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COMPUTER EXPERIMENTATION AND SCENARIO METHODOLOGIES TO SUPPORT INTEGRATION AND OPERATIONS PHASES OF MISSION ENGINEERING AND ANALYSIS

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ABSTRACT

Mission engineering is a recently proposed concept that needs practicable means to implement. Integrating a new system into technical and organizational architectures is a critical part of this initiative. Additionally, it requires an in-depth understanding of the system's operational employment. This paper describes the development of the integration and operations support system, an innovative use of scenario methodologies, computer simulation, and experimentation to shape a strategic analysis framework for mission engineering. A scenario from an actual computer aided exercise, Cobra Gold 2018, is the backdrop of the support system. The Joint Theater Level Simulation drives the operational vignettes for the training audience in this multinational exercise. Our approach is to automate the exercise, thereby creating an experimentation environment for a knowledgeable team to form credible, analytically derived insights about a new system. We generalize this approach and provide a use-case via a planned study on future naval capabilities.

1 INTRODUCTION TO MISSION ENGINEERING AND ANALYSIS

Under the United States National Defense Authorization Act for Fiscal Year 2017 (United States House of Representatives 2016), mission integration management entered into prominence. The tenets of this Act place emphasis on systems engineering and coordination of major interfaces among the military departments. These joint efforts produced mission engineering (ME), which Gold (2016) defines as the "deliberate planning, analyzing, organizing, and integrating of current and emerging operational and system capabilities to achieve desired warfighting mission effects." From an engineering perspective, the system of interest (SoI) is the "mission," where different weapon systems are just one category of components (Wasson 2016). The system lifecycle is the time period from which the conflict situation first emerges to when the mission is accomplished. There are three major processes in the ME lifecycle: system acquisition, system integration into a system of systems (SoS) architecture, and actual operations that execute the mission plan (Figure 1). Hernandez, Karimova, and Nelson (2017) refined the initial definition of ME by including mission and support plans as part of the SoI, and highlighted continuous analysis to inform transitions between ME processes. The result is mission engineering and analysis (MEA). As depicted in the center of the MEA model, there is an emphasis on how the primary processes are buoyed by systems engineering (SE) and systems analysis (SA) techniques, which are employed during mission planning and execution (Hernandez et al. 2017).

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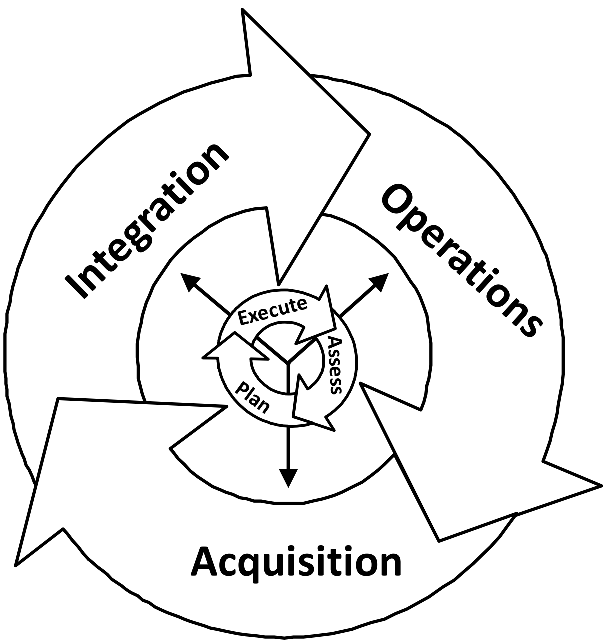


Figure 1: Transitions among primary MEA processes are continuous (Hernandez et al. 2017).

As in the military decision making process (MDMP), cross-talk and evaluation continue throughout the planning, execution, and assessment stages of an operational scenario. This nuance is not recognized explicitly in the original ME model (Gold 2016). The MEA uses the MDMP as the foundation for structuring activities, but it applies SE and SA methods to develop products in each of the major processes. The resultant framework provides a high-level methodology that can address engineering and non-engineering problems. However, neither the ME nor MEA processes provide the means to support exchanges between the major processes. We developed the integration and operations support system (IOSS) to facilitate the implementation of MEA and to increase the utility of the overall framework.

