



Objectives and Capabilities of the System of Systems Survivability Simulation (S4)

by Raymond Bernstein Jr., Richard Flores, and Michael Starks

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Survivability/Lethality Analysis Directorate

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14. ABSTRACT This technical note documents the development of the System of Systems Survivability Simulation (S4) to date. The objective of S4 is to provide a survivability, lethality, and vulnerability (SLV) methodology that will support system-of-systems (SoS) analysis and the necessary transformation from a Forces-based, materiel-centric Cold War posture to a mission-centric, effects-based asymmetric warfare focus. S4 is focused on the collection of decision-making processes (DMPs) at all levels of the hierarchy and the time-varying interaction with information and knowledge that support the war-fighting capability.				
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1. Introduction and Motivation

During the cold war the U.S. had time on its side. As Army forces lined up across the Fulda Gap from their Soviet counterparts, they had a significant qualitative advantage in their equipment. These U.S. forces also had the advantage of being supported by the strongest economy in the world, which in turn portended the continuation of that advantage for as long as necessary.

It took the U.S. a long time to design, develop, and field equipment during that era; it also took a long time to make appropriate modifications to tactics and operational doctrine. These lengthy cycles were regarded as an affordable cost, since we faced a principal adversary that was both technologically unsophisticated (at least relative to the U.S.) and operationally very conservative and hierarchical. The situation has dramatically changed since the fall of the Berlin Wall.

The U.S. is now engaged in war with non-national enemies. These enemies do not have an elaborate program of defense research, development, test, and evaluation (RDT&E) and they do not have large cadres of uniformly well-trained troops. What the terrorist enemies do have, however, are very rapid cycle times for fielding lethal technologies and for figuring out how to use that technology to maim and kill American soldiers. The decision processes on both sides of this conflict are decidedly non-traditional.

In addition to the new challenges associated with non-national enemies, there is another important new challenge that has evolved over the past decade. U.S. military policy has moved rapidly in the direction of greatly increased emphasis on force deployability. The conventional design process for U.S. ground combat forces has tended to reduce deployability in favor of survivability. As vehicles were equipped with heavier armor or more armor, they became more difficult to transport to a foreign theater. Since rapid deployability has become a national and Army priority, traditional means for assuring Army system survivability (i.e., up-armoring) are no longer the most practical. Future system survivability for ground combat vehicles will consequently be much more dependent on self-defense technologies (e.g., active protection systems, active armor) in concert with the use of situational awareness and the enabling communications network, sensors, information processing, and decision aids. In short, Future Force survivability in conventional warfare will be less dependant on individual vehicle protection and more dependant on the incremental survivability obtained by being part of a system of systems (SoS).

There is unwarranted optimism in some quarters of the analytical community that the Army can solve problems of quantifying SoS survivability issues by diligent application of existing Army analytical tools. This is implausible at face value since these tools were developed to assess individual items of equipment. As we see it, “SoS” names a large, important, but still largely undefined Army problem.

We need to share our vision of the SoS problem so that the reader can better understand the System of Systems Survivability Simulation (S4) as a response to it. A logical starting point is to understand what change has occurred on the battlefield that resulted in a requirement to analyze the battlefield SoS. After all, there have always been many systems (e.g., tanks, helicopters, soldiers, etc.) connected via different forms of communications on the battlefield. What has changed?

The fundamental change involves the type, quantity, and quality of information on the battlefield, coupled with the speed with which it is or will be available via the Army's communications networks. The availability of such information in the envisioned environment to every soldier, not solely commanders, offers a unique opportunity to evolve a new dimension in the art of war. While technical hurdles remain before this capability is fully realized, the planned communications networks afford the possibility of having otherwise autonomous and independent entities on the battlefield operate as one, as an SoS. Army doctrine is that the whole (an SoS) has greater combat power than the sum of its parts. This result is from the sharing of continuous, real-time, accurate information between the various systems on the battlefield, which leads to significant gains in performance, lethality, and survivability.

The notion of a significantly more lethal and survivable whole resulting from the continuous sharing of real-time accurate information is at the core of both the Army and S4 visions. Continuous, real-time, and accurate battlefield information provides the input needed by each military entity on the battlefield to make timely and winning decisions. These decisions and their consequences are then transmitted to other entities on the battlefield that in turn use them as inputs to their own decision-making processes. The goal of S4 is to model the complex dynamics of these battlefield decision processes. A critical component of the S4 project is the development of a communications model that addresses the requirement to have continuous, real-time, information flow modeled within S4.

One consequence of SoS success being a function of the information transmitted throughout the battlefield is that the vulnerability of the communications network has first order effects on the survivability of the SoS. A closely related premise is that on an information-dense battlefield, the decision-making processes are the primary drivers of battlefield dynamics. War-fighting technology will always be important, but survivability now hinges principally on decision quality.

No significantly new SoS is realized if the communications network does not or cannot provide continuous, real-time, accurate information. The absence of the communications network capability described above results in a traditional, platform-centric force. This information providing capability is the glue that links the different systems on the battlefield into a more capable whole. Adequately modeling this characteristic of the Future Force poses a significant challenge.

A new set of fundamental analytical questions must be answered as we begin to understand the "new battlefield physics." We need quantitative measures to intelligently consider continuous, real-time, and accurate information. The following are examples of relevant questions for this endeavor: How much information is enough? How much is too much? How much is optimum? How do we know how much is enough, too much, or optimum? How fast does the information need to be available? What happens if the information flow is stopped or seriously degraded? Analytical tools or models to answer these basic questions do not exist today.

Our strong emphasis on an appropriate communications model for S4 is a direct response to this void. Input and output parameters and metrics are being developed and theories are being formulated to describe and quantify the “physics of information and information flow.” As this body of knowledge grows, insight into the inherent vulnerabilities of such a system will be gained. It will be possible to develop recommendations and programs to enhance the survivability of the communications network and thus the SoS. In the future, we expect that the effects of information warfare and electronic warfare attacks on the SoS can similarly be determined in a scientifically credible manner.

It is our firm belief that the Army’s analytical requirement is for a model that has decision processes at its core. It is not the technology-driven ground system capabilities that are the critical parameters in the survivability of the SoS. The technology-driven system capabilities can be considered, and are being considered, as initial conditions to the model, but not as objects under independent study. New technology provides increased context and complexity given the insertion of a new battlefield technology. The information flow and associated decision processes start with these initial conditions so that S4 can determine the best available solution to perform the mission. It is the decision processes, connected via communications networks as described above, that are the Achilles’ heel of the SoS.

It follows that a larger national focus on military decision cycles and decision processes is warranted. The U.S. must bring its unmatched scientific and engineering expertise to bear in order to explicitly address relationships between decision variability and the variability of combat outcomes. Only by subjecting these relationships to careful scientific treatment can the most appropriate tactical decision processes be matched to desired combat outcomes.

It is not practical for the Army to undertake a program of focused evaluation of Army decision processes at the neurophysiological level of each soldier. For the near term, a more aggregated analytical approach is required, by which we mean a methodology that includes as many as possible of the higher-level variables that drive and are driven by tactical decision making. Key high-level variables would express doctrine, tactics, commander’s intent, equipment, available intelligence, knowledge of enemy intent, planning process, and plan revision.

In the analytical process we envision, the decision-making process (DMP) for tactical situations must be construed in such a way that decisions are made based on orders from above; prior (actual or assumed) knowledge; and new perceptions and deductions. Key sources of fresh perceptions in combat are organic sensors and communication devices. Based on these classes of input (i.e., orders, prior knowledge, and perception) a decision maker, whether in the world or in our analytical process, should be able to revise plans in the face of changing circumstances.

