Proceedings of the Annual General Donald R. Keith Memorial Conference
West Point, New York, USA
May 2, 2024
A Regional Conference of the Society for Industrial and Systems Engineering

User-Friendly Monte Carlo Simulation to Support Risk Analysis in the Military Decision-Making Process

Htut Khaung Oo and Nicholas Coronato

Department of Systems Engineering,
United States Military Academy,
West Point, New York 10996

Corresponding author's Email: htutkhaung.m.oo.mil@army.mil

Author Note: Collaboration with members of the Department of Systems Engineering, United States Military Academy was integral in developing a stochastic model for the Risk Common Operating Picture. Nicholas Coronato was the primary advisor and guided efforts to mature the model for use. The views expressed herein are those of the authors and do not reflect the position of the United States Military Academy, the Department of the Army, or the Department of Defense.

Abstract: The Military Decision-Making Process (MDMP) facilitates collaborative planning as higher headquarters continually share information concerning operations with subordinates and adjacent units. Traditional risk calculation in the Mission Analysis and Course of Action Development may falter in a rapidly changing operational environment. The United States Army's conventional risk assessment plan measures risk in two areas: Probability (likelihood of an event) and Severity (potential consequences). Military planners are forced to make subjective evaluations of risk. This research introduces a risk assessment tool that uses Microsoft Excel and Monte Carlo simulation through the SIPmath package. The "Stochastic Risk Common Operating Picture" (S-RCOP) tool allows planners to input mission variables associated with both threat-based and environment-based risks. The model's "dashboard" allows decision-makers to visualize a range of potential risk outcomes. Commanders who embrace a quantified and auditable risk assessment methodology will make better decisions based on accurate predictive analysis of potential outcomes.

Keywords: Risk Analysis, Decision-Making, Monte Carlo Simulation

1. Introduction

The Military Decision-Making Process (MDMP) serves as a systematic planning methodology essential for comprehending and executing military operations (Department of the Army, 2016). Comprising seven steps, the MDMP underscores the importance of thorough analysis, clarity, sound judgment, and collaboration among commanders and staff. Its iterative nature allows for adjustments as the understanding of the situation evolves, driven by the time-sensitive imperative to prepare forces adequately before mission execution (Benson, 2019). This investigation aims to improve risk assessment procedures during two integral phases of planning: Mission Analysis and Course of Action (COA) Development.

Mission Analysis involves initial intelligence preparation, critical fact development, and identification of key information requirements (Department of the Army, 2016). Notably, Step 7 (Begin Risk Management) and Step 17 (Development of COA Evaluation Criteria) play pivotal roles in this process, setting the stage for COA Development. Risk management, as outlined in ATP 5-19, is crucial for identifying, assessing, and controlling operational risks during COA Development (Department of the Army, 2021). Three types of risks are typically considered: threat-based, accident-based, and environment-based (Department of the Army, 2016). Threat-based risks are hazards related to mission and enemy elements which require thorough intelligence preparation. Accident-based risks involve hazards related to training, staffing, equipment maintenance, and morale. Environment-based risks encompass considerations of terrain and weather during mission execution.

Hazard assessment leads to an initial estimation of risk level using the Risk Assessment Matrix (see Figure 1), which accounts for both the probability and severity of an uncertain consequential event (Wampler et al., 1998). Commanders assume a pivotal role in risk acceptance, recognizing the inherent uncertainty in military operations. ADP 5-0 provides three risk reduction factors: minimizing the risk of friendly losses, avoiding risks jeopardizing the operation's success, and minimizing the risk of civilian casualties and collateral damage. These factors are crucial when navigating risk in mission settings (Department of the Army, 2019).

Army doctrine identifies five critical screening criteria for COAs: feasibility, acceptability, suitability, distinguishability, and completeness (Department of the Army, 2019). COA Development involves assessing relative combat power, combining numerical force ratios with intangible factors, and generating options aligned with the commander's guidance

(Wampler et al., 1998). Risk integration in COA Development occurs by considering threat-based, accident-based, and environment-based risks during shaping, decisive, and sustaining operations. This ensures that COAs remain viable when exposed to potential risks (Benson, 2019).

