2020

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Original Publication Citation

Handley, H., & Heimerdinger, D. (2020). The impact of human assurance on satellite operations. In U. Tatar, A. V. Gheorghe, O. F. Keskin & J. Muylaert (Eds.), *Space infrastructures: From risk to resilience governance* (pp. 153-165). IOS Press. https://doi.org/10.3233/NICSP200017

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Space Infrastructures: From Risk to Resilience Governance
U. Tatar et al. (Eds.)
IOS Press, 2020

doi:10.3233/NICSP200017

The Impact of Human Assurance on Satellite Operations

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Abstract. Mission assurance is a method to guarantee mission success against a known set of risks; mission assurance is generally represented as a probability against a threshold of acceptable performance. Human assurance can be considered as the likelihood of acceptable operator performance given a set of conditions that include the operator, the system, and the environment. Standard mission assurance models tend to assume a qualified crew, but do not include other aspects of the internal or external environment that may impact the reliability of the human operator. A human assurance model can be created that allows the exploration of the variability in operator performance due to the likelihood of different risks. An example human assurance model has been created for the detection of adverse trending satellite data and the need to modify the existing mission schedule to address the satellite emergency. The model leverages the Human Viewpoint framework to capture the human-focused data within the mission context. From this data, sources of risk can be identified for the socio-technical system and a risk framework developed. The resulting risk model allows exploration of the characteristics of both the operator and the operating environment, as well as the impact of organizational mitigations, on the likelihood that the socio-technical system will meet mission assurance thresholds. The method provided can be used to identify the limitations of human system performance against the established criteria.

Keywords. Human Assurance, human viewpoint, socio-technical analysis, risk model

1. Introduction

Mission assurance is measure that indicates whether a mission will be successful given a set of risks. Mission assurance is "a process to ensure that assigned tasks or duties can be performed in accordance with the intended purpose or plan" [1]. Mission assurance is a sort of guarantee that the mission will be successful with a given set of risks; high mission assurance is defined to mean functionally correct and satisfactory performance within the predicted risk framework. Mission engineering focuses on the integration and interoperability of all component systems, providing an end-to end gap analysis of mission threads to provide mission assurance evaluations [2]. It ensures that all required capabilities and supporting infrastructures are available as needed. System assurance is defined as the probability that the system will perform its intended function under the

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specified operating conditions. This can be extended to include the human operator; human assurance can be considered the probability of acceptable operator performance given a set of conditions that may include the operator, the system, and the environment. However, the impact that the human operator has on the systems that compose the mission thread are key to the mission success; mission capabilities consist of the interactions of the operators with the systems [3]. Mission assurance thresholds assume a qualified crew, but do not necessarily include other aspects of the internal and external environment that may impact the performance of the human operator. A guarantee of performance for socio-technical systems should include characteristics of the operator in the mission context as a separate component of mission assurance.

The objective of the human assurance evaluation is to ensure acceptable human performance for operators interacting with systems to support mission success. Human assurance thresholds within a mission can be evaluated by leveraging human-focused data and applying a risk-based approach. The Human Viewpoint can be used to capture different aspects of the human operators as part of a socio-technical system analysis and applied to evaluate aspects of different mission threads. The Human View models were designed collect and organize human-focused data in order to understand the way that humans interact with other elements of the system [4]. These models capture information on the tasks that have been allocated to system operators, what information is required to complete the tasks, and level of proficiency that is needed in different roles [5]. Diagrams that provide workflow analyses can be used to capture the human assurance mission thread, identify where human operators impact the mission risks, and provide a model to explore the impact of these risks on overall mission assurance. The model can also be used to evaluate mitigations to improve the human assurance to meet expected criteria.