DMPs take place at multiple echelons on the battlefield, and they should be construed as such in our analytical process. Although, in principle, these echelons run from the foxhole to the White House, it is a sensible practical procedure to begin our methodology development with the individual combat entity and only the first few levels of command. At each level, decision making should be modeled as being conducted by autonomous agents, with appropriate processes and inputs determined by the echelon of the agent.

For a model of U.S. tactical DMPs to be properly exercised under credible stress loading, enemy DMPs must be modeled with equivalent robustness. Both sides must have several echelons of autonomous agents; appropriate tactical objectives and commander's intent; and the ability to undergo appropriate changes in perception due to organic sensors and communications.

In the remainder of this technical note, we will briefly describe the current state of our S4 model. S4 is a multi-level, agent-based combat model with a focus on the survivability of U.S. equipment and forces as a function of DMP variability.

2. Objective

The objective of S4 is to develop a survivability, lethality, and vulnerability (SLV) methodology that will support the necessary transformation from a Forces-based, materiel-centric Cold War posture to a mission-centric, effects-based asymmetric warfare focus. The S4 embodies a collection of processes that revises strategies and behavior dynamically at all levels within the modeled military hierarchy and provides time-varying interactions of those processes with information that supports war-fighting objectives. The model produces one process for every agent on the battlefield (i.e., a soldier, tank, sensor, or platoon) and then organizes them into multilayer collectives. Each agent's revision process includes information and knowledge from local sensors, remote sensors via the network, its engagements and encounters, and its general situational awareness/understanding. That these capabilities are necessary for any adequate treatment of the postulated SoS has been previously discussed (1).

3. Approach

A comprehensive approach to SLV analysis (SLVA) must account for the tangible, physical, objectively measurable factors, as well as for the intangible, cognitive, ultimately subjective factors (traditional war-fighter expertise) that constitute mission success (tactics and doctrine). Implied requirements for the model include the following:

- Blue force tactics, doctrine, and decision making must be simulated in enough resolution to permit modeling of threat effects on all battlefield decision making, including the interactions of spatially separated battlefield entities.
- Co-evolution of friendly and enemy tactics, doctrine, and decision making is required as an inherent aspect of the process. This in turn implies that both Blue and Red must be adaptive within the model.
- SLVA of Future Force systems *inherently* requires an SoS perspective. This includes modeling information sharing via communications, transformation of information into an actionable form, and the decision processes that act on this information. All "relevant" interactions between decision makers must be adequately captured in the model to include characteristics such as decision cycle times for survivability to be accurately assessed.

- New performance, effectiveness, and survivability metrics are required to capture these time-varying (i.e., dynamic) interactions between decision makers in the context of the information available to them.

S4 is focused on the collection of DMPs *at all levels of the hierarchy*, and the time-varying interaction with information and knowledge that support the war-fighting capability. There is one DMP for each decision maker, referred to in the model as an agent (e.g., soldier, tank, platoon, etc.), on the battlefield. The level of aggregation of a decision maker will depend upon the particular issues the model is addressing. Currently, the lowest level decision maker modeled is at the platform level (e.g., manned combat systems (MCSs) and recon and surveillance vehicles (R&SVs)), as illustrated in fFigure 1.

These are aggregated at the Combined Arms Battalion (CAB), company, and platoon levels, as shown in figure 1. Unmanned aerial vehicles (UAVs) and unattended ground sensors (UGS) are currently modeled as relatively simple DMPs and are included for completeness.

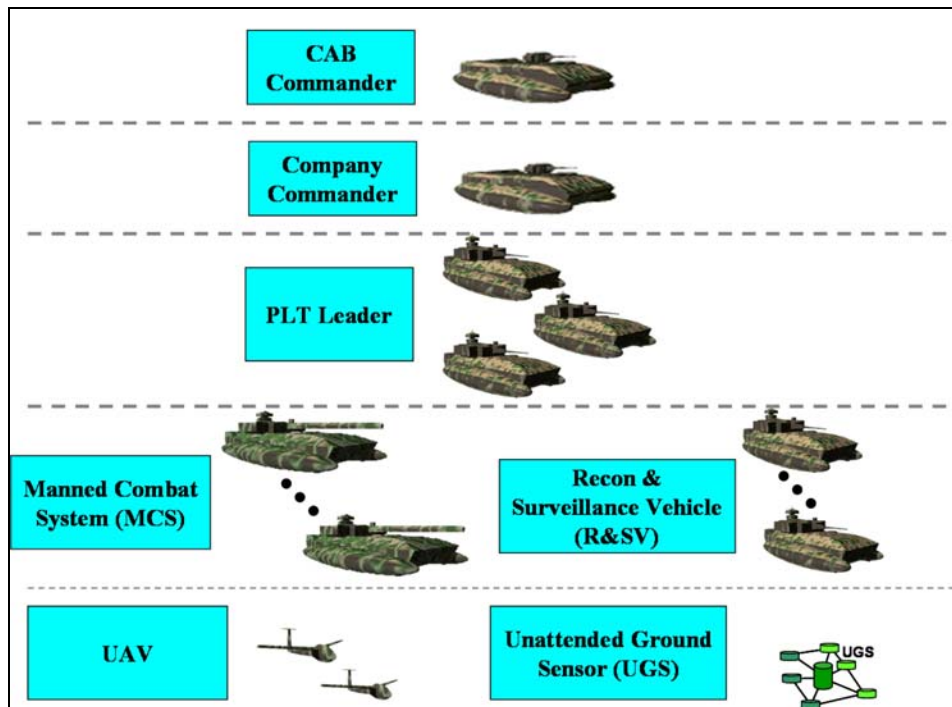


Figure 1. Exemplar S4 DMP hierarchy.

NOTE: PLT = platoon.

Each decision maker's current set of perceptions (i.e., the information obtained through sensors and communications) is modeled explicitly. Since each decision maker has an individual set of perceptions, there can and will be errors and omissions in this set of perceptions. This also provides for differing views between decision makers during the execution of a given run. This approach to modeling what a decision maker knows provides the basis for examining the full range of information operations to include deception and jamming. There is a ground truth version of the simulated world (not available to any decision maker) that is used to evaluate

events simulated in the world, such as the effectiveness of a weapon firing, whether a sensor detected a platform, and whether a particular communications transmission was “heard” by its intended recipient. The ground truth version is also used to capture what an agent should have been aware of, if not for communications breakdowns, sensor problems, misidentifications, etc.

Examples of the types of information and knowledge that supports the DMPs in the model includes information and knowledge collected from sensor data, such as position and movements of entities on the battlefield; current military objectives and tasks of battlefield units; events, such as engagement of forces; and equipment status, such as communications. Information is collected and disseminated explicitly through organic sensors and communications.

DMPs must be modeled such that the idea of the commander’s intent, planning, and orders, as well as a given entity’s need to respond to current circumstances within its environment, are taken into account. The degree to which an agent simply carries out orders (e.g., move to a new position) or responds to the present situation (e.g., reacts to an immediate threat) can vary spatially over the battlefield and over time. The model must and does allow for this.