RISK ASSESSMENT MATRIX		**Probability** *(Expected frequency)*				
		Frequent: Continuous, regular, or inevitable occurences	**Likely:** Several or numerous occurences	**Occasional:** Sporadic or intermittent occurences	**Seldom:** Infrequent occurences	**Unlikely:** Possible occurences but improbable
Severity *(expected consequence)*		**A**	**B**	**C**	**D**	**E**
Catastrophic: *Mission failure, unit readiness eliminated; death, unacceptable loss or damage*	**I**	**EH**	**EH**	**H**	**H**	**M**
Critical: *Significantly degraded unit readiness or mission capability; severe injury, illness, loss or damage*	**II**	**EH**	**H**	**H**	**M**	**L**
Moderate: *Somewhat degraded unit readiness or mission capability; minor injury, illness, loss, or damage*	**III**	**H**	**M**	**M**	**L**	**L**
Negligible: *Little or no impact to unit readiness or mission capability; minimal injury, loss, or damage*	**IV**	**M**	**L**	**L**	**L**	**L**
LEGEND:	**EH -** Extremely High Risk	**H -** High Risk	**M -** Medium Risk	**L -** Low Risk		

Figure 1. Risk Assessment Matrix (Department of the Army, 2021)

2. Stochastic Modeling Approach – SIPMath

Risk (in military operations and otherwise) is rarely static and should not be considered certain. Describing risk levels as a single estimate is a fallacy that permeates the business world; in the military, the stakes are considerably higher. Dr. Sam Savage describes this problem as the "Flaw of Averages" – plans based on *average* assumptions are wrong *on average* (Savage, 2012). Stochastic modeling can be utilized to help address the uncertainty associated with risk. In systems engineering, this involves the use of statistical techniques to model and analyze systems, processes, or phenomena that exhibit randomness. This kind of randomness is abundant in military intelligence, environmental conditions, and virtually any other consideration of the dynamic battlefield. Primarily, stochastic modeling helps decision-makers visualize a variety of outcomes under multiple factors and conditions (Harrison, 2010).

Monte Carlo simulation is a popular example of a stochastic model as it simulates the outcomes of a probabilistic event in a probability distribution (*SIPmath Standard*, 2019). This can be applied to the problem of risk assessment in the MDMP; the Monte Carlo simulation can account for a variety of mission or environmental situations (inputs) and produce a probability distribution of potential risk outcomes (outputs) (Harrison, 2010). Seeing a probability distribution of successful outcomes (or failure) for a mission can help commanders make better-informed decisions.

SIPmath, a software to model stochastic data, can be used to analyze risk and uncertainty. The open SIPmath standard developed by Dr. Sam Savage refers to computations done with Stochastic Information Packets (SIPs). This models uncertainty as an array of possible outcomes. The basic concept of SIPmath is simple: uncertainties are represented as thousands of possible outcomes. SIPs are actionable in that they may be used as inputs to interactive simulations in Excel. SIPs are additive, in that the results of multiple simulations run on different platforms may be aggregated. Finally, SIPs are auditable, because the trials are simply data with associated metadata (*SIPmath Standard*, 2019). For the MDMP and risk assessment, SIPmath offers a way of representing risk in terms of possible outcomes for a mission. The software's interoperability with Microsoft Excel allows it to be widely utilized and easily presentable for commanders in need of robust but rapid situational analysis.

ISBN: 97819384962-4-0

Furthermore, due to the array of uncertainties present in threat and environmental conditions, Monte Carlo simulation is an excellent tool for utilizing uncertain variables to visualize a probability distribution.