This chapter presents an example of the human assurance method applied to a satellite operations mission thread. Once a satellite is launched into its orbit, it must be in frequent contact for satellite management and data collection, i.e., satellite state-of-health must be monitored, and commands provided. Satellite operations consists of the three operational nodes plus the satellite as shown in Figure 1: The Mission Operations Center (MOC), the Network Operations Center (NOC), and the Ground Station (GS). The MOC creates payload requests for different utilizations of the sensors and communication systems that are onboard the satellite to acquire, process and distribute data. The NOC coordinates the demand from all sources for the satellite capabilities; these managers control and broker the usage of the satellite networks. The GS communicate and control the individual satellites providing 24/7 monitoring and management the satellites.

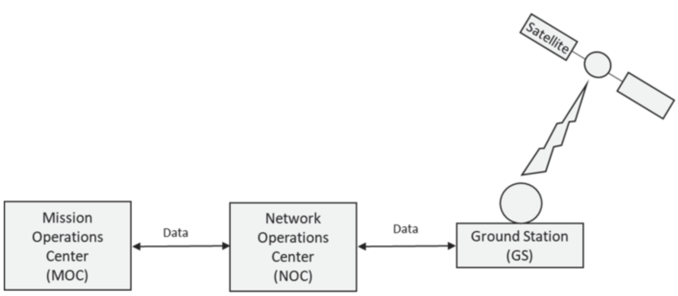

Figure 1. Satellite Operations

2. Methodology

The method to develop the human assurance model consists of three steps: capture the pertinent human-focused data for the mission context, perform a socio-technical analysis to identify the points of uncertainty, and develop the risk model to evaluate the human assurance [6].

2.1. Human-Focused Data

The Human Viewpoint was designed to identify the human limitations and constraints of a sociotechnical system in order to support system architecture development. The Human View models capture different sets of data that aid in understanding multiple aspects of the human component of a system. These composite views include details of human tasking, role descriptions and training gaps in order to define requirements for the system interfaces and human operators [7]. The Human Viewpoint consists of a set of seven integrated products that can be used to support the integration of humans, organization, technology, and information. A summary of the Human Views is shown in Table 1.

Table 1. The Human Views

Human View	Description
Concept	Representation of the high-level human-system entities and relationships for the problem domain
Constraints	Repository for different sets of human limitations
Tasks	Description the human-specific activities
Roles	Description of the job functions defined for the humans interacting with the system
Human Network	Depiction of the human to human communication patterns that occur
Training	Accounting of training requirements, strategy, and implementation
Metrics	Repository for human-related values, priorities and performance criteria

The Human View can be used to identify the conditions of both the operator and operating environment that may impact outcomes propagated through the mission thread. Since the Human View models capture relationships across the socio-technical boundary, it can be used to suggest alternatives that may help mitigate the human associated risks.

2.2. Socio-Technical Analysis

A human assurance evaluation is a type of socio-technical systems analysis [8]. Socio-technical systems are associated with the interaction of operators and technology through work processes [9]; the Human View models capture the human operator activities and coordination required to accomplish the mission objectives. A key-thread analysis at the human operator level is the evaluation of a sequence of tasks in order to identify the human risks; this is similar to a mission thread analysis performed at the system capability level. A key thread analysis provides a projection of how a given sequence of tasks will perform under different circumstances, and the implications of changes to both the human and/or technology on the process outcomes.

Human assurance evaluations are performed on key threads which represent small, actionable statements describing a piece of system functionality [10]. These are used to provide the context and metrics for the system certification. These key threads can be described using an activity diagram that represents the work process of the interactions of operators and systems derived from the human assurance story. The activity diagram can be used to identify the environmental, organizational and technical factors that impact the operator's ability to correctly perform the required mission tasks. For each activity or information exchange in the key thread, the conditions that influence the outcomes in the work process can be identified. The analysis identifies the risks that may impact the ability of the operator at the node to meet the mission objectives.