In summary, the S4 model decision makers at all levels of the battlefield make decisions based on the information made available to them through sensors and communications. The environment that decision makers operate in must be sufficiently rich so that when a decision is made, the corresponding actions must have an appropriate effect in the simulated environment. These effects must be in turn be perceived appropriately by other decision makers. Finally, the time varying state in the simulation (i.e., sufficient information to reconstruct what has happened) must be made available for SLVA. In section 4, the model and corresponding process is described.

4. Model and Analytical Process Description

An overview of the S4 model is depicted in figure 2. The focus of the S4 model is the manner in which the various agents are represented (depicted in the center of figure 2). Each agent is represented with a DMP that has communication mechanisms used to share information. The model also represents sensing, maneuver, and engagement sufficiently to provide context for battlefield DMPs. The agent modeling technology provides for the ability to represent agents such as platforms (e.g., MCS, R&SV) and higher level decision-making entities.

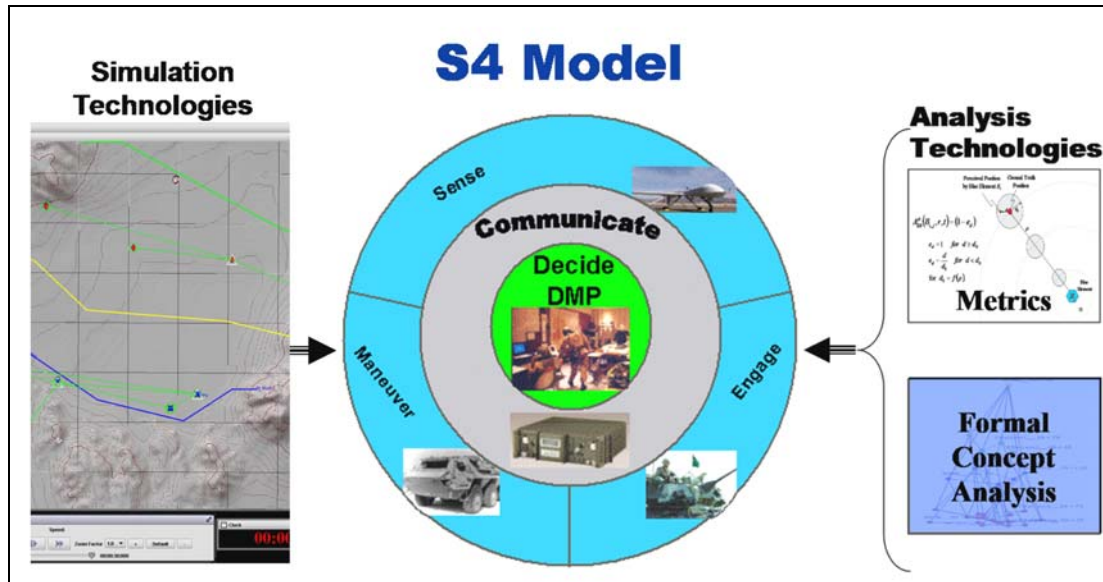


Figure 2. S4 overview.

This simulated combat takes place on three-dimensional terrain. Initial conditions for the model run, such as number, type, location, and orders of Blue and Red forces as well as their DMPs, are inputs to the simulation. Interactions are governed through a discrete time simulation model. Model execution is characterized by a sense, decide, and action loop that takes place for each agent in the simulation every half second (the discrete time interval). During the sense cycle, each agent is given the opportunity to acquire information through organic sensors and communication channels with other agents. During the decide cycle, each agent is allowed to use the information available to it to reason whether or not actions (e.g., sense, move, shoot, and communicate) are to be taken. During the action cycle, all agent actions are carried out and the results posted in the simulation environment. This process is repeated until the simulation terminates. As the model executes, state data is collected and stored persistently for later analysis. Sufficient ground truth data is also collected to allow the simulation to be played back and viewed from any participant's perspective and for detailed analysis of a particular decision maker's thought process to be performed.

The top level process for utilizing the S4 model is shown in figure 3. The process begins by the identification of an issue that is turned into one or more questions (referred to as "Question" in figure 3). A vignette is created along with the necessary simulation inputs. A critical aspect of this step is the construction of the parameter space (i.e., the parameters and associated values to be varied in different simulation runs). The simulation is executed for all combination of values (i.e., the cross product of all parameter pairs) in the parameter space, and the resulting state data is stored persistently. Metrics are generated and the runs analyzed. The relationship between the metric space and data results are then established. With these results, questions can be answered with both quantitative results and qualitative understanding.

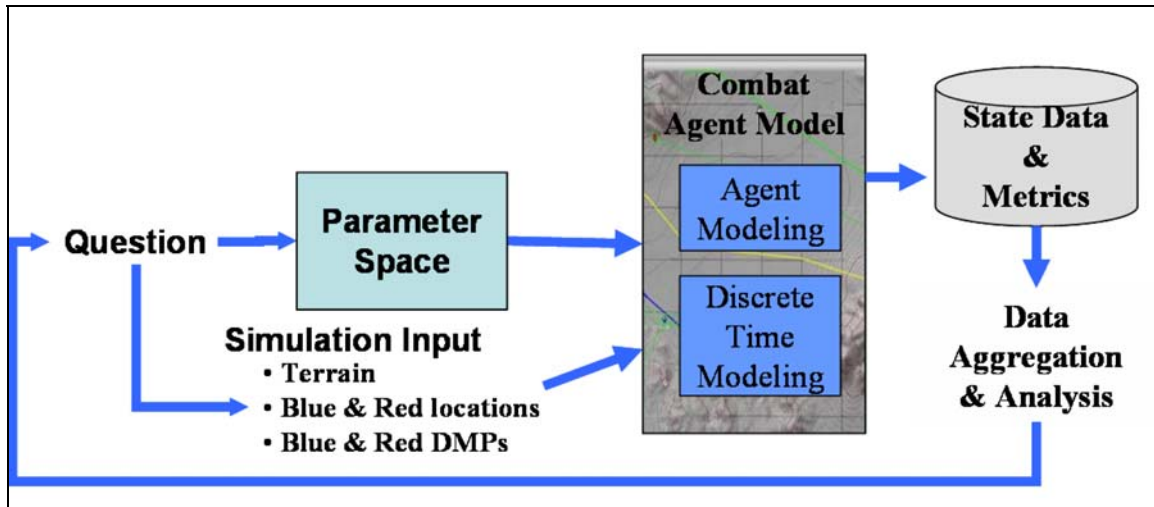


Figure 3. S4 top level process.

The structure and process for providing the relationships between the parameter space and the performance measures is illustrated in figure 4. As shown in figure 4, relationships between parameters, metrics, and measures of performance (MOPs) and measures of effectiveness (MOEs) are hypothesized before the simulation runs are made. Analysis is then conducted over the runs to establish or invalidate these relationships. Focused analysis can also be enhanced using a single run with observational tools that allow close scrutiny of the consequences of decision making in a given simulation run. Such analysis can provide a domain interpretation to the previously postulated relationships. Answers to domain questions frequently result in another look at the data that, in turn, sheds more light on the domain.

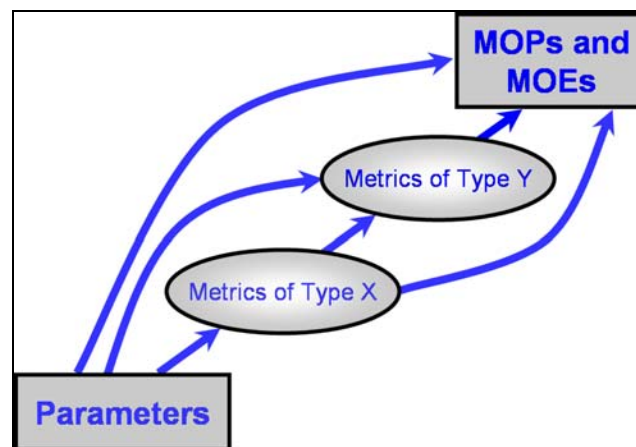


Figure 4. Parameters, metrics, and performance measures.

