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Human Performance Modeling for System of Systems Analytics

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Abstract

A Laboratory-Directed Research and Development project was initiated in 2005 to investigate Human Performance Modeling in a System of Systems analytic environment. SAND2006-6569 and SAND2006-7911 document interim results from this effort; this report documents the final results. The problem is difficult because of the number of humans involved in a System of Systems environment and the generally poorly defined nature of the tasks that each human must perform. A two-pronged strategy was followed: one prong was to develop human models using a probability-based method similar to that first developed for relatively well-understood probability based performance modeling; another prong was to investigate more state-of-art human cognition models. The probability-based modeling resulted in a comprehensive addition of human-modeling capability to the existing SoSAT computer program. The cognitive modeling resulted in an increased understanding of what is necessary to incorporate cognition-based models to a System of Systems analytic environment.

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Executive Summary

A Laboratory-Directed Research and Development project was initiated in 2005 to investigate Human Performance Modeling in a System of Systems analytic environment. SAND2006-6569 and SAND2006-7911 document interim results from this effort; this report documents the final results. The problem is difficult because of the number of humans involved in a System of Systems (SoS) environment and the generally poorly defined nature of the tasks that each human must perform. A two-pronged strategy was followed: one prong was to develop probability-based human models similar to those used in relatively well-understood probability based human performance modeling; another prong was to investigate more state-of-art human cognition models.

Probability based performance modeling involves decomposing jobs into discrete tasks, often with decision points, such that the range of possibilities in performing the tasks is covered. Human Error Probabilities are then associated with the tasks, allowing a calculation of the estimated probability of failing (or succeeding) at the job. To apply this basic idea to a SoS environment, human activities are generalized so that anything a human does over some period of time is considered to be a task. Basic Error Rates, which can be found in the literature, are then assigned according to the general difficulty of the activity that the human is performing. With the assumption that it takes time to recover from an error when it is made, there is an analogous situation between human performance modeling and hardware reliability modeling—human error rate is similar to component failure rate and human recovery time (time-to-reset) is similar to system downtime (time-to-repair). As with hardware systems, the environment can also affect human performance. Performance-Shaping Factors (PSFs), as defined in SAND2006-7911 and including stress and fatigue, can be used to modify the human Basic Error Rate.

Sandia has already developed a System of Systems Analysis Toolset (SoSAT), which performs complex system-of-systems reliability modeling. As part of this LDRD, SoSAT 1.0 was modified to incorporate probability-based human performance models (HPMs). Parameters for the HPM include Basic Error Rate, Catastrophic Failure Probability, Time-to-Reset, and parameters associated with PSFs. Modifications to SoSAT included a user-interface capability for the input of HPM parameter values and statistical output of HPM results, as well as changes to the some of the calculations that SoSAT performs. One of the major modifications was the implementation of the concept of a resource pool. The resource pool of mechanics is used to perform maintenance activities and can repair several platforms, sequentially or in parallel.

An example problem for the military domain was developed to test the modeling capability of SoSAT with HPM. The problem involves a company of two platoons involved in a seven-day mission. HPMs included Platoon Leaders, NCOs, and platform drivers. The results of the example problem indicate that human errors contribute to approximately 30% of the unavailability of the force, a fraction that is consistent with values reported in the literature.

Cognitive modeling involves a more detailed picture of the human performance. For this LDRD, an information-processing model of a single human—a mechanized infantry Platoon Sergeant (PSG)—was developed. The PSG was chosen because he has primary responsibility for managing platoon logistics. The scenario chosen involved a Hasty Defense Consolidation and Reorganization Operation in the middle of a three-day high-intensity operation. The PSG model is affected by background events that modulate the tasks required by the PSG and by discrete

events that occur in response to stochastic external events and PSG actions. The actions taken by the PSG involve a limited-attention model.

A DLL bridge was created that allowed the cognitive model to communicate with SoSAT. Although the model building was successful, difficulties were encountered with SoSAT integration and development of the example problem. Questions remain about whether the cognitive modeling can be generalized to the multitude of human positions involved in an SoS. The cognitive modeling performed for this LDRD might be better restricted to modeling persons in positions of authority, primarily involved in decision making, such as the brigade and battalion commanders.

The probability-based modeling resulted in a comprehensive addition of human-modeling capability to the existing SoSAT simulation tool. This capability will be used in future work with existing customers. The cognitive modeling resulted in an increased understanding of what is necessary to incorporate cognition-based models to a SoS analytic environment. The cognitive-modeling work points to areas that are important to future advances in SoS human performance modeling.

1. Introduction

As early as 1960, an Air Force report stated that humans contributed to 20-53% of system failures (Shapero et al., 1960). The military has subsequently identified Human Performance Modeling (HPM) as a significant requirement and challenge as can be seen in the Department of Defense's (DoD) Defense Modeling and Simulation Office's (DMSO) Master Plan (DoD 5000.59-P 1995). In the plan, the DMSO identified the capability to robustly represent individuals and group behaviors as a critical need. The DMSO officially recognized human behavior representation as a prominent technology challenge. Specifically, the challenge is to develop and integrate accurate sub-models of human behavior in a manner that accounts for human perceptual, cognitive, and motor output in the task being modeled. To this goal, the military is currently engaged in programs devoted to HPM in various military contexts. Examples include the Human Performance Modeling Integration (HPMI) Program within the Air Force Research Laboratory focused on integrating HPMs with constructive models of systems (e.g. cockpit simulations) and the Navy's Human Performance Center (HPC) established in September 2003.