2.3. Risk Model

The socio-technical analysis identifies the potential factors that contribute to the risk model of human assurance. A risk-based decision model can be developed to evaluate factors from the environment, the organization and the deployed technology on the likelihood of operator success. The dependencies between the activities can be used to create a risk framework for analysis. The creation of the decision model follows the MIRROR approach: model the system, identify the uncertainty, develop the risk framework, perform the risk calculations, identify the objectives, and evaluate the results [11]. The result is a risk-based decision model for use in identifying the risks associated with the human component and to certify that human performance remains within acceptable mission assurance criteria. It allows the likelihood of different factors to be varied in order to assess the impact on the human assurance threshold and can predict combinations that produce a high risk of missing the human assurance target. Typical human focused risks are shown in Table 2.

Table 2. Typical Human Focused Risks

Context	**Risks**
Environment	Tempo of Operations
	Degradation of Information
Organization	Incorrect Operator Assigned
	Lack of Operators Available
	Time on Station Exceeded
Technology	Information Bottlenecks
	Lack of Decision Support
	System Usability

An important use of the human assurance model is to evaluate the impact of different risk mitigations that can be adopted on the predicted human assurance value. The risk model is designed based on the current configuration of the system operators and associated risks. The model can then be modified to include suggested ameliorations predicted to improve the human assurance profile. The risk profiles for the two models can be compared to evaluate the degree that the human assurance is improved, and tradeoff with the cost of the implementing the change.

It is important to note that the key to a successful risk-based decision analysis is access to the many probabilities required that drive the calculations; note for this paper that notational probabilities have been used to populate the risk models. However, in most cases existing data can be used to derive a probabilistic human assurance model of the mission thread. The example in the next section illustrates an application of the methodology.

3. Example – Schedule Deconfliction for Satellite Emergency

3.1. Mission Description

Satellites perform specific missions and operate in various orbits. Once a satellite is launched into its orbit, it must be in frequent contact for satellite management and data collection. Satellite communications are conducted through networks that support many different missions and are scheduled across globally distributed ground stations. Remote ground stations (GS) relay satellite telemetry to analysts at a Mission Operations Center (MOC). This telemetry contains the data that the satellite gathers through its sensors, as well as "health" data on the various subsystems of the satellite. The satellite state-of-health telemetry is requested from the ground controller in the MOC during the satellite standard pass. The MOC gets state-of-health data for trending purposes; the analysts monitor the data for indicators that the satellite is functioning normally. However, if the satellite health data starts trending adversely, that is parameters for a certain attribute are tending towards a set threshold, an emergency for that satellite is declared.

If an analyst identifies the state-of-health data as "adverse trending" it means that some operational parameters of the satellite are going in the wrong direction. The analyst may not immediately put the satellite in an emergency condition, but it may indicate that something is going wrong. Typically, the analyst "on-console" is looking at state variables trending and seeing whether those cross an operational threshold, such as a battery voltage value, or a degradation in performance, such as the batteries are charging less and less over time. These trending values may be very subtle, and an analyst might not notice them if they are fatigued. Additionally, the console may not detect these subtle changes and may not trigger an alert until after a specific threshold is crossed. These slight changes parameters might portend a problem that should be monitored so that an early intervention can be made. For example, on the International Space Station there was a very minor increase in a joint voltage over time that, upon inspection, revealed that metal filings were in the joint. If this had not been noticed early on, it could have developed into a serious issue. As it so happened, a bright engineer noticed the trending data and a potential crisis was averted (D. Heimerdinger, personal communication, 2019).

A satellite emergency starts with an anomaly. This could be a loss in pressure of a propellant tank or coolant loop, degradation or loss of thermal control, sensor failure, attitude control loss or degradation, loss or degradation of the communications link, etc. When something starts operating in a significant off-nominal performance that could cause serious impact or loss to the mission, that is classified as an emergency. When an emergency occurs, the MOC wants to communicate with the satellite at the earliest next opportunity. In order to do this, orbital analysis must be done to determine whether the satellite is visible to any GS. This requires orbit propagation, conjunction, and radio frequency interference calculations. In addition, based on the telemetry, other considerations such as the satellite's attitude control are taken into consideration, i.e., is it spinning, does it require pointing of the arrays to mitigate power loss, does it have to do a maneuver to avoid debris, etc. These are very complex calculations and any errors can exacerbate the situation by miscalculating whether it is in sight of a ground or space-based antenna or miscalculating the satellite's attitude issues. In these complex cases, experienced orbital analysts are less likely to contribute to data errors.