2 INTEGRATION AND OPERATIONS PROCESSES IN MEA

2.1 Integration

Integration in MEA examines how new systems and capabilities are incorporated into an existing SoS. Emphasis is on analyzing interactions between the embedded system and the executing organization and the mission conditions. The SE process continuously recalls the system requirements and the context for system use (Blanchard and Fabrycky 2011). Studies that derive from the SE process include incorporating human operators who interact with the system, or adapting an organization's maintenance system to the reliability and availability characteristics of a new system. Essential to the successful integration of the system is an analysis of its role according to doctrinal and operational policies. This point echoes Gibson, Scherer, and Gibson (2007) who posit that SA = Operations Analysis + Policy Analysis.

A holistic analysis of the SoI and its relationship with constituent systems and the operational environment is the focus of integration. The IOSS applies scenario analysis and systems thinking as essential techniques for examining and planning the successful integration of a system. Wargaming and other scenario methodologies are valuable for visualizing the entirety of a problem or potential solutions (Gilad 2008). Scenario planning is essential for constructing conditions that involve an active, intelligent adversary with opposing objectives (Chermak 2011). It places the player in a conflict situation that must be resolved. The scenario includes variables in the form of other systems and subsystems, organizations, policies and procedures. Engineers can review current strategies, internal processes, and knowledge of the workforce in these exercises. The ability to see multidimensional relationships of a problem play out in a scenario is the most potent principle in systems thinking (Gharajedaghi 2006).

2.2 Operations

A new system's role and contribution to mission accomplishment is a critical point of analysis in MEA. The application of national power—diplomatic, economic, informational, and military—flows from strategic decisions down to operational execution. For the purposes of this paper, we center on military operations. Military command and military operations implement system capabilities to accomplish mission goals (DA 2012a). Thus, the IOSS examines a system's contribution to successful achievement of operational objectives.

Military activities occur at tactical, operational, and strategic levels. At all levels, mission planning is essential, and in this sense, tightly coupled with MEA. The MDMP is a proven method for assessing an operational problem to develop a solution. It results in an operations order or plan, which provides a concept of operations for completing the mission (DA 2012b). The operational plan implements a system in context of the mission and presumes that the system is completely integrated at the component and subsystem levels, and is ready for use in a combat environment.

Wargames are a primary tool for analyzing courses of actions in the MDMP (DA 2012b). In MEA, games and experimentation are effectual verification and validation techniques for understanding and determining the degree that a system contributes to mission success. These analyses include development of relevant metrics and an approach for comparing alternatives. They derive from the SE process and cross pollinate with other engineering phases such as test and evaluation (Blanchard and Fabrycky 2011). As incorporated in IOSS, wargaming techniques, operations analysis, computer simulation, and experimentation produce an analytically defensible case for the operational merits of a system.

3 ON THE DEVELOPMENT OF THE IOSS

3.1 Cobra Gold 2018: A Computer Aided Exercise

The working scenario for the IOSS is based on an actual computer aided exercise (CAE). The exercise scenario is rich with conflict situations and numerous vignettes to examine different topics and systems. In model based SE (MBSE) and modeling and simulation based SE (MSBSE), the operational environment (OE) is fused into a scenario (Clymer 2009; Gianni et al. 2015). An accepted system model enters the simulated scenario so that stakeholders can gain shared insights about it. Data collection to support evaluation of system performance and conceptualization of system employment are two major reasons for using models and computer simulations (Clymer 2009). The project team's overall intent is to automate the CAE and to create a structure for scientific experiments on the model of a new system.

Cobra Gold 2018 (CG18) is a multinational exercise consisting of live and virtual military units from Indonesia, Japan, Malaysia, Singapore, South Korea, Thailand, and the United States. Interagency and non-governmental agencies also played major roles in the operational scenario. Operations occurred in a fictional landmass called Pacifica. A multinational force (MNF) used combined air, land, and sea power to meets its mission and perform a number of key tasks. These tasks included achieving air superiority, peace enforcement, maritime interdiction, counter piracy, and humanitarian assistance.

The CG18 scenario has the necessary elements for an analyst to investigate the performance of current, new, or envisioned systems. From this scenario, specific vignettes make it possible to stress a system and visualize its relationship within a network of systems and physical surroundings.

