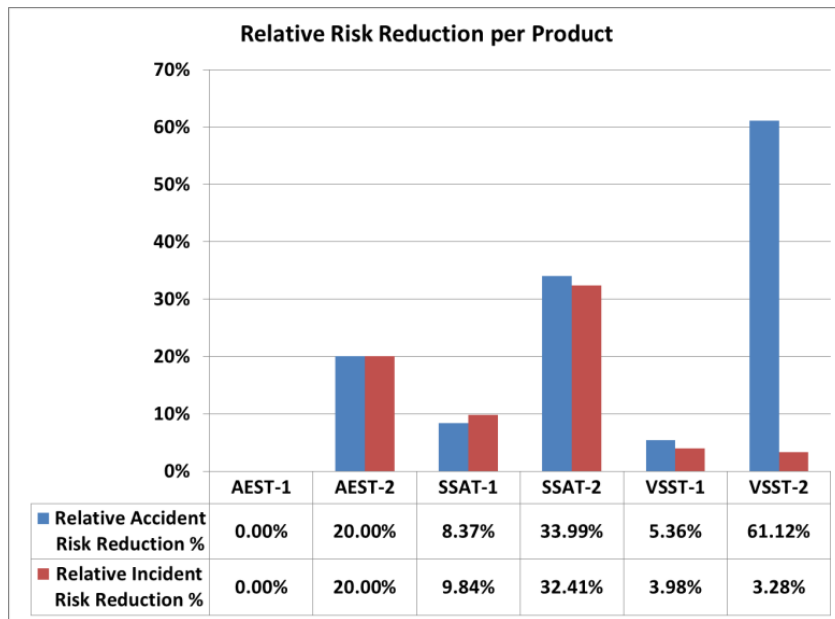
The main purpose of developing high-level, system-integrated aviation safety models is to provide a quantitative metric to support AvSP management in technology PA. As previously discussed, AvSP portfolio elements are evaluated against several metrics including the portfolio's expected impact on historic and future safety risks in Part 121, 135 and 91 operations as well as NASA's high-level goals and objectives (i.e. National aeronautics R&D programs and the JPDO safety objectives). Besides portfolio elements' impact on safety risks, their technology readiness level (TRL), technical development risk (TDR), implementation risk (IR), cost (both expected implementation cost and programmatic cost) are also within the scope of the SAIT PA process (Jones et al. 2013). Although demonstrated within the AvSP PA process, the modeling effort's contribution described in the next sub-

sections could be used by future NASA programs/projects (e.g. the new Airspace Operations and Safety Program, AOSP, or its Safe Autonomous Systems Operations Project, SASO) as well as other organizations (e.g. FAA NextGen). Following sections highlight the model results including relative risk reduction, sensitivity analysis and gap analysis, which are detailed in the following sub-sections.