The satellite emergency triggers a request to either gather more health data from the satellite or to issue a command to the satellite for a correction. The MOC requests to schedule a window at a ground or space-based antenna to contact the satellite so that communications can occur as soon as possible. In these cases, the mission that requires the satellite contact typically gets the highest priority services. This then causes other missions to potentially lose planned scheduled satellite contacts. Conflicts arise because of the satellite emergency requires rapid network reconfiguration to meet the emergency while also satisfy other satellites missions.

The Network Operators Center (NOC) processes the emergency request and identifies all mission support schedule conflicts. Schedule conflicts occur when the orbital window to contact the ailing satellite occurs at a time that was already allocated to another satellite. Mission support requests are per satellite and result in a satellite-to-ground station communications schedule. At times of high operation tempo, multiple conflicts may occur; certified schedulers interact with the both the MOC and the GS to resolve the conflicts. These schedule conflicts, often cascading from one event to several missions, must be addressed in order to revise the schedule to contact the ailing satellite and still meet as many mission commitments as possible.

The schedule is also dependent on the status of available GS. A ground antenna can go down due to many reasons including system failures, communication failures, and adverse weather. When an unscheduled GS event happens, it often requires a phone call or a manual entry into a terminal to notify the NOC that the site or system is down. It is then up to the NOC to notify all affected users. For example, if voice communication is impacted due to weather, a user may not notice that the status of the GS has changed. This can result in unintentionally bumped or lost mission satellite contacts. Once the status has been updated, schedulers work to revise the contact schedule and reallocate the required mission contacts. Once all conflicts are addressed an updated schedule is released. The new mission support parameters are then communicated to configure the GS and the revised schedule is shared with other mission users.

3.2. Step 1 – Human-Focused Data

The human assurance story for this example is to "revise the contact schedule in response to a satellite emergency while minimizing the loss of other mission data". The human assurance criteria is to maintain a 98% schedule completeness. The first stage of developing the human assurance model is to collect the human-focused data needed to support the analyses. A Human Viewpoint was previously completed for this mission in a different context; the objective of the prior work was to determine the staffing requirements for the satellite operations crew to support changes to remote ground stations [12]. For this current example, three example Human View models were completed based on the existing models.

The Task data is shown in Table 3. This model identifies the high-level tasks associated with each of the operational nodes of the satellite operations as depicted in Figure 1. The Role data is shown in Table 4; this describes the general duties of each of the roles. Note only the roles in each of the nodes that interact within this mission thread are included in the model. The Human Network data is shown in Table 5. This data provides the sequence of the interactions of the roles completing the mission thread. These three models provide the information required to develop the activity diagram for the socio-technical analysis.

Table 3. Task Data

Node	Generalized Tasks
Satellite	Create Telemetry
Ground Station	Process/ Relay Telemetry
	Provide Ground Station Status
	Configure Ground Station
Network Operations Center	Process Emergency Support Requests
	Identify Mission Support Conflicts
	Integrate Alternative Mission Support Requests
	Develop Emergency Mission Support Requirements
Missions Operations Center	Analyze Telemetry
	Create Real Time Emergency Request for Mission Support
	Identify Alternative Mission Support Options

Table 4. Role Data

Node	Mission Operations Center		Network Operations Center		Ground Station
Role	Data Analyst	Orbital Analyst	Mission Controller	Mission Scheduler	Operator
Job Type	19-2021.00 - Atmospheric and Space Scientists	17-3021.00 - Aerospace Engineering and Operations Technicians	11-3021.00 - Information Systems Managers	15-1142.00 - Network Systems Administrators	55-3017.00 Sensor Technicians
Description	Interpret data gathered by satellites to prepare reports requiring detailed knowledge	Operate integrated computer systems consoles and data acquisition equipment, used to track space vehicles.	Plan, direct, or coordinate activities for electronic data processing, information systems, and systems analysis,	Monitor network to ensure network availability to all system users.	Operate equipment to identify, track, and analyze objects.