3. Stochastic Risk Common Operational Picture (S-RCOP)

With SIPmath as the modeling tool and Excel as the modeling software, a Stochastic Risk Common Operational Picture (S-RCOP) was developed using Monte Carlo simulation as the basis for quantifying risk. Threat-based risk and environmental risk are modeled to demonstrate initial capabilities for quantifying operational risk in mission planning. As a proof of concept, only a few numeric parameters were selected for their ease of estimation; this is data that an operations officer and her staff should have access to or could reasonably estimate. Many more examples of threat-based risk and environmental-based risk could be incorporated into S-RCOP. The risk factors that are currently accounted for in S-RCOP were chosen based on a desire to account for ill-defined threats with an easily estimated metric that can be adjusted as tactical conditions change. *Friendly to Enemy Ratio*, for example, is data that can be rapidly estimated by a staff planner and input to a risk calculation model. By transforming readily accessible data into useful information, the staff officer develops a more robust vision of tactical risk (Christianson, 2016). If the planner can estimate a probability distribution for the input parameters, then any risk factor can be added to S-RCOP. For this report, accident-based risk was not included, as much of this risk is up to commander's discretion and cannot be gathered in an intelligence report for a mission. Accident-risk data is gathered when accidents occur, and these phenomena are not explicitly accounted for in military plans.

Five specific assessment areas were chosen to demonstrate SIPmath capabilities in the categories of threat-based and environmental risk. The three areas that make up threat-based risk in S-RCOP are as follows: *Friendly to Enemy Ratio*, *Friendly to Enemy Armed Weapons Ratio*, and *Enemy Distance to Friendly*. The two areas that comprise environmental risk in the model are *Hours Required to Traverse the Terrain* and *Lunar Illumination Level*. Each of these factors reflects theoretical planning considerations in US military doctrine used in the Global War on Terror and the interwar years (Christianson, 2016). Figure 2 is a user's view of S-RCOP.