3.2 Exercise Driver: The Joint Theater Level Simulation (JTLS)

To elicit response from the training audience in CG18, the exercise sponsor employed the JTLS, which has supported Unified Commands in training exercises for over 35 years. The most current version of the simulation is JTLS – Global Operations (JTLS – GO), an interactive, internet-enabled application. For our purposes, we refer to JTLS – GO simply as JTLS. Originally designed as a tool for development and analysis of joint, combined, and/ or coalition operations, it models multi-sided operations with logistics, special operations forces, and intelligence support. Today, JTLS is primarily used as a training support model that is theater-independent (https://www.rolands.com/jtls/j_over.php). Nearly two years before executing the exercise, the sponsor had chosen to use the JTLS during the planning phase of CG18.

3.3 Data Collection Scope

A major task for the research team was to develop a means to run different instantiations of the scenario without human players. As such, a process to automate decision making and order entry into JTLS was essential. Automating the activities in a scenario required reconstruction of the storyline in which certain conditions preceded decisions and actions. Therefore, the data collection effort focused on the data elements that are necessary for creating a scenario (Curry and Perla 2011). Figure 2 is the underlying storyline structure for the CG18 scenario. It contains the data elements that the team needed.

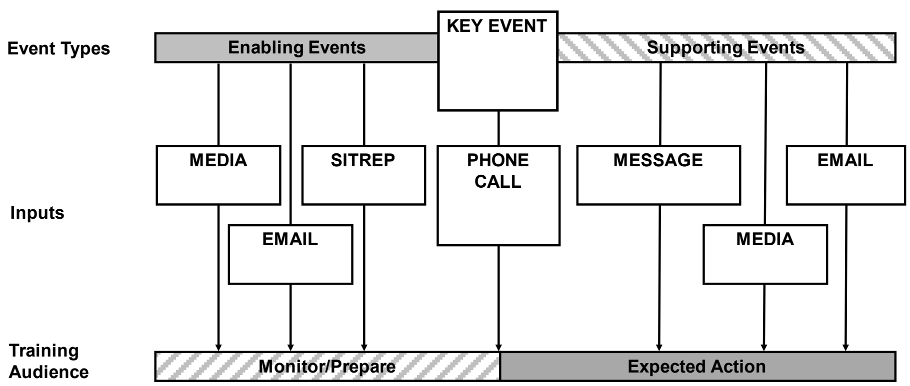


Figure 2: The storyline structure in an exercise parallels the team's data requirements.

A study of Figure 2 determined where to place the team to gather data. For instance, "Expected Actions" from the training audience included verbal interchange between key players. Data collection recorded end-to-end discussions and the ensuing JTLS orders that culminated into activities and outcomes. Team members were stationed in response cells where JTLS players communicated with the training audience, as well as technicians to translate the training audience's operational vision into JTLS orders. Because the team's focus was on naval activities, data collectors were located in the Marine Corps cell and in the Navy cell. Data collectors also had access to the technical control cell and to the enemy cell.

3.4 Software Development for the Automated Technical Controller (ATC)

Simulation setup for most any CAE is complicated. JTLS exercises are no exception. Prior to starting a game, it must be configured from a scenario, which exists as a collection of files and folders. Part of the configuration process establishes ports on the computer for networked services to communicate with each other. To begin a JTLS game, a human Controller initiates the web services via the Web Service Manager (WSM), starts the Combat Events Program (CEP), and then sends a start order through the Web Hosted Interface Program (WHIP) to the CEP. A human also sends an order to the CEP to stop the game. Developing an ATC makes single or multiple simulation runs possible without a human in the loop (HITL).