Table 5. Human Network Data

Seq	Information Flow	From Node: Role	To Node: Role
1	RF Telemetry	Satellite	Ground Station: Operator
2	Telemetry	Ground Station: Operator	Mission Operations Center: Telemetry Analyst
3	Emergency Declaration	Mission Operations Center: Telemetry Analyst	Mission Operations Center: Orbit Analyst
4	Emergency Schedule Request	Mission Operations Center: Orbit Analyst	Network Operations Center: Mission Controller
5	Schedule Change	Network Operations Center: Mission Controller	Network Operations Center: Mission Scheduler
6	Status	Ground Station: Operator	Network Operations Center: Mission Scheduler
7	Schedule Conflicts	Network Operations Center: Mission Scheduler	Mission Operations Center: Orbit Analyst
8	New Request options	Mission Operations Center: Orbit Analyst	Network Operations Center: Mission Scheduler
9	New Schedule	Network Operations Center: Mission Scheduler	Network Operations Center: Mission Controller
10	New Schedule Voice Communications	Network Operations Center: Mission Scheduler	Ground Station: Operator

3.3. Step 2 – Socio-Technical Analysis

An activity diagram is used to capture the work process of the roles, described in the Human View Role model, as they interact as described in the Human Network model. An activity diagram shows the sequence of tasks (derived from the Human View Task model) and the resulting data transformations. The activity diagram represents the key thread for the human assurance evaluation. The diagram can then be annotated to identify where probabilistic data representing human errors resulting from internal and external factors should be included in the model.

Because human resource policies vary among organizations, the human assurance evaluation for this key thread is performed in two sections, one for each of the two participating operational nodes. A simplified version of the mission thread for the MOC is shown in Figure 2. This starts with the analysis of the satellite telemetry in order to identify adverse trending data. The socio-technical analysis adds the likelihood of operator errors to the key thread. In this case, the likelihood of the adverse trending data being detected can be linked to the fatigue level of the operators. The longer the operator has been on-console, the more likely an adverse trend may be missed. The next activity creates the satellite emergency request. This request includes the orbital data to contact the satellite; any orbital tasking error will propagate through the process and lead to a mission tasking error. The probability of exact orbital information depends on the proficiency of the operator – more experienced operators are more likely to make the correct schedule request. The outcome of the key thread is to create the emergency request by including the two sets of satellite parameters.