The following paragraphs will highlight selected aspects of different echelons of decision makers presently implemented in the S4 model.

The CAB and company DMP view is illustrated in figure 5. As can be seen from the insert at the middle left of figure 5, there are four primary levels of decision making presently in S4. This overview concentrates on the top three echelons, namely CAB commander, company commander, and the platoon leader. The CAB commander provides overall direction to the forces. A range of plausible tactical options are encoded in a template structure prior to simulation runtime. An S4 template uses a small number of concepts to illustrate a tactical option such as purpose, task, and areas of interest. Also shown are directions of attack for each platoon. The “current plan” is expressed as that template with the best match to the current observations. Based on input from the CAB commander, each company commander in turn selects a template from the library and provides a purpose and task to each platoon leader.

The information specifying a Situation-Response Template (SRT) is entered through the middle pane on the right. At simulation runtime, this same graphical user interface (GUI) is used to view the current simulated mental state of the commander. Note that all of the SRTs are reviewed periodically during a simulation run and listed from best to worst match in the lower right-hand pane.

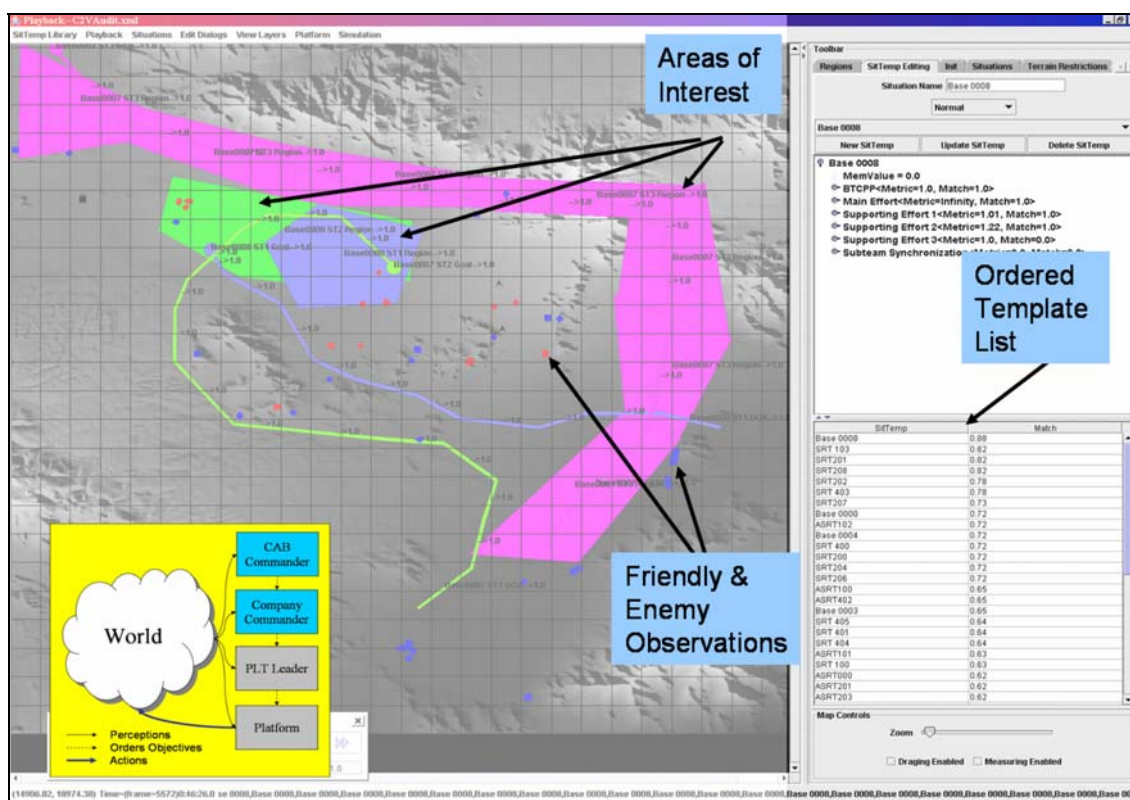


Figure 5. CAB and company commander DMP view.

The platoon GUI (figure 6) has a similar look and feel to that of the CAB and company commander; however, it only presents information concerning the platoon. The platoon receives direction (purpose/task) from the company commander and translates this into particular commands for the platforms in the platoon. The platoon leader's current objective is interpreted based on current observations of friendly and enemy activities. In the graphic, the particular platoon is the group of Blue units with the red dotted circle around it that represents its effective range. The center of the circle is based on the centroid of the platoon; the range corresponds to the effective range of the MCS.

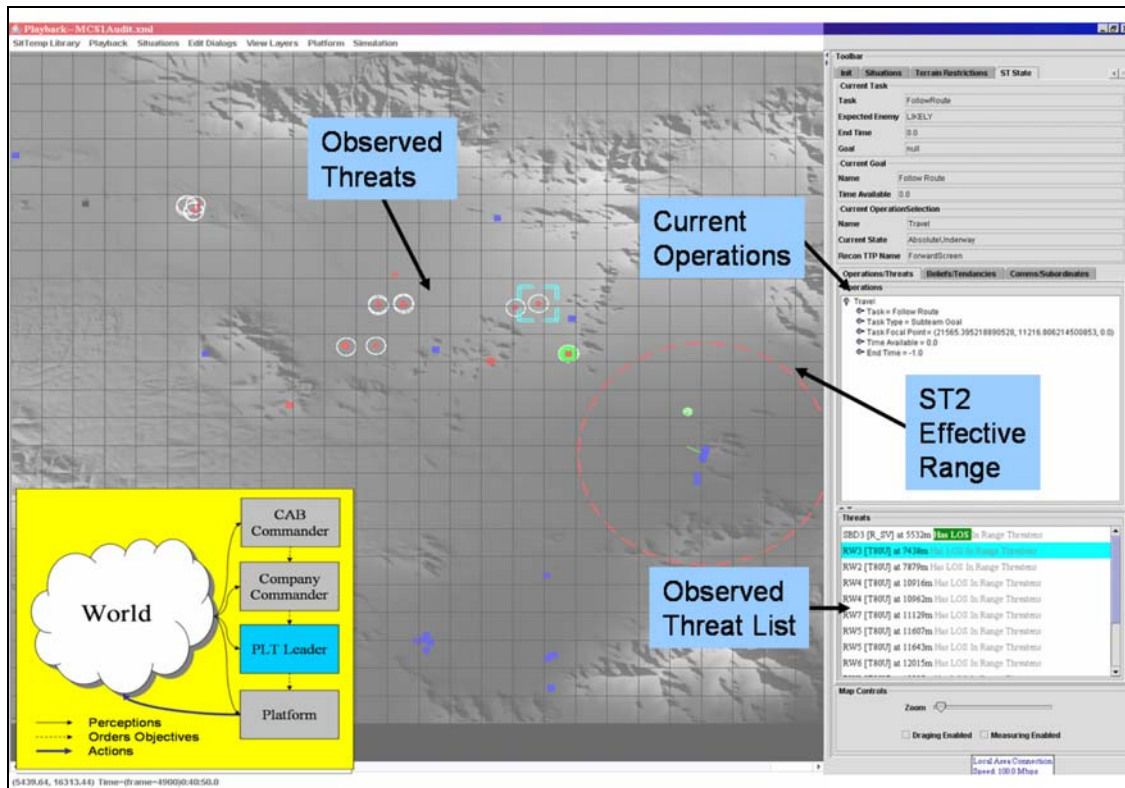


Figure 6. Platoon leader DMP view.