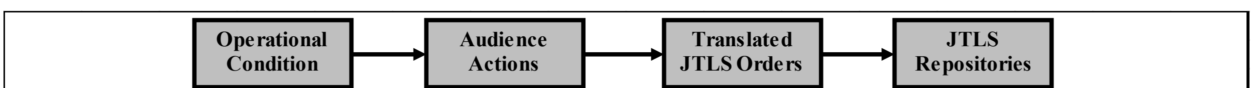
Automating the JTLS required a thorough understanding of the software and its internal activities, as well as its interfaces with external software. The automation program exists as a "wrapper" about the JTLS and must perform the following functions:

- Create a game from a scenario. This is necessary to run replications that supports experimentation. Each run is an instantiation of a scenario for which analysts can modify random number seeds.
- Configure the game. Automation includes setting up the computer ports so that multiple, concurrent instances of a game can be run simultaneously (on one computer).
- Start web services. JTLS requires a number of web services to run in its environment. They include: Apache Web Server, JTLS Object Distribution Authority (JODA), XML Message Service (XMS), and Order Management Authority (OMA).
- Start the CEP. The CEP is the underlying simulation engine and must be running for JTLS to operate. It is the only vehicle to initiate activities in the JTLS.
- Send a start game order to the OMA.
- Systematically and periodically collect and parse messages for metrics of interest, anecdotal information, and simulation time.
- Post-process game output (primarily from JTLS messages) and convert pertinent data into a usable format. After game completion, experimenters and subject matter experts must perform analyses to address research questions and game objectives.

3.5 The Automated Player (AP) and Decision Matrices

To automate the operations of JTLS entities requires an understanding of orders. Human players interacted with the CAE by sending orders, viewing unit status and other metrics, and receiving messages via the WHIP. An advantage of using JTLS is that its entities already have some ability to perform actions automatically so that a human player does not have to micromanage each entity (e.g., planning a route and moving from its current location to a new location).

For an AP to submit orders in place of human players requires information from the state of the game. Software within the ATC for monitoring JTLS messages can provide the state of the simulation to the AP. Similarly, ATC software that sends game orders to the OMA can be used for specific component players to send other orders to the OMA. The biggest challenge for creating the AP was in developing and implementing the decision matrices or other suitable computational representation so that the AP's actions reflect reasonable actions to a given situation that a human player would make. The team identified the set of messages or simulation input that contained the necessary situational information that would prompt the necessary game orders. Figure 3 is an approach for tracing conditions to decisions and orders, which subsequently require data from different JTLS sources such as the simulation database and unit reports.



Conditions				Actions				JTLS Orders				Data Sources			
A	B	C	D	1	2	3	4	i	ii	iii	iv	a	b	c	d
X	X		X		X				X	X	X		X	X	
		X					X				X		X		

Figure 3: Mapping CAE conditions with JTLS orders to develop decision matrices.

Automating a player for an extended period is a significant challenge for a programmer. The team elected to scope the problem so that AP actions involved only a slice of the CG18 scenario. Specifically, a continuous 24-hour period of events during the second and third day of the exercise fit the project team's purpose. This time segment was the most active period for naval operations. In a wargame, "turns" are specific intervals of time in which player decisions are adjudicated so that new conditions may be presented to the training audience for a new round of interactions and decisions (Sabin 2012).

Developing an AP must account for the military component (response cell) in which the player resides. Roles that players assume dictate the types of decisions and actions that they make (Lindren and Bandhold 2009). The required set of JTLS orders must follow if the decisions are to have any impact on the game. Consequently, these orders need data. Consider Figure 3 where a player monitors conditions A, B, C, and D. If the player sees that conditions A, B, and D are present (marked by an "X"), then it triggers a decision to take action 2. To execute action 2 in JTLS requires orders ii, iii, and iv to be entered into the simulation. The data to complete the orders may exist in the unit database or in a unit report. Software to automate this sequence of activities uses decision matrices with constructs similar to this conceptual model.

3.6 Incorporating Experimental Designs

Constructing an experimentation environment is the next step in developing the IOSS. It requires expanding the functionality of the ATC and the AP(s) to generate and run a complete set of experiments. Following Figure 4, the first step in experimentation is identifying the factors of interest. These are variables that analysts or study sponsors believe have an impact on relevant metrics of the game. Based on the number of factors, the team constructs a design of experiments (DOE) that may be ingested into the JTLS architecture in much the same way a database becomes part of the exercise configuration. A function to initiate the DOE in JTLS will be part of the ATC. The ATC prepares each instantiation of the scenario and the number of replications, along with a new random number seed. For each run, the AP conducts the necessary activities for the JTLS instantiation. Software to extract relevant data from each run produces a sample of observations for analysts to study.