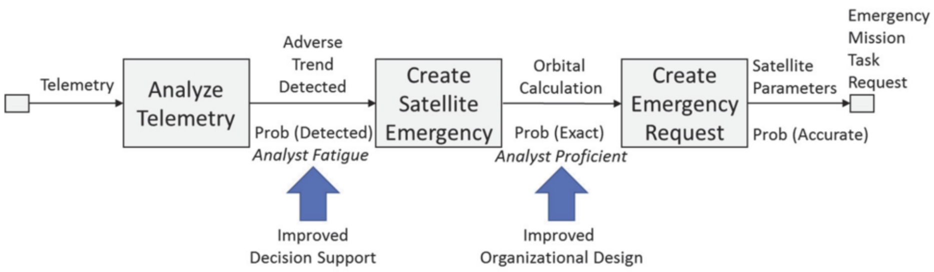

Figure 2. MOC Mission Thread Socio-technical Analysis

A similar socio-technical analysis can be done for the mission thread in the NOC as shown in Figure 3. When the Emergency Mission Task Request is received from the MOC, conflicts in the mission schedule that are impacted by the new request are identified. At any given time, there are multiple mission requests being serviced by the NOC; this schedule complexity may cause some missions to be dropped from the mission schedule. However certified schedulers are more likely to identify and deconflict the complete set of missions impacted by the change. In order to redistribute these missions, the updated status of all GS is requested in order to identify alternative pass calculations for the conflicted mission requests. Since many of the GS are in remote areas, timely status updates are not always received, and the status of all antenna is not readily apparent. This lack of information impacts the ability to make schedule revisions due to possible incorrect assumptions of an unavailable asset. The outcome of this key thread is the reconfigured schedule that includes the mission and asset parameters.

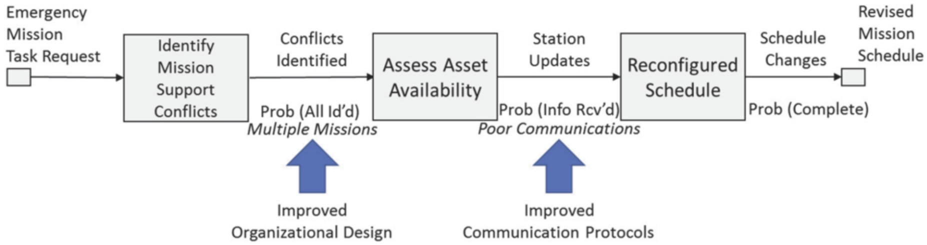

Figure 3. NOC Mission Thread Socio-technical Analysis

3.4. Step 3 – Risk Model

The last step is to develop the risk model based on the annotated key threads provided by the socio-technical analysis. The diagram shown in Figure 2 captures the human influences on the likelihood that the adverse trending data is detected, and the exact orbital data is calculated, both contributing to an accurate emergency mission task request. These values can be captured in a risk model, as shown in Figure 4. The risk model is an event tree that captures the probabilistic outcome of each activity of the key thread sequence. For example, the probability of the adverse trend being detected is based on the fatigue state of the operator; operators in the last segment of their shift are more likely to be fatigued. This notational probability was generated by identifying the number of last shift segments across all shifts and operators. The outcome of the next activity is the probability of an exact orbital calculation; this notational value was generated by identifying the number of experienced orbital analysts across all shifts. Finally, the probability of accurate satellite parameters is fixed based on the given mission assurance value; the human assurance model modifies this value by finding its expected value across the event tree. As shown in the Figure 4, for this example with nominal probabilities, the baseline value for the Emergency Mission Task Request remains within the human assurance guidelines of 98%. The model can then be used to vary the values for the likelihood of operator fatigue and experience in order to evaluate the boundaries of the human assurance value.