The GUI in figure 6 illustrates those Red units that are identified as threats with white circles around them. A Red unit that is both a threat platform and within its effective range to the platoon will have a green-filled circle. The list of observed threats is contained in the lower right pane and is color coded to match the graphic. We are aware that SRTs are not a scientifically ideal emulation of human DMPs; however, many experts in neurophysiology believe that we are many years away from being able to reduce these thought processes to the underlying physical, chemical, and biological processes. The Army cannot afford to wait for these reductions to be discovered and articulated.

The SRTs in S4 may be regarded as a significant generalization of the decision tables that have long played a significant role in Force-level combat analysis. The traditional decision tables have typically been used to alter platform behavior in the combat simulation. Our SRTs are generalizations in several respects. First, there is a different set of decision variables relevant to each echelon of the decision making being simulated. Second, the decisions being simulated

concern more abstract military purposes (e.g., does it still make sense to take that hill?) than traditional tables (e.g., hide if you're shot at). Third, the decision driver itself is a complex numerical "voting" function rather than a binary tripwire.

The communications model in S4 is the model that enables decision-making agents to communicate their perceptions, issue orders, and report friendly status.

Communications is presently modeled using a "wireless Ethernet like" protocol, broadcasting to all on a network. Multiple networks are presently used to implement the communications plan for both Blue and Red. The two constraints imposed on communications attempts is line-of-sight constraints and a communications range. Simple contention is modeled for voice communications. In CY 2005, this wireless protocol based capability was enhanced substantially with the communications network model developed for the Training and Doctrine Command (TRADOC) at White Sands Missile Range (WSMR), NM, by members of the S4 team on behalf of the Survivability/Lethality Analysis Directorate (SLAD) of the U.S. Army Research Laboratory (ARL). This is a model under development that supports different levels of fidelity/abstraction, such as explicit voice and data communications, signal propagation, explicit protocols (e.g., Transmission Control Protocol/Internet Protocol (TCP/IP)), and explicit devices (e.g., Joint Tactical Radio System (JTRS)). A summary of the planned model features is shown in figure 7.

	Model Category	Description
Comm Models	Network Planning	Knowledge regarding the coordinated use of communication channels, protocols, etc.
	Information Exchange (IE) Facilities	IE triggers, msg creation, content, addressing, knowledge sharing, back ground traffic
	Communication System Models	Core TCP/IP protocols, MANET protocols, data link protocols, radio systems, antenna systems
	Signal Propagation	Used to model link connectivity, signal distortion, and interference
	Electronic Attack	Various ECM & ECCM models
	Information Warfare	Network attacks, spoofing, etc.

Figure 7. Enhanced communication model features.

NOTE: ECM = electronic countermeasure, ECCM = electronic counter-countermeasures, and MANET = mobile ad hoc network.

In order to account for the full spectrum of information operations attacks, networking protocols will be explicitly modeled. The modeling blueprint for the Lower Tactical Internet is shown in figure 8. Note that they are illustrated in context with the Open Systems Interconnection (OSI) and TCP/IP protocol layers. An expanded version of the protocols, used to take into account JTRS protocols, is illustrated in figure 9. Of near term interest is the data link layer protocols associated with Wideband Network Waveform (WNW) and Soldier Radio Waveform (SRW).

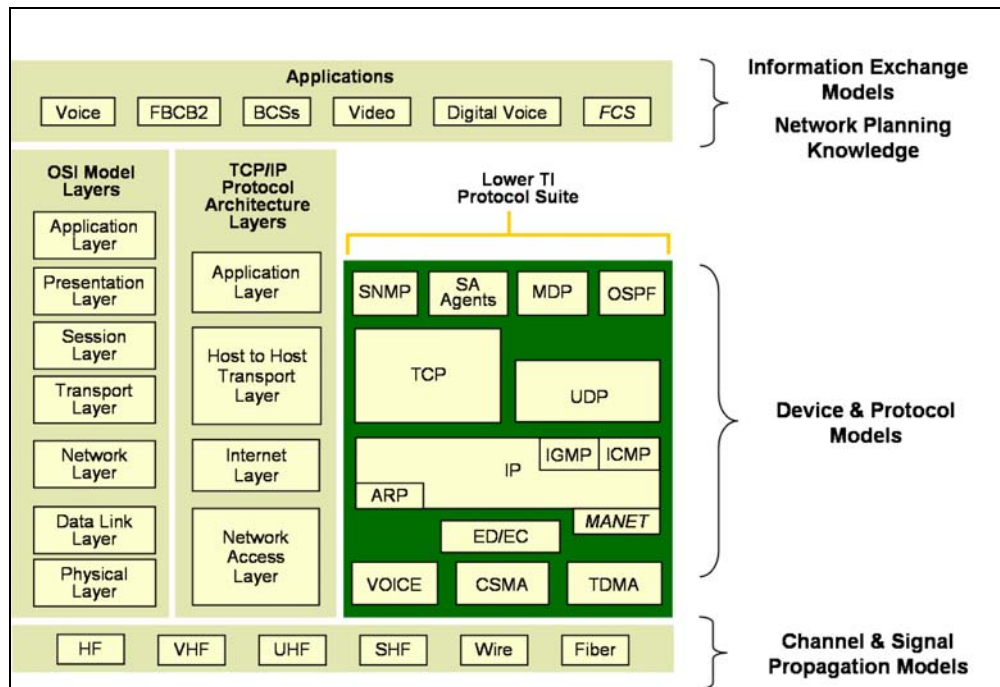


Figure 8. Lower tactical Internet network protocols.

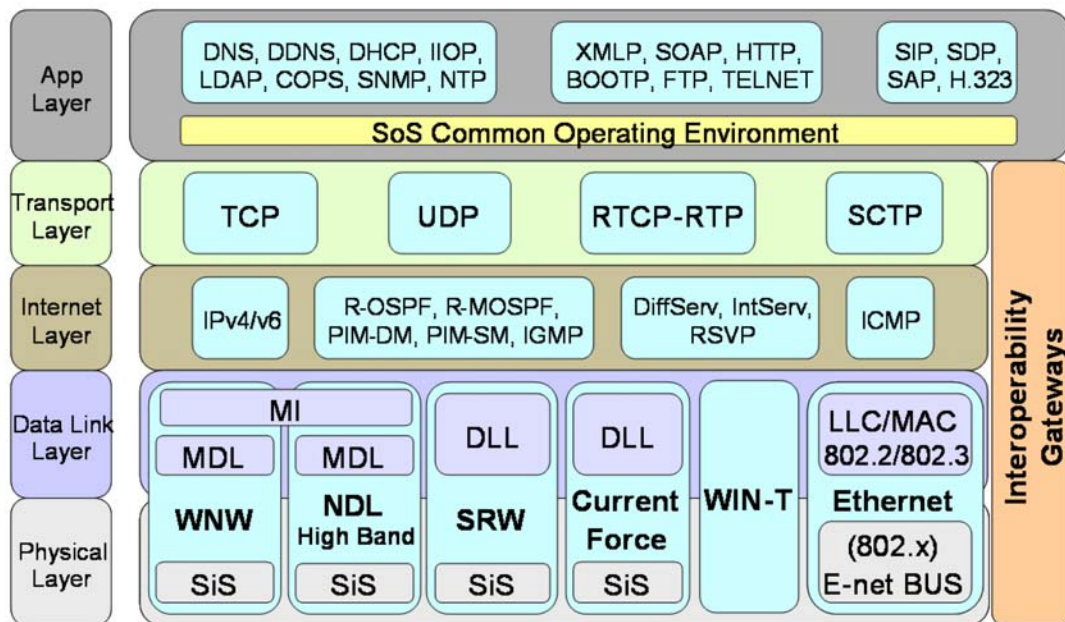


Figure 9. The JTRS-enhanced protocol stack.