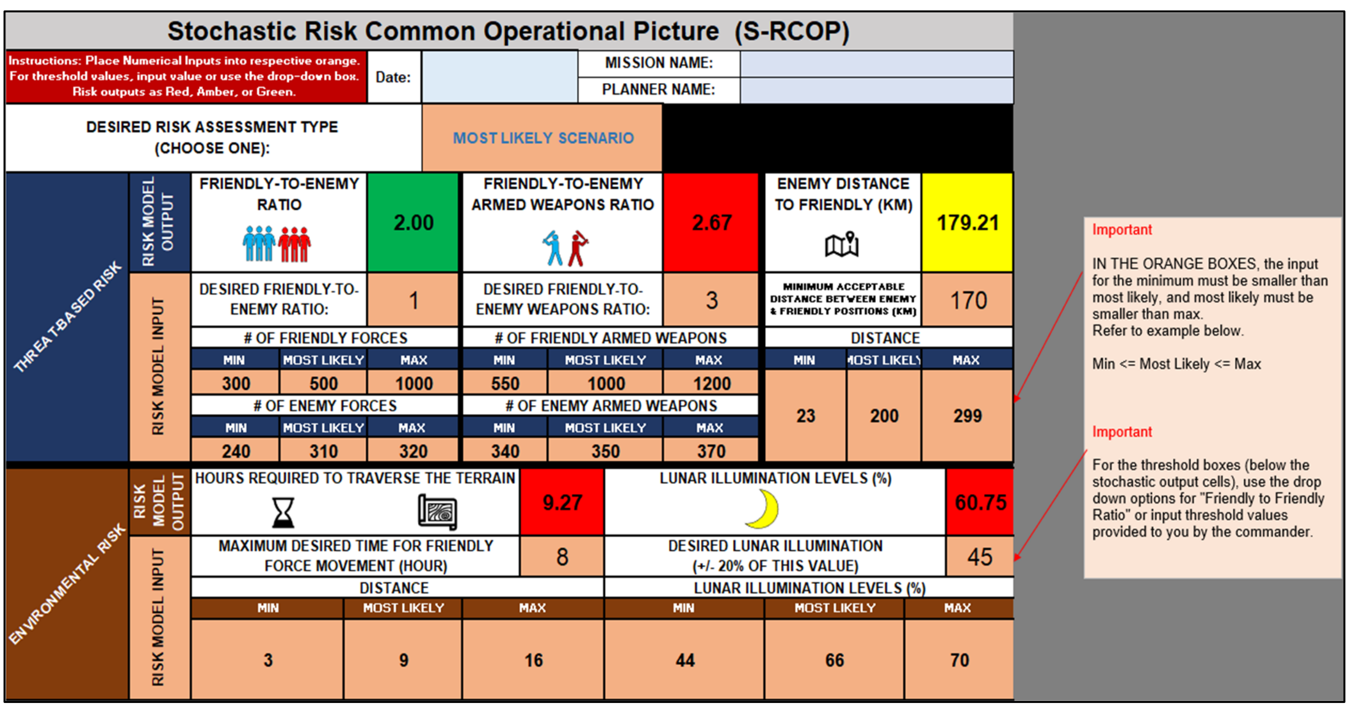

Figure 2. S-RCOP user interface. The user adjusts only orange boxes and the dashboard updates automatically.

This model uses an Excel macro to compute risk levels; as the planner adjusts the input data in orange cells, 1,000 new simulation outputs are calculated according to the underlying probability distributions. All other cells are locked to prevent inadvertent modification to the model. Within each risk's subtopic, there are two distinct areas to input numbers – "Threshold Values" (Figure 3) and "Risk Inputs" (Figure 4). The model updates automatically once the user changes inputs. Figure 2 depicts a mission scenario which the commander would notice high risk areas of the mission by identifying three cells that are shaded red. The lunar illumination is greater than 45% ± 20%, friendly forces will require 9.27 hours to conduct movement across terrain (8 hours is acceptable here), and the friendly-to-enemy weapons ratio is lower than desired.

As noted earlier, a key screening criteria for any COA is "acceptability." A mission's acceptability is represented in S-RCOP with "Threshold Values." These are user-defined limits that act as boundaries for the risk undertaken for each subtopic. The S-RCOP model uses the threshold to compare against an expected risk distribution. *Friendly to Enemy Ratio* as outlined in ADP 3-0 is accounted for within threat-based risk; *Friendly to Enemy Ratio* and *Friendly to Enemy Armed Weapons Ratio* thresholds can be set at any level, such as 1:1, 2:1, or 3:1. This concept aligns with Army doctrine publications (Christian, 2019). For *Enemy Distance to Friendly* and *Hours Required to Traverse Terrain*, the threshold value must be manually inserted with a range from 0 to 10,000 km. *Lunar Illumination* levels fall in a range from 0 to 100%. This gives the user freedom to represent commander's risk tolerance limits which can then be used to compare with Risk Inputs as shown in Figure 3. The spreadsheet model has controls on specific cells to prevent the user from trying to prescribe nonsensical parameters (such as lunar illumination above 100%).

DESIRED FRIENDLY-TO-ENEMY RATIO:	1	DESIRED LUNAR ILLUMINATION (+/- 20% OF THIS VALUE)	50

Figure 3. Example Threshold Values. The planner consults with the commander to decide the limit of acceptable risk. By defining simple threshold values, the planner allows the model to highlight unacceptable risks (as in Figure 5).

"Risk Inputs" are cells where users can place raw data taken from an intelligence report. As data is often communicated with point estimates, it is advisable to consider the full distribution of possible outcomes. This justifies the use of a Monte Carlo Simulation in S-RCOP. The model asks the user to define only the Minimum, Most Likely, and Maximum parameters as the basis. These parameters can be drawn directly from raw intelligence data or, in the absence of trustworthy data, estimated from previous experiences. When defining the parameters (see Figure 4), the input for the "minimum" must be less than or equal to the "most likely" case, and "most likely" must be less than or equal to the "maximum" (Excel forces this data validation to occur). Upon changing Risk Inputs, a user-defined number of simulation iterations are instantaneously generated through SIPmath's Monte Carlo simulation (*Monte Carlo Simulation*, 2023). There is no need for the user to initiate a new simulation run as SIPmath performs instantaneous random sampling. The dynamic nature of S-RCOP is advantageous in this way.