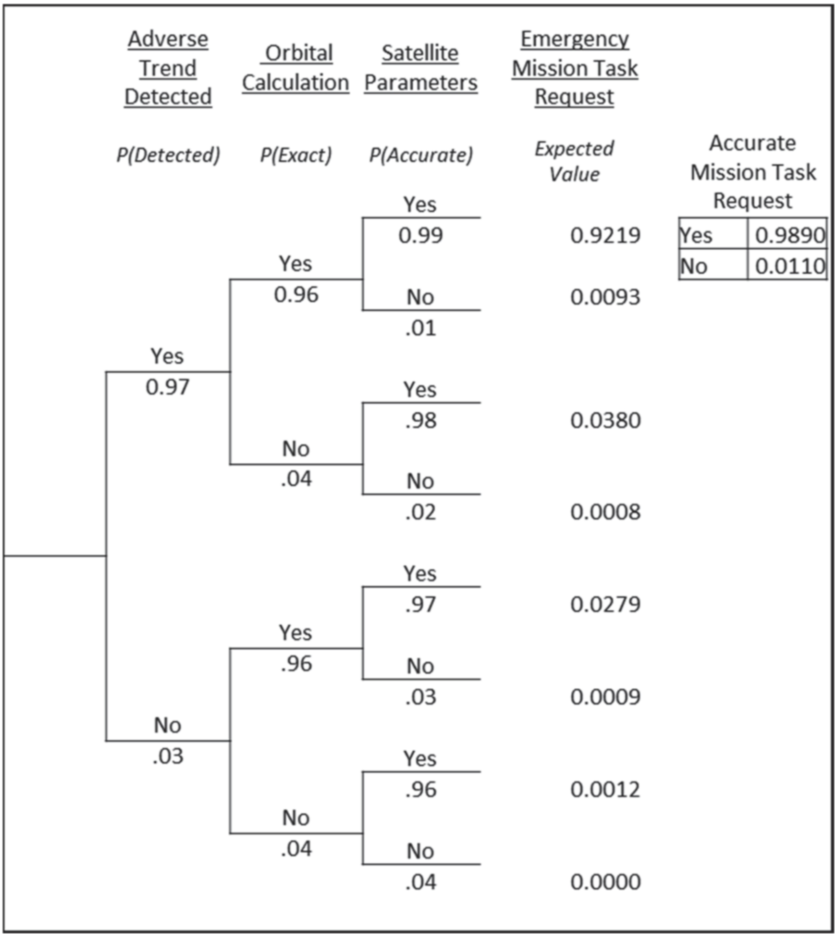

Figure 4. Risk Model for MOC Emergency Mission Task Request

One of the benefits of this approach to human assurance is the ability to evaluate different risk mitigations proposed to improve human assurance. These mitigations can be implemented in the risk model to assess their ability to improve the likelihood of operator success. For example, operator fatigue that may mis-identifying the adverse trending data can be improved with additional decision support from the mission console. Likewise, the use of expert orbital analysts can improve the accurateness of the orbit data. These ameliorations can be included in the risk model to evaluate whether the cost of the improvement is worth the positive impact to human assurance. Table 6 gives an example of ameliorations and the impact on the human assurance values.

Table 6. Risk Amelioration Values

	P(Detected)	*P(Exact)*	Accurate Mission Task Request
Baseline	0.97	0.96	0.9890
Improved Decision Support for Data Analyst (Better Console HMI)	0.98	0.96	0.9892
Improved Decision Support for Data Analyst and Improved Organizational Design (Proficient Operator Assigned)	0.98	0.97	0.9896

The same process can be followed to create the risk model for the NOC. The diagram shown in Figure 3 captures the human influences on the likelihood that all mission conflicts are identified and that timely information on the GS status is received. These values can be captured in a risk model as shown in Figure 5. In this case, the probability that all mission conflicts are identified is dependent on the number of active missions; as the number of active missions increases, the complexity of generating a schedule that aligns all satellite passes with mission requirements increases. For this example, this probability is generated by approximating the availability window for the set of satellites. Likewise, the probability of timely ground station status is based on the reliability of the cellular network. The probability of correct schedule changes is fixed based on the given mission assurance value; the human assurance model modifies this value by finding its expected value across the different combinations of the event tree. As shown in the figure, with the nominal probabilities, the baseline value for the Revised Mission Schedule remains within the human assurance guidelines of 99%. This model could also be used to evaluate mitigations to improve the human assurance in this portion of the mission thread. For example, the impact of using only certified schedulers and improved communications protocols with the GS could be evaluated for improvements in human assurance.