Engagement, maneuver, and sensing models in S4 are modeled to provide sufficiently rich context for decision making, but not to model precise physical representations of the real world counterparts. Therefore, relatively simple models have been used initially to represent them in S4. For example, engagement is modeled as a stochastic process with the probability of hit, a function of distance, target, size, movement, and armor.

Sensing is based on an information quality curve (negative exponential function with respect of distance), sensor quality, and target size. Platforms are modeled in space and time (i.e., at any period in time, a platform has a position in x, y, z space). Linear models are used to compute speed and acceleration. Note that each of these areas is modularized from a software engineering perspective such that more sophisticated models can be substituted as needed.

5. SoS Analysis

This section presents our approach to using S4 for the analysis of SoS problems. Two alternative views or perspectives of this process are presented with the intent that collectively they will better illuminate this complex problem. First, a linear view is presented in figure 10. This view begins with a specification of the threat. The threat, referred to hereafter as the Red force, consists of a description of the types, characteristics, and quantities of Red forces. A similar specification of Blue forces must also be provided to counter the Red force mix. A specification of the environment that the Red and Blue forces will operate and interact in is also required. Environmental factors include terrain, man-made infrastructures, and weather. Second, using the above information and a mission for each force, a two-sided mission analysis can be conducted taking into account mission, enemy, terrain, time, troops available, and civil considerations (METT-TC), resulting in specified tactical choices for Blue and Red. This process is illustrated graphically on the far left-hand section of figure 11. Note that this process can be, and typically is, different for Blue versus Red mission analysis reflecting differing national or service traditions.

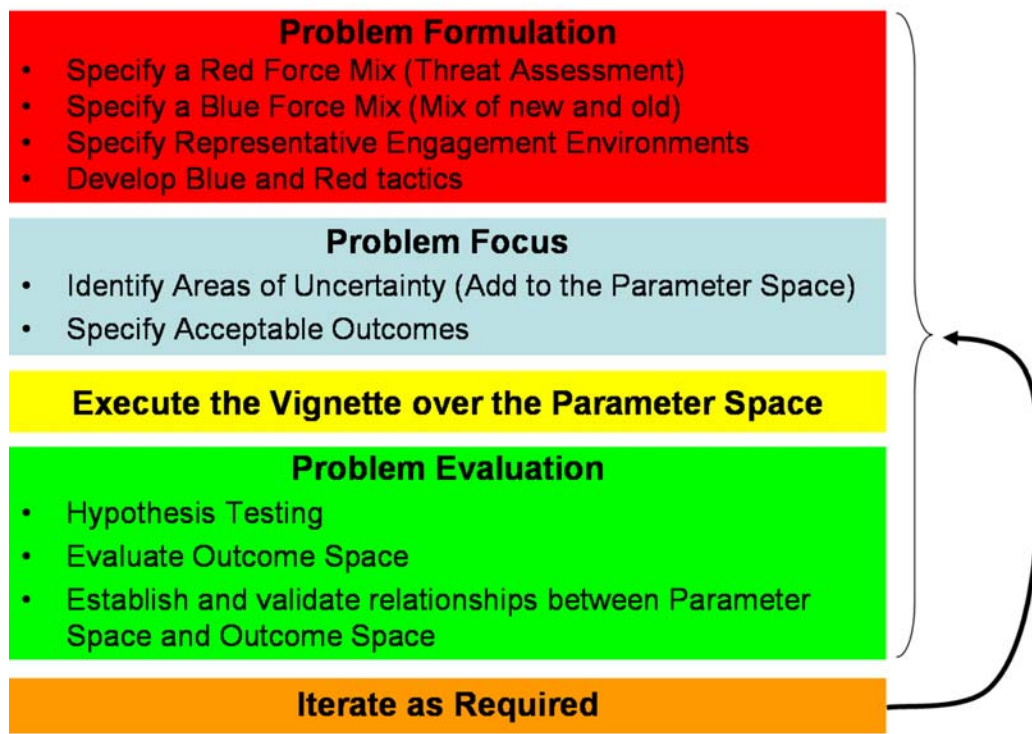


Figure 10. Linear view of the SoS process.

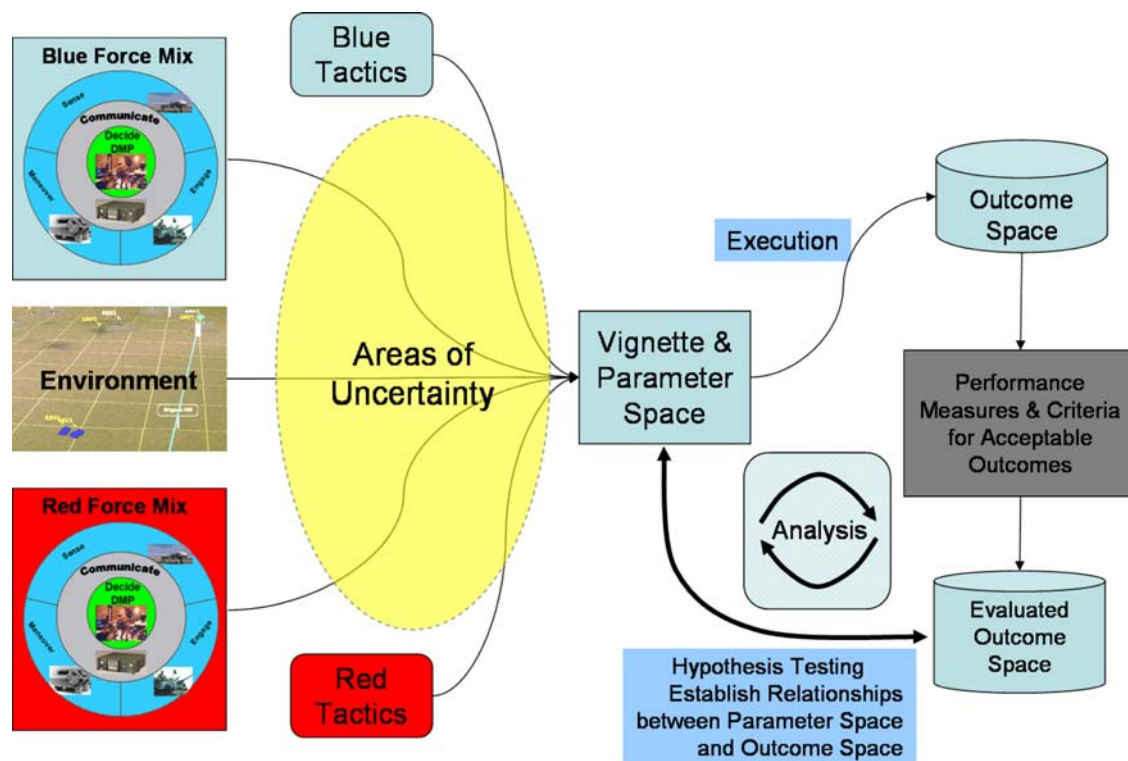


Figure 11. A graphical view of SoS analysis.