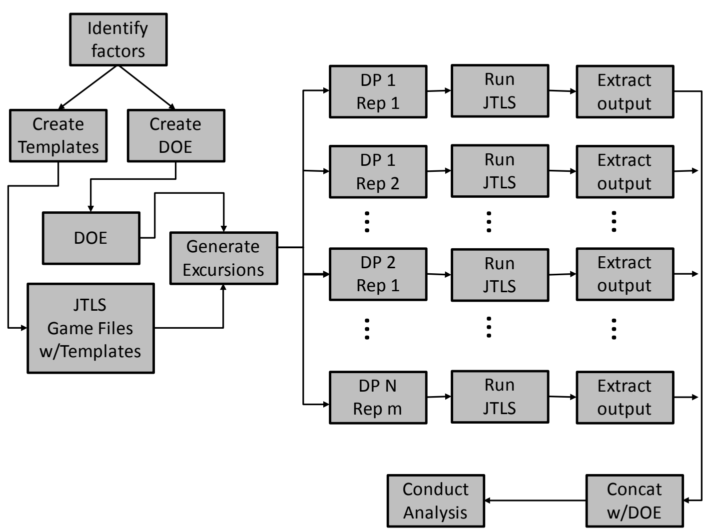


Figure 4: Incorporating experimentation in JTLS.

3.7 Progress in Phase 1 Development

This research effort comprises two phases. Phase 1 develops the ATC and AP. Phase 2 incorporates experimental designs, experimentation that includes automated modification of input parameters, and data farming and analysis tools. At the first stage of development, the team has written software prototypes, designated "jtlsfarmer," in Python3 (https://www.python.org). Completion of Phase 1 affords a capability to inject entities with new or planned capabilities into the scenario. An analyst can study a future capability without a supporting cast of hundreds of simulation technicians, thousands of players, and training units.

The jtlsfarmer breaks down the terabytes of text from JTLS into data elements that the team can use for analysis, as well as informing the AP. There are 297 different message formats in JTLS. The team identified three key message formats that the software program must first parse. The jtlsfarmer extracts unit status and losses as a result of attrition from combat or other events. These data are necessary for post-processing and development of operational effectiveness measures. Additionally, jtlsfarmer deconstructs the static and dynamic vocabulary files and converts them into a database format that will provide a mapping of coded values in messages to actual values in the simulation.

While work in Phase 1 simultaneously supported Phase 2, the focus was clearly on Phase 1. The team first executed a fully automated instance of a game from start to finish (minus the AP). Successful development of the AP positions the team for Phase 2.

3.8 An Initial Construct for Developing an IOSS from Other CAE

While the development of the IOSS is presented in terms of CG18 and the JTLS, the process that this paper describes is applicable to other simulations and exercises. As noted earlier, the choice of CG18 and the JTLS aligned with a customer's need to investigate unmanned systems for maritime operations.

Cayirci and Marincic (2009) present a model for preparing a CAE. The process has a number of similarities to the approach that has been described in this paper. Accordingly, we introduce a corresponding structure for transforming a CAE into a customer defined IOSS (Figure 5).