# OF FRIENDLY FORCES		
MIN	MOST LIKELY	MAX
300	500	1000
# OF ENEMY FORCES		
MIN	MOST LIKELY	MAX
240	310	320

Figure 4. Example Risk Inputs for S-RCOP. The staff planner comes upon these estimates after reviewing some form of current data, such as an intelligence report.

At times, the planner or decision-maker may be interested in seeing how different risk tolerances might affect the assessment. Therefore, S-RCOP includes the ability to choose between presenting the "Worst-Case" and "Most Likely" scenarios. In "Worst Case Scenario," the model uses the extreme simulated outputs (minimum or maximum value) as the basis for providing a recommendation. The outputs that are shown in the model highlight the most extreme output generated within the simulations. The most extreme output within the 1,000 different iterations was chosen, as this is considered the limit of risk that can be undertaken before a mission is canceled. In other words, if the S-RCOP shows even the smallest likelihood of an adverse outcome (i.e., *lunar illumination* above an acceptable level), the staff would be informed of the risk being faced in the worst of possible scenarios. This is akin to consideration of the "Most Dangerous Course of Action" in US Army doctrine (Department of the Army, 2019). For the Most Likely Scenario, the 50th percentile is chosen from the list of 1000 generated simulations. This was chosen as it represents the percentage of a distribution that is equal to or below the median, thus representing the most likely scenario. It serves as a proxy for the "Most Likely Course of Action" as defined in military doctrine (Department of the Army, 2019).

Cross-referenced with the threshold values, the spreadsheet's output cells are automatically colored red, yellow, or green to depict where the Worst Case or Most Likely output falls relative to the threshold. Red indicates that the associated inputs render the mission high risk. Yellow indicates moderate risk, which must be considered thoroughly before advancing. Green indicates that the expected risk is low.

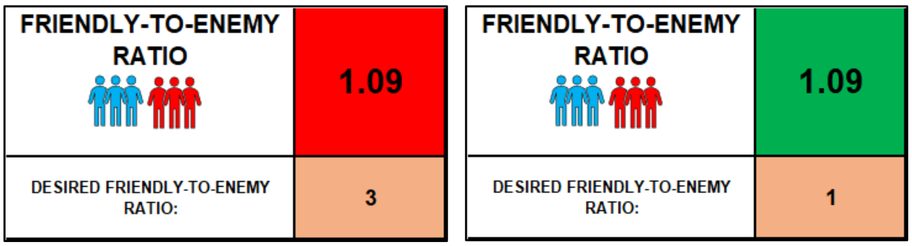

Figure 5. Final output comparison with Threshold Values. Since the desired friendly-to-enemy ratio was set to "3" on the left, the worst-case simulated outcome of 1.09 is colored red; the simulated mission falls outside of the commander's tolerance. When the friendly-to-enemy ratio is within the commander's acceptable limits (as seen in the right panel of Figure 5), the cell is shaded green.

As mentioned, there are advantages to displaying summarized outcomes on a dashboard (i.e., Figure 5). While stochastic event outcomes are more precisely described as a distribution, briefing a commander on the whole range of possibilities is not always advisable. Military leaders are not typically trained in reading a probability distribution, but commanders are familiar with the "Worst-Case" and "Most Likely" scenario assessments. As for the model itself, this aids in design and engineering resiliency. In engineering and system design, worst-case scenarios help determine the maximum risk that a system may face, ensuring that it withstands these extreme conditions. For the MDMP, this denotes the highest level of risk that a commander might undertake at the outset of a mission.

Upon request, the S-RCOP tool is capable of displaying more information for the statistically savvy commander as shown in Figure 6. If an S-RCOP user needs more information on the distribution of simulated outcomes, they need just a rudimentary understanding of the SIPmath tool to output the full distribution. The charts in Figure 6 were produced with less than ten clicks of the mouse.