**Relative Risk Reduction**

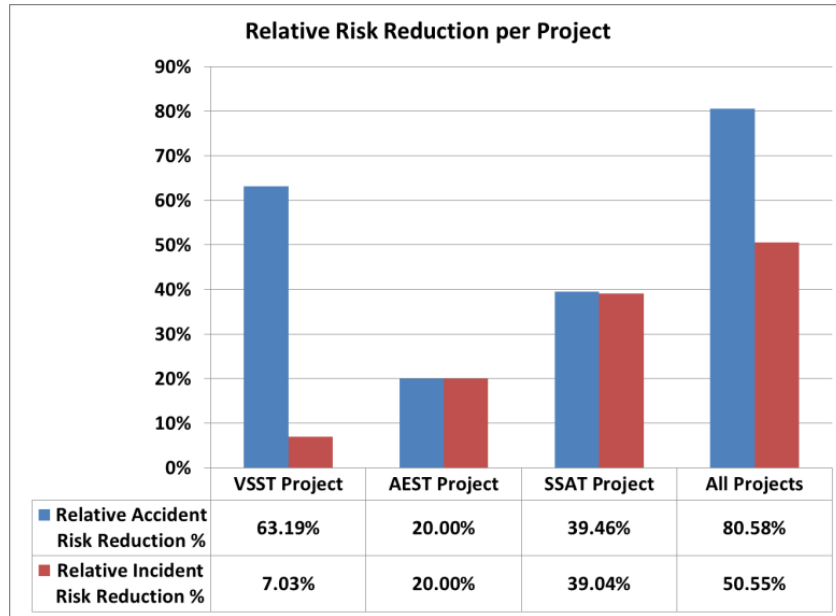
The BBN model is a probabilistic model. The probability of the occurrence of any causal variable (represented by a node) can be computed individually. This computation is typically performed for the end node (output node) in the network. For the AvSP models, the relative risk reduction of a given causal variable is a measure calculated by dividing the absolute risk reduction by the probability value from the baseline model. The absolute risk reduction is defined as the difference between the probability value from the baseline model and that from the model with inserted products. The relative risk reduction is a quantitative measure and very beneficial because it indicates the mitigation impact of the safety products. The relative risk reduction can be calculated to examine the individual contribution of a safety product or the combined contribution of a group of products (such as products of each TC or of each project) in reducing the target risk. For the FLAP model, both *Automation Related Accident Rate* node and *Automation Related Incident Rate* node are the outputs of interest. Therefore, the relative risk reductions on automation-related accident and incident of each notional product were computed and are shown in Exhibit 3. Similarly, the relative risk reductions on automation-related accident and incident per each project and all projects are presented in Exhibit 4.

**Exhibit 3.** Notional Relative Risk Reduction per Product



The exhibits suggest that, based on their placements, the products may have different accident and incident reduction impacts (e.g. VSST-2 has the greatest impact on accident risk reduction among all products, whereas AEST-2 has equal impact on both accident and incident risk reduction). Note that the values below are generated by randomly assigned percentage impacts by product for illustration purposes. However, the actual product impact assessment is developed from the SME inputs by considering the status of the parent nodes as well as the presence of multiple products on the same node. It should also be noted that the risk reduction impact in the BBN propagates from the node at which the product is inserted to all downstream causal factor nodes. Because of the use of Bayesian calculus, risk reduction impacts computed from different groups of multiple products are not additive. For instance, the sum of individually-calculated products impact from three projects (i.e., 122.65%) is not equal to the integral products impact of all projects (i.e., 80.58%) as shown in Exhibit 4.

**Exhibit 4.** Notional Relative Risk Reduction per Project



**Sensitivity Analysis**

The sensitivity analysis capability of the Hugin Software helps modelers and decision makers rank the causal factors for a highly concerned risk variable in the model. The software generates sensitivity values of all the network nodes with respect to an identified *hypothesis variable* in the baseline model. From a PA perspective, the amelioration of a sensitive causal factor (node) will have more impact in reducing the probability of the *hypothesis variable* when compared to a less sensitive node. In the FLAP model, the *Flight Anomaly* node is designated as the hypothesis variable since reduction of such anomalies inherently limits automation related accident and incidents. Note that the sensitivity values are not synonymous to probability values presented in the earlier sections.