The second major step in SoS analysis is referred to as Problem Focus in figure 10. Problem Formulation (the first step in figure 10) sets the stage to allow a review of weaknesses and uncertainties for the Blue forces. The nature of these weaknesses and uncertainties is strongly a function of time until engagement (i.e., the amount of time before the engagement is anticipated to begin). If, for example, engagement is imminent, there are few degrees of freedom (e.g., no more forces and supplies are likely to become available). However, tactics could be evaluated in more detail and might include changes to organization structure or assumptions regarding Blue and Red's will to fight. As the time line is extended, more degrees of freedom should be considered, such as Blue force composition in numbers and type. If the time line is extended through several months or years, this analysis could consider technology options. Note that these areas of uncertainty are considered in the simulation model using parameters.

This process is illustrated in figure 11 as the yellow ellipse labeled "Areas of Uncertainty," taking as input the situation specified by the identification of the Red and Blue force mixes, the environmental constraints, and the tactics. The result of the Problem Formulation and Problem Focus is the Blue and Red force composition and size; their placement on the battlefield; and techniques, tactics, and procedures. This aspect is illustrated in the center of figure 11 as the "Vignette and Parameter Space."

In addition to identification of the relevant uncertainties, another component of the Problem Focus step is a specification of acceptable outcomes. Acceptable outcomes are specified in terms of metrics, typically MOEs and MOPs. These are reflected in figure 11 as "Criteria for Acceptable Outcomes" on the far right-hand side of the figure.

Once the parameter space is specified via the Problem Focus process and the vignette is defined via the Problem Formulation phase, the vignette is executed over the parameter space. Generally, the parameter space is covered exhaustively for discrete valued parameters and sampled for continuous parameters. Each simulation run, defined by the simulation model vignette and a point on the parameter space, generates the state data, all metrics, the MOEs, and the MOPs for the run. Execution of the parameter space is illustrated in figure 11 as the arrow labeled “Execution” that links “Vignette and Parameter Space” to “Outcome Space.”

This collection of data, coupled with the parameter space, provides the information necessary for performing the fourth major process, Problem Evaluation (as shown in figure 10). The first step, hypothesis testing, utilizes observation and analytic tools coupled with subject matter experts to search for inconsistencies within a single simulation run, and more critically, across multiple simulation runs. This step is shown in figure 11 as a double-ended arrow linking “Vignette and Parameter Space” to “Evaluated Outcome Space.”

Once hypothesis testing has reached an acceptable level of confidence, the outcome space is evaluated with respect to the acceptability criterion as specified in the Problem Formulation stage. Since the acceptability criterion is generally specified by more than one variable, this process results in a multidimensional outcome space. This process is shown in figure 11 as the sequence of arrows on the right-hand side of the figure linking “Outcome Space,” “Performance Measures and Criteria for Acceptable Outcomes,” and “Evaluated Outcome Space.”

The last and most crucial step is generating relationships between the underlying variables in the parameter space and the effectiveness metrics captured in the outcome space. Given the relationships established by the data, the objective is to establish a fuller understanding of them. The most useful established relationships are those that pass operational and tactical common sense tests illuminating the kinds of SoS effects we are trying to better understand, and in the best case, hold up over a broad range of initial conditions. An invalid relationship (e.g., a simulation run that suggests that a MCS is invulnerable due to too small of a platform signature level; therefore, invisible) generally implies a modeling artifact that leads to a simulation model revision that, in turn, requires repeated execution of the model. Once the relationships are vetted, the relationships between parameter space and outcome space are available to present to decision makers. Implications of choices can then be examined with substantial underlying supporting detail. This process is shown in figure 11 as the double-ended arrow labeled “Establish Relationships between Parameter Space and Outcome Space,” seen on the lower right-hand of the figure.

There are two approaches to SoS analysis taken in the S4 project: question driven analysis and exploratory analysis. The analysis process described previously is referred to as question driven analysis. Question driven analysis is the primary method for conducting analysis. It provides a holistic view of analysis and is characterized by the fact that the hypotheses to be tested are understood when the analysis begins. It is, however, complemented by a second method referred to as exploratory analysis, a method in which only themes, but not specific hypotheses, are known at the outset of the analysis, and a result of the analysis is to pose relevant questions related to the themes. These methodologies are illustrated in figure 12.

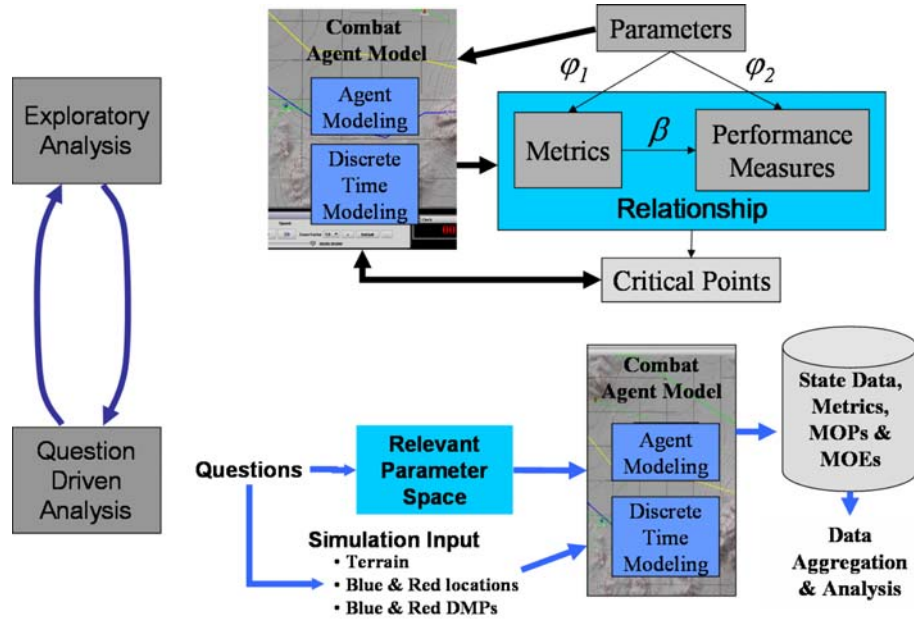


Figure 12. S4 analysis view illustrating question driven analysis and exploratory analysis.

Note that exploratory analysis may only involve a single simulation run, searching for interesting relationships within the run. Observations of relationships can be used to generate and refine questions for the question driven analysis. Exploratory analysis can also be used to gain insight and understanding of relationships established through question driven analysis.

6. Accomplishments

This SoS analysis has been developed, using S4, over the past four years. Opportunities for improvement have been identified and implemented for each S4 development cycle. In the first development cycle, a force of a mixed platoon or Blue tanks and sensor vehicles were apposed by a platoon of Red tanks. Analysis considered both time series data within a single run as well as metrics for multiple runs over a small parameter space consisting of two parameters, risk tolerance and uncertainty tolerance. Two classes of metrics, situational awareness accuracy and situational awareness coherence, were defined and implemented. A set of performance measures were also included in the analysis. Off-the-shelf formal concept analysis tools were used to establish relationships between parameter values, metrics, and performance measures. For this specific vignette, it was shown that a risk tolerant decision maker was more successful completing the mission than one that was not.