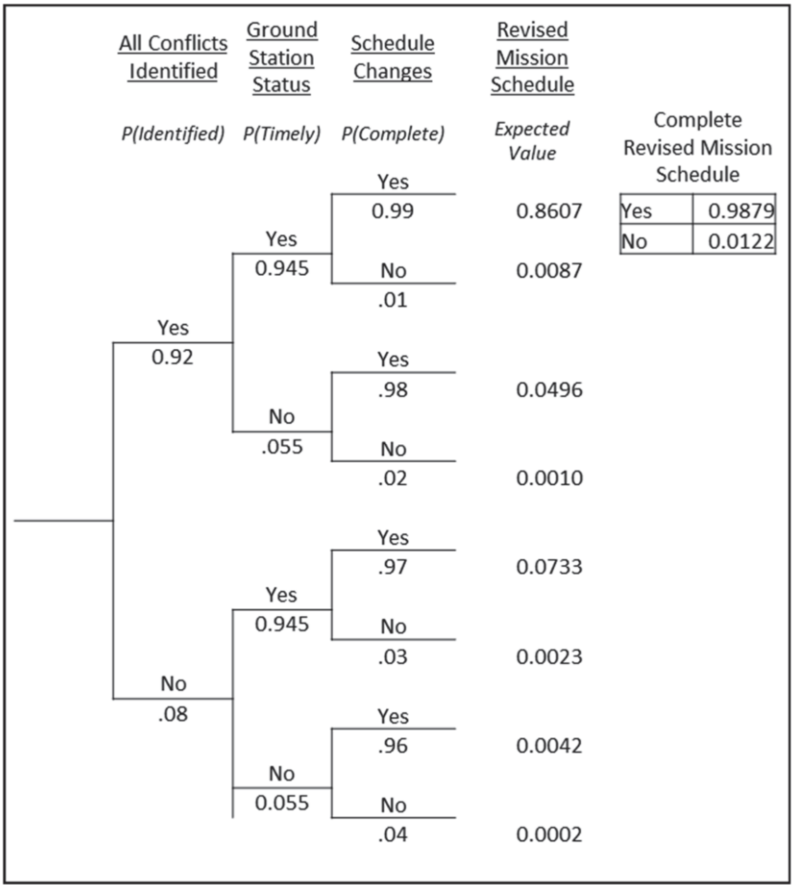

Figure 5. Risk Model for NOC Revised Mission Schedule

These two models provide the human assurance analysis for the two different operational nodes involved in the mission thread. However, the overall mission assurance for the key thread carries the expected value outcome of the first segment to the input node of the second segment. The resulting human assurance value of the process is .9890 * .9879 = .9770. This falls just under the human assurance threshold of 98%. The human assurance risk model can now be used as a diagnostic tool to evaluate the sources of human risk and suggest ameliorations. This approach to human assurance, i.e. human-focused data collection, socio-technical analysis, and risk model development provide a “deep dive” into the human component of the mission thread and its impact on the mission assurance guarantee. The combined risk model allows the evaluation of the overall human assurance value to ensure it remains within bounds as different human focused parameters are varied.

4. Conclusion

The traditional approach to evaluating mission assurance assumes a qualified operator and generally ends the mission thread analysis at the human-system interface. However, that approach does not include other aspects of the internal or external environment that may impact the performance of the human operator. Human assurance can be considered as the probability of acceptable operator performance given a set of conditions that may include the operator, the system, and the environment. The socio-technical analysis and resulting risk model allow the analysis the impact of the human operators on the mission thread analysis. The model allows for exploration of different likelihood values due to different organizational policies as well as the impact of suggested risk mitigations. The human assurance risk model can consider risks from both the internal and external environment and allows them to be varied to see the impact on the ability to maintain the human assurance threshold. The results can be used in the mission thread analysis to understand under what set of risks the human assurance "guarantee" is valid.

The combination of the Human Viewpoint models for human-focused data collection and socio-technical analysis to identify the risks of human operators interacting with technology provides the inputs to the risk model used to certifying that human performance remains within acceptable threshold for the mission thread. This approach is extendable to multiple contexts to evaluate human assurance requirements. It also highlights, however, the numerous probabilities required for a successful risk analysis, even for a small model. The satellite operations example illustrated the use of the method to develop a risk model to evaluate the human assurance for revising the contact schedule in response to a satellite emergency while minimizing the loss of other mission data. The human assurance value for this example fell just below the desired threshold, providing an opportunity for the model to be used for further investigation.

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