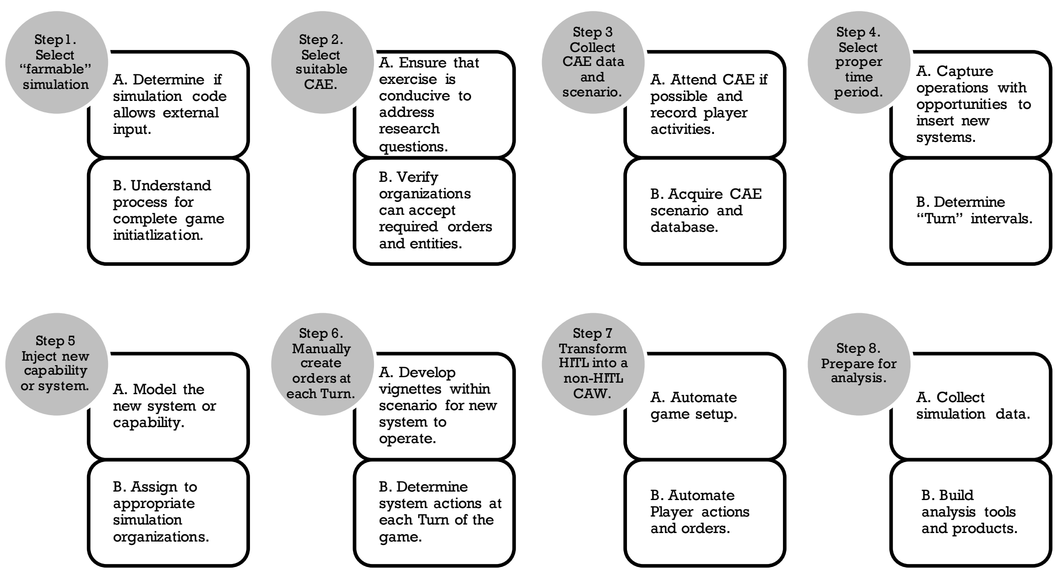


Figure 5: A structure for transforming a CAE into an IOSS.

The steps in Figure 5 begin after considering a CAE and the associated simulation software. Step 1 examines the computer simulation to determine if its architecture is open enough to accept orders from external routines. A check to ensure that the scenario and operations have utility for the customer makes up Step 2. The third step is simply data collection. The team that transforms the CAE must understand the context of the orders that are recorded in the simulation, as well as the exercise results. Step 4 consists of identifying a period that captures the activities that most meet customer objectives. Additionally, the team determines the time intervals for the game "Turns." This step is critical because it provides the opportunity for where a HITL can submit orders in the first run of the exercise. These orders are later submitted without a HITL in Step 7. In Step 5, the team models the new systems and\ or capability that will be incorporated in the CAE for study. Step 6 corresponds with Step 4; the team creates the vignettes and manual orders that the new system executes at each Turn. Step 7 automates the game setup, which supports a replication of a simulation run. This step also automates Player submission of orders. Finally, the complete IOSS must collect simulation data to support analyses that address the research objectives. While we will not attempt it in this paper, this abbreviated explanation for creating an automated CAW from a HITL CAE could be the start of a taxonomy for CAE-derived automated wargames.

4 APPLYING IOSS TO EXAMINE FUTURE NAVAL CAPABILITIES

The U.S. Navy Warfare Systems Directorate (N9) is charged with examining future capabilities that support the strategic vision for maritime forces. However, the Directorate has limited organic assets to perform the necessary analyses related to this mission. As such, N9 seeks a self-contained, experimentation environment to develop insights regarding the impact of projected naval capabilities on military success. To illustrate the IOSS's value, we describe its planned use for investigating new unmanned system technologies in the CG18 scenario.

4.1 Opportunities to Improve Naval Forces with Unmanned Aerial and Underwater Vehicles

Maritime forces in CG18 had a number of major tasks: embargo, interdiction, and an amphibious raid. Within these operations the team observed opportunities to improve the naval force (Table 1). For instance, on Days 2 and 3 of the exercise, the enemy launched a series of theater ballistic missile attacks against the MNF. However, the air defense radar systems with the MNF units were inoperable and thereby were "blind" to incoming missiles. Without a credible missile defense, the MNF was extremely vulnerable to the attacks and suffered significant personnel and equipment losses. This incident generated an idea for modeling a UAS with radar capabilities that could communicate with the air defense units.

Table 1: Examples of CG18 events that could benefit from inserting unmanned system capabilities.

CG18 Day	Observed Events	Emerging Issues	Unmanned System Capability
Day 2	SAMs shoot down 2 x P-3C during the aircrafts' patrol missions.	Decrease in the MNF ISR capability will require diversion of other assets.	Unmanned Aerial Systems (UAS)
Day 2	The USS ABC is ordered to shadow MV XYZ; requires closing speed ≥ 32 knots.	USS ABC speed insufficient. Delayed actionable intelligence; require other assets.	UAS, Unmanned Underwater Vehicle (UUV)
Days 2 & 3	Series of theater ballistic missiles are launched against MNF at regular intervals. Air defense radars inoperable.	Degraded air defense. System is "blind." No ability to target incoming missiles.	UAS

4.2 Process for Conducting UAS and UUV Studies

Study of future UAS and UUV capabilities would follow MSBSE and MBSE approaches in which experimentation is central. The core of both processes is on innovative and interdisciplinary design to develop complex systems. The critical element is the model of the system. Examining the model in a specified scenario provides stakeholders a common understanding of the system's operational capabilities and interactions with battlefield surroundings. Simulation based engineering defines three levels of analysis: mission, functional, and processes or interactions (Clymer 2009). The IOSS focuses on the system's mission level capabilities (operational value) and its interactions (integration within the SoS).