**Exhibit 5.** Normalized Causal Factor Sensitivity with respect to *Flight Anomaly* node

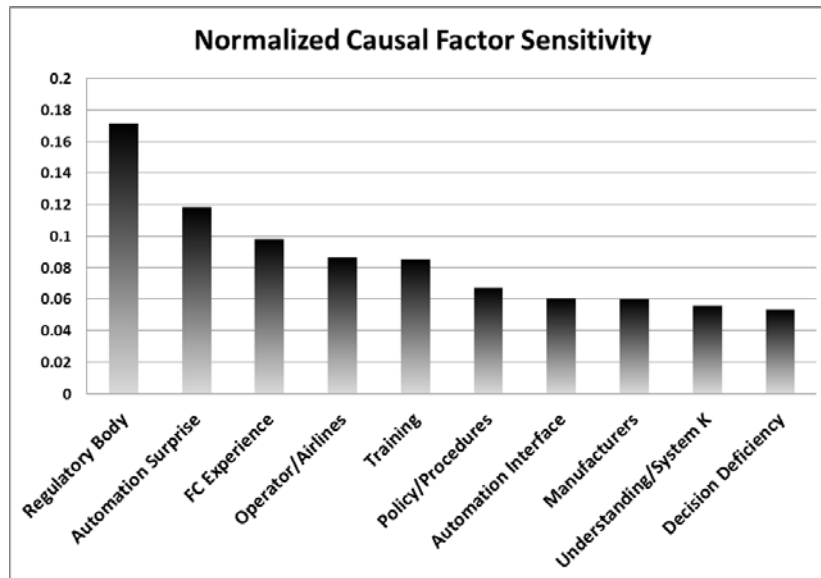




Exhibit 5 shows the top ten causal factor sensitivity values normalized against that of the *Flight Anomaly* node. The model suggests that the *Regulatory Body* node is the most sensitive node and can greatly impact the probability of a flight anomaly, and therefore, automation related mishaps. According to the preliminary results, the *Regulatory Body* node is a factor in only 23% of all accidents and incidents, however, due to its high influence on all downstream nodes (e.g. *Manufacturer, Operator/Airline, Automation Design*, etc.), it was determined to be the most sensitive node in affecting the outcome of the model. Also, the *Automation Surprise* node (with 65% probability) was identified as the second most sensitive node. Given its high sensitivity and probability, products that can reduce the probability of *Automation Issues* or its parent nodes inherently have a significant impact in lowering automation related accidents and incidents. The sensitivity ranking and individual causal factor occurrence probabilities present valuable information to decision makers from a program management point of view. Consequently, the information extracted from the model alone can be used to develop a balanced AvSP technology portfolio.

**Portfolio Gap Analysis**

Another outcome of accident models for technology assessment process is the ability to perform portfolio gap analysis. Following the insertion of AvSP products, the model nodes and notional products shown in Exhibit 2 are placed on a gap analysis matrix (Exhibit 6).

**Exhibit 6.** Notional Gap Analysis

Causal Node Name	AEST Products (2)		SSAT Products (2)		VSST Products (2)	
	AEST-1	AEST-2	SSAT-1	SSAT-2	VSST-1	VSST-2
<b>Final Recovery</b>						X
<b>Flight Anomaly</b>		X		X		
<b>Decision Deficiency</b>				X		
<b>Automation Surprises</b>			X			X
<b>Automation Issue</b>					X	
<b>Flight Skills Degradation</b>						

The matrix highlights the causal factors that are not addressed by the current AvSP portfolio (e.g. *Flight Skills Degradation* node), or portfolio elements that don't have an impact on the modeled incident/accident (e.g. AEST-1 product). It also can help identify cases where too many portfolio elements are applied to a causal factor area that may not be the high sensitive or high probability accident and incident contributor. This information, along with the node sensitivity data given above provide decision makers with valuable knowledge in identifying novel technologies or areas in need of work and balancing the portfolio elements.

**Conclusions**

A well-balanced portfolio is crucial to program managers in order to achieve the project's envisioned goals. NASA's AvSP technology portfolio is assessed by SAIT using several qualitative and quantitative metrics. This paper illustrates one of the metrics that uses aviation safety models in BBN to gauge and rank the products' impacts on reducing a predetermined safety risk. Besides the product impacts, the modeling effort alone also allows decision makers to identify the critical and high probability causal factors that affect the occurrence of an incident/accident. Coupled with the other metrics like cost, implementation risk, readiness level considered in the PA process, the modeling effort provides valuable information to program managers not only for AvSP but also potentially for other projects/programs within NASA as well as other organizations.

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