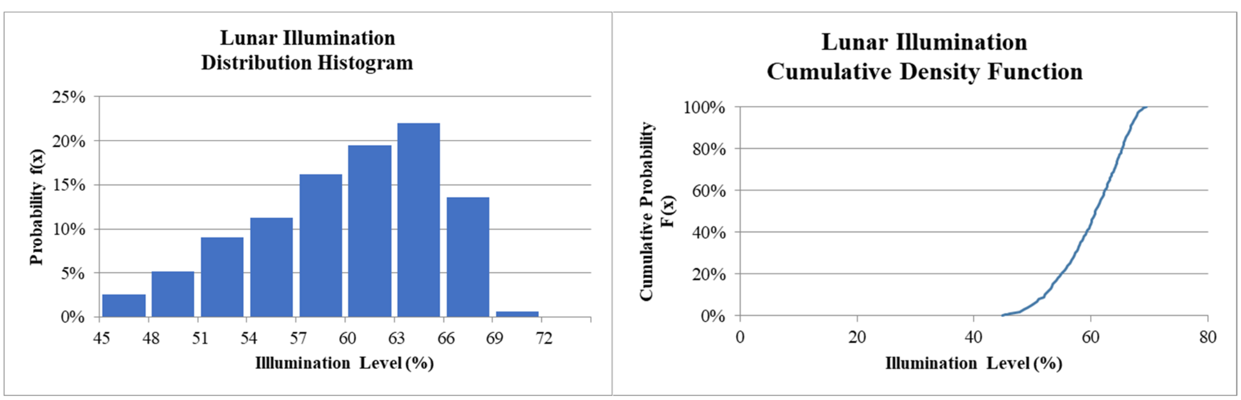

Figure 6. Graphical depiction of the simulation output for *Lunar Illumination*. This example histogram and cumulative density function can help the planner to communicate the full range of possible outcomes to be expected on the evening of a tactical mission. These outcomes are derived from 1,000 simulations and based upon the planner's input of readily available lunar data.

4. Conclusion

The MDMP serves as a crucial framework for planning and executing military operations, emphasizing collaboration, thorough analysis, and adaptability. Within the MDMP, the Mission Analysis and Course of Action Development phases utilize risk, requiring commanders to make subjective evaluations using traditional risk assessment methods. S-RCOP was designed with the military planner in mind as an effort to account for the decision maker's uncertainty from the risk evaluation process during COA Development. Its utility is in its simplicity. The tool does not require special software beyond the Excel macro SIPmath, which is open-source and free. It only requires that the planner estimate the basic parameters of probability distributions for a few stochastic events. By displaying the results immediately in a dashboard format, military planners can develop and describe risk assessments "on the fly." The obvious color-coded output facilitates communication with the decision-maker. This approach goes beyond traditional risk matrices, offering decision-makers a comprehensive and auditable risk assessment methodology (*SIPmath Standard*, 2019).

Commanders who embrace this quantified risk assessment methodology gain a significant advantage. They can make better-informed decisions based on accurate predictive analysis of potential outcomes. The S-RCOP's ability to model Worst-Case and Most Likely Scenarios enhances its utility in decision-making and planning, providing a nuanced understanding of the risks associated with mission variables. Overall, the S-RCOP contributes to a more resilient and adaptable approach to military decision-making in complex and uncertain operational environments.

5. Future Work

The next step for S-RCOP is to test the tool during the planning of a real or simulated military scenario. The tool takes five minutes to learn and could be shared amongst a military staff that is responsible for planning an upcoming exercise. This could be incorporated into war games or real exercises. Staff planners will provide valuable feedback for the improvement of the model's functions and display. In a future study, the unit commanders who receive their risk assessments via S-RCOP will be interviewed to determine their opinions. An intensive usability study would assist the developers in finding areas for improvement.

Microsoft Excel is widely available and already familiar to US military planners. However, a tool of this nature is perhaps better suited as a standalone application for more computational power and an optimal user interface. Some aspects of S-RCOP could be automated, such as the collection of lunar illumination data and the calculation of geographic distances between friendly and enemy forces. More research is required to determine whether a mobile phone version of an S-RCOP app would be useful at the tactical level.