Analysts modified the JTLS's unit and system prototypes to model UAS and UUV attributes that aligned with future capabilities in which the naval enterprise plans to invest. Unified Commands, as well as the international JTLS users, have already accepted the JTLS unit and system templates. Analysts would manipulate the prototypes to reflect the behavior of the unmanned system. For instance, a small submarine could be changed to operate as a UUV with equal or enhanced speed as the submarine. However, its defense capability may be less than a submarine with humans to operate it. In the case of the UAS, an ability to swarm and create an ad hoc radar system is a possibility.

While the MSBSE approach would normally develop a scenario to insert the system model, this project had a readymade environment in CG18. Analysts can study different operations and vignettes for the UAS or UUV in the JTLS CG18 scenario. Once an acceptable system model is developed, the analyst can build the activities using the JTLS rules and the decision matrices for specific force component response cell. These studies provide an understanding of interrelationships among different variables in the scenario, which are near impossible to examine with more conventional approaches. For instance, a system that is associated with n different domains would involve $2^{n-1} - 1$ interactions. As n increases, the exponential growth in the number of interactions quickly makes it impractical to exhaustively examine them. Computer experimentation and efficient designs create a comprehensive picture of the system that can be methodically studied for significant variables, as well as important interactions (Koehler and Owen 1996).

4.3 Data Farming and Analyses

While data mining explores a store of available information, data farming grows or generates data through experimentation. Applying customized experimental designs, analysts collect samples that can withstand analytic scrutiny. The IOSS's ability to run replications of each instantiation of the scenario provides statistical rigor for constructing a solid understanding of decisions and operational conditions with regard to their relationship to game outcomes and relevant measures of effectiveness (MOE).

Efficient experimentation and cluster computing can investigate a large number of design points that cover the design space. Applying valid estimates of the MOE, the experimenter can develop analytic products to gain insights about the system. Figure 6 is a notional graph for illustrating a comparative analysis for different configurations of a UAS, based on the ability to classify enemy SOF who have entered a particular defense zone (MOE #1).

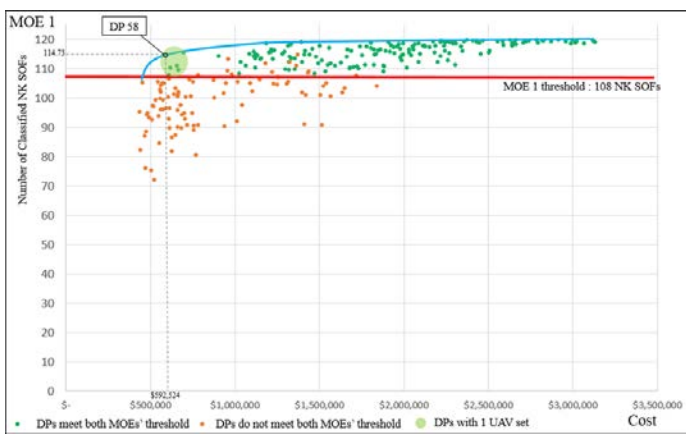


Figure 6: Analytical products can include an efficiency frontier to develop a cost position (Kim 2017).

The curve shows that a number of UAS configurations successfully achieve a threshold for MOE #1, but do not achieve the threshold for a second MOE. The shaded area shows options that meet both MOE for the least amount of money.

IOSS can also examine how a system performs in stressor scenarios, severe conditions in which the system can fail. Figure 7 presents results of a notional weapon system in a conflict situation involving two factors: weapon distance from the target and time before sunset (Hernandez 2017). In this case the combat environment instead of the system attributes act as the factors for the experiment.