During the second cycle, decision making was expanded to include platoon and company level decision makers. The company commander decision-making model provided the capability for a subject matter expert to insert situation-specific knowledge and courses of action as an input to simulation execution. Additionally, situational awareness metrics were augmented with situational understanding metrics that were a measure of the company DMP performance relative to that process's decisions based on ground truth data.

An example of analysis on a single simulation run is shown in figure 13. Situational awareness and situational understanding metrics were used together to instrument a simulation run as a time series. Phases of the battle are illustrated, such as the rise of Blue's knowledge of Red, denoted by the rising red line labeled "Enemy Positions." This period, labeled "IPB", represented Blue's preparation of the battlefield during the first 40 min of the simulation. Blue's DMPs are illustrated in the bottom panel. Each line represents belief in alternative Red intentions. A course of action is selected at minute 40 and remains in place for the remainder of the battle. Note, however, at minute 77, there is a 5-min window where the "Blue Terminate" (blue line labeled "Blue Term") course of action is gaining weight due to substantial losses by Blue during this period. This exemplifies S4's ability to ferret out critical points or near critical points in this case with the analysis tools.

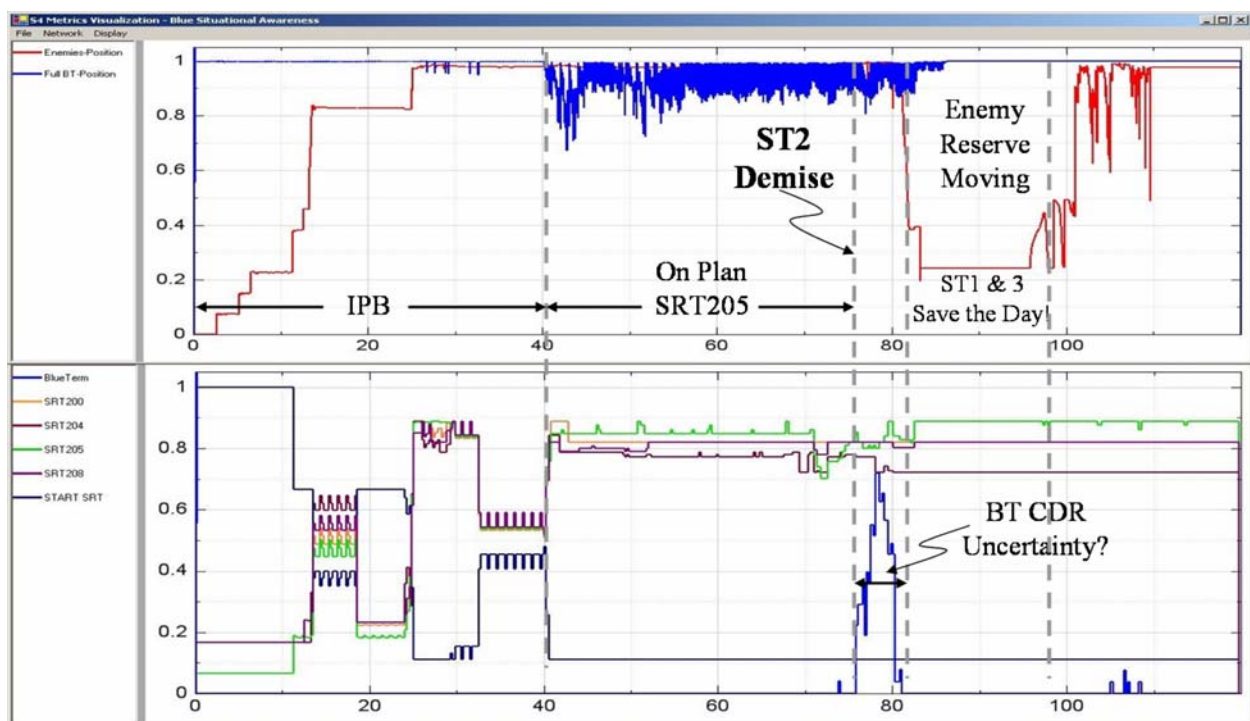


Figure 13. Situational awareness and situational understanding metrics in a simulation run.

This single run analysis is complemented with formal concept analysis (FCA) across multiple simulation runs. This analysis technique searches for relationships between parameters; situational awareness and situational understanding metrics; and performance measures. A study was conducted to determine the effect on situational awareness and situational understanding metrics given the presence and absence of UAVs. A decisive positive relationship was demonstrated of increased situational awareness and situational understanding with the presence of UAVs.

In the third cycle, platoon DMPs have been revised to incorporate purpose into its decision making. The Blue forces have been augmented with indirect fires and Future Combat System robotic vehicles. Analysis in this cycle is in progress and is exercising the analysis tools that were developed during the end of the second cycle, including techniques that explore

relationships that have a time delay between the cause and effect. Additionally, work is underway to exercise the simulation in an urban warfare setting. This initial look at urban warfare is cast in the context of convoy protection with emphasis on Improvised Explosive Devices (IEDs).

7. Conclusions

The S4 model and simulation provides a comprehensive framework for addressing SoS survivability, lethality, and vulnerability analysis. Significant progress has been made in the development of the model and analysis techniques, as well as in the software implementation. The S4 model has been developed with emphasis on decision making and system performance with respect to the relationships to battlefield metrics such as situational awareness and situational understanding. S4 has been demonstrated multiple times in this context over the last several years and provides a unique means for measuring and analyzing decision making, situational awareness, situational understanding, and performance in a context that allows the analyst to observe activities in the domain. S4 provides a powerful capability to make analytic measurements, establish relationships between the various measures, and provide the observability in the domain processes to ask and answer why relationships exist.

A current major focus is the impact of communications and information flow on decision makers as well as the impact of information and electronic warfare on battlefield commanders. It is anticipated that S4 will provide significant contributions illuminating vulnerabilities in these areas, thereby preserving the lives of U.S. soldiers and material as well as serving as a force multiplier for the U.S. Army.

References

1. Starks, M.W.; Flores, R. *New Foundations for Survivability/Lethality Vulnerability Analysis (SLVA)*; ARL-TN-216; U.S. Army Research Laboratory: White Sands Missile Range, NM, June 2004.

Acronyms

ARL	U.S. Army Research Laboratory
CAB	Combined Arms Battalion
DMP	decision-making process
ECCM	electronic counter-countermeasures
ECM	electronic countermeasure
FCA	formal concept analysis
IED	Improvised Explosive Device
JTRS	Joint Tactical Radio System
MANET	mobile ad hoc network.
MCS	manned combat system
METT-TC	mission, enemy, terrain, time, troops available, and civil considerations
OSI	Open Systems Interconnection
PLT	platoon
RDT&E	research, development, test, and evaluation
R&SV	recon and surveillance vehicles
S4	System of Systems Survivability Simulation
SLAD	Survivability/Lethality Analysis Directorate
SLV	survivability, lethality, and vulnerability
SLVA	SLV analysis
SoS	system-of-systems
SRT	Situation-Response Template
SRW	Soldier Radio Waveform
TCP/IP	Transmission Control Protocol/Internet Protocol
TRADOC	Training and Doctrine Command
UAV	unmanned aerial vehicle
UGS	unattended ground sensor
WNW	Wideband Network Waveform
WSMR	White Sands Missile Range

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