For future work, this model can be easily expanded to include additional threat-based and environmental risks. Making a more expansive risk management model will not only improve a commander's awareness of the risks associated with a mission but also help planners communicate a more holistic COA. Suggested threat-based risks that can be included are cyber threats, threats to or from Unmanned Aerial Systems, and anti-aircraft threats (Park et al., 2018). Environmental considerations could also expand to urban operations, obstacles, and Chemical Biological Radiological Nuclear threats (Feuer, 2023). The more subtopics that can be included in the model, the better the product will be to communicate risk management. Additional model inputs and outputs will increase the complexity of the model but will only increase simulation time slightly.

Bayesian inference should be investigated for use in a military tactical risk model. In a Bayesian model, the parameters of the underlying probability distribution for a stochastic event are considered uncertain (rather than the data itself). Before observing new data (i.e., military intelligence), one has beliefs about the value of a proportion parameter and models these beliefs with a prior distribution. Once new data arrives, one updates one's beliefs by computing the posterior distribution, which can be summarized in the form of inferences (Albert, 2009). Bayesian models can account for many situations where Monte Carlo simulation would be inappropriate or inadequate. As conditions change on the battlefield, a staff's common operating picture would benefit from a Bayesian model's ability to update prior beliefs as new data is observed.

6. Citations and References

Albert, J. (2009). *Bayesian Computation with R* (2nd ed). Springer.

Benson, K. (2019, April 25). *Tactical Risk in Multi-Domain Operations*. Modern War Institute. https://mwi.westpoint.edu/tactical-risk-multi-domain-operations/

Christian, M. J. T. (n.d.). *An Examination of Force Ratios*.

Christianson, M. J. (n.d.). *The Search for Suitable Strategy: Threat-Based and Capabilities-Based Strategies in a Complex World.*

Department of the Army. (2019). *The Operations Process* (ADP 5-0). https://armypubs.army.mil/epubs/DR_pubs/DR_a/ARN18126-ADP_5-0-000-WEB-3.pdf

Department of the Army. (2016). *Operations* (ADRP 3-0). https://usacac.army.mil/sites/default/files/publications/ADRP%203-0%20OPERATIONS%2011NOV16.pdf

Department of the Army. (2021). *Risk Management* (ATP 5-19). https://armypubs.army.mil/epubs/DR_pubs/DR_a/ARN34181-ATP_5-19-000-WEB-1.pdf

Department of the Army. (2019). *The Operations Process* (ATP 2-01.3). https://armypubs.army.mil/epubs/DR_pubs/DR_a/ARN18126-ADP_2-01.3-000-WEB-3.pdf

Feuer, A. (2023). Environmental Warfare Tactics in Irregular Conflicts. *Perspectives on Politics*, *21*(2), 533–549. https://doi.org/10.1017/S153759272200189X

Harrison, R. L. (2010). Introduction To Monte Carlo Simulation. *AIP Conference Proceedings*, *1204*, 17–21. https://doi.org/10.1063/1.3295638

Monte Carlo Simulation: History, How it Works, and 4 Key Steps. (n.d.). Investopedia. Retrieved October 5, 2023, from https://www.investopedia.com/terms/m/montecarlosimulation.asp

Park, K.-S., Cheon, S., Kim, S.-P., & Eom, J. (2018). Security Threats and Scenarios using Drones on the Battlefield. *Convergence Security Journal*, *18*(4), 73–79.

Savage, S. L., & Markowitz, H. M. (2009). *The Flaw of Averages: Why We Underestimate Risk in the Face of Uncertainty*. John Wiley & Sons.

SIPmath Standard. (n.d.). Probability Management. Retrieved October 5, 2023, from https://www.probabilitymanagement.org/sipmath-1

Wampler, R. L., Centric, J., & Salter, M. S. (1998). *The Military Decision-Making Process (MDMP): A Prototype Training Product.:* Defense Technical Information Center. https://doi.org/10.21236/ADA343154