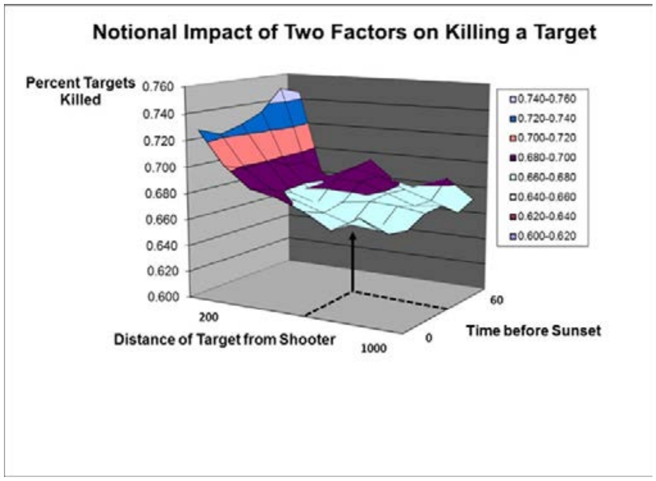


Figure 7: IOSS can identify interactions that stress the system to the point of failure. (Hernandez 2017).

Figure 7 shows that an inversely dominated condition occurs when there is less than thirty time units before sunset and the weapon is more than 600 units from the target (Hernandez 2017). In short, the weapon system performed worse at this pairing of factor values than in all other combinations. Similar investigation of system interactions with other systems and environmental variables is possible.

There are numerous analysis techniques that experimental data can support. With IOSS, engineers applying the MEA approach can develop a research methodology that incorporates experimentation and scenario analysis. Another important element of building the IOSS was designing tools that can adapt to assessment needs. To keep the IOSS current, work to automate the creation of analytic products is ongoing.

5 CONCLUSIONS

The IOSS is a fundamental, but critical step in building analytic support tools for MEA. As a strategic framework to organize analyses in MEA, IOSS serves as a continuum to inform all stakeholders during system development. While IOSS targets integration and operations phases of MEA, analyses feeds the acquisition process as well. The result is a powerful instrument to aid system design and development.

Constructing the IOSS was a major effort. Taking the human out of the loop from an executed HITL game is a tremendous undertaking. The effort required automating the game mechanics and the human player. The latter task presented the greatest challenge. To create an AP, the team decomposed the problem into manageable parts. First, scoping the timeline to 24 hours made the number of automated decisions and activities manageable. Leveraging the JTLS internal automation further reduced complications with some tasks. Focusing on specific MNF components, the team was able to streamline mapping decisions to the desired operations, and associated JTLS orders. Subject matter experts compared the automated decisions and outcomes with the actual exercise to test the veracity of the AP's choices.

The IOSS is a toolset that can provide analytically derived evidence to support decisions. It complements existing tools that afford other perspectives while emphasizing different aspects of the new system(s) and accompanying environments. As Gibson et al. (2007) explain, system analysis is an iterative process for gaining an understanding of relevant characteristics of the SoI. Sequential analysis can involve different research techniques at each step. We have adopted computer-based models in IOSS. This approach can include models that can differ in fidelity, dimensionality, or operational scale. However, IOSS maintains a mission level focus of the system to support a strategic perspective of MEA processes.

The utility of IOSS resides in the analytic rigor that it facilitates. The statistical methods that IOSS can support is a direct result from generating data samples with sufficient pedigree to withstand close examination. As such, data farming through computer experimentation is critical to IOSS. The ability to replicate different instantiations of a scenario and initiate different random number seeds are equally important. Experimentation is a significant value added to MEA with little to no additional investment. Libraries of experimental designs are available for employment in the game setup.

A notional implementation of IOSS to study future capabilities for the Navy's N9 highlights its value. Developing the IOSS in context of an executed CAE opened numerous vignettes that can explore different future capabilities. Such studies guide construction of a concept of operations, as well as insights to the potential contributions that new capabilities can add to the success of the force.

This paper describes the development of the IOSS. Moreover, it highlights the innovative application of modeling and simulation, experimentation, and scenario methodologies in a stand-alone system that facilitates statistically rigorous studies about new systems that are entering existing organizations. IOSS enables successful integration of a system by identifying notable interaction within a SoS, while quantifying a system's operational value. The generalized approach to develop an IOSS offers future value to MEA.

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