The primary challenge is that, in most SoS domains, the problems being analyzed are large in scale. Most HPM initiatives look at integrating detailed cognitive models that capture fine grained details of human perception, decision making, and response with detailed systems models and simulations (e.g., Lebiere et al., 2003). It is not feasible to integrate such fine grained cognitive models with systems models and perform SoS scale analysis.

Sandia National Laboratories (SNL) has been in the forefront of modeling system of systems (SoS) with the SoS Analysis Toolset (SoSAT). SoSAT modeling, and most SoS modeling efforts to date, have focused on military hardware systems, analyzing performance attributes such as mobility, lethality, availability, etc.—the human element has been ignored. However, humans are the driving force behind all military SoS operations. Sustained military operations produce deficits in soldiers' cognitive/physical performance abilities that can result in inefficiencies and errors, negatively affecting overall SoS performance. Omitting them from an analysis might cause the largest performance factor of the SoS to be missed and produce results that can be misleadingly optimistic.

Recognizing these issues, Sandia initiated a Laboratory-Directed Research and Development (LDRD) project to investigate HPMs in a SoS analytic environment. The goal of this LDRD project was to integrate HPM with SNL's SoS analytical framework and provide a computationally tractable solution toolset that will allow for robust treatment of humans and human performance in SoS modeling and simulation.

1.1. Objective and Scope

The purpose of this report is to document the final results of the Sandia LDRD entitled Human Performance Modeling for System of Systems Analytics. Interim results are documented in SAND2006-6569 and SAND2006-7911 and will not be discussed here, except by reference.

Included in this report is a description of a modeling effort similar to that first developed for Human Reliability Analysis. The description of the probability-based method has sections containing a specification of parameter values and an example problem. This effort is intended provide a working HPM capability for the SoSAT simulation tool. Also included is a description of an effort based on cognitive modeling. The cognitive modeling effort is intended to be investigatory.

All modeling described here addresses humans (soldiers) involved in a military SoS. The probability-based modeling focuses on human errors, including errors resulting in system failures and errors resulting in system delays, primarily in a logistics context. The cognitive modeling focuses on decision errors, again primarily in a logistics context. Of particular interest is HPMs that accurately reflect the expected deficits in soldiers' performance resulting from many factors during sustained operations.

1.2. Strategy

Two methods have been identified in the literature (Trucco and Leva, 2006) to construct HPMs: (1) 1st-generation models that are based on previous work first developed for Human Reliability Analysis (HRA), and (2) 2nd-generation models based on cognitive modeling. A two-pronged strategy was developed to investigate both of these methods. As probability-based modeling first developed for HRA is currently more mature, this method was deemed to be safer and more likely to achieve results. As cognitive modeling is newer and more innovative, this method was deemed to be exploratory and of use to future advances in SoS modeling.

Both methods were structured for implementation in SNL's unique, existing System of Systems Analysis Tool, SoSAT. SoSAT is currently being used to investigate issues such as operational availability and fuel usage and resupply in a brigade-level system of systems. Humans play an integral role in operations and logistics of the brigade. This LDRD work will focus on how to effectively and efficiently insert human performance models (HPMs) into SoSAT to allow a more realistic assessment of brigade functioning.

1.3. SoSAT Overview

System of Systems analysis is necessary to understanding the characteristics of large-scale inter-disciplinary problems that involve multiple distributed systems that are embedded in networks at multiple levels and in multiple domains. In the pursuit of modeling and analyzing complex system of systems (SoS) capabilities, a multi-system time simulation capability called System of Systems Analysis Toolset (SoSAT) has been developed. Figure 1.1 presents an overview of the SoSAT concept.

SoSAT development was driven by the need to support the Future Combat Systems Brigade Combat Team (FBCT); however SoSAT can be applied to various systems of systems problems. The FBCT is the Army's modernization program consisting of a family of manned and unmanned platform systems, connected by a common network, enabling a modern modular force, providing our soldiers and leaders with leading edge technologies and capabilities allowing them to dominate in complex environments.

SoSAT is a time-step stochastic simulation tool designed to model and simulate the multi-echelon operation and support activities projected to be conducted by FBCT. Figure 1.2 presents a high-level picture of the simulation architecture used in SoSAT. It provides logistics analysts with the ability to define operational and support environments and ascertain measures of its performance effectiveness based on multiple trials. SoSAT characterizes sensitivity changes to all platforms, support systems, processes and decision rules as well as vehicle reliability and maintainability (R&M) characteristics. It is designed to be a robust decision-support tool for evaluating the readiness and sustainment of the FBCT to include fuel, water, ammunition and maintenance operations. SoSAT can also take into account external conditions (e.g., storms or extreme terrain) and combat damage. Simulation output results assist the user in identifying platform, as well as system of systems level performance and logistics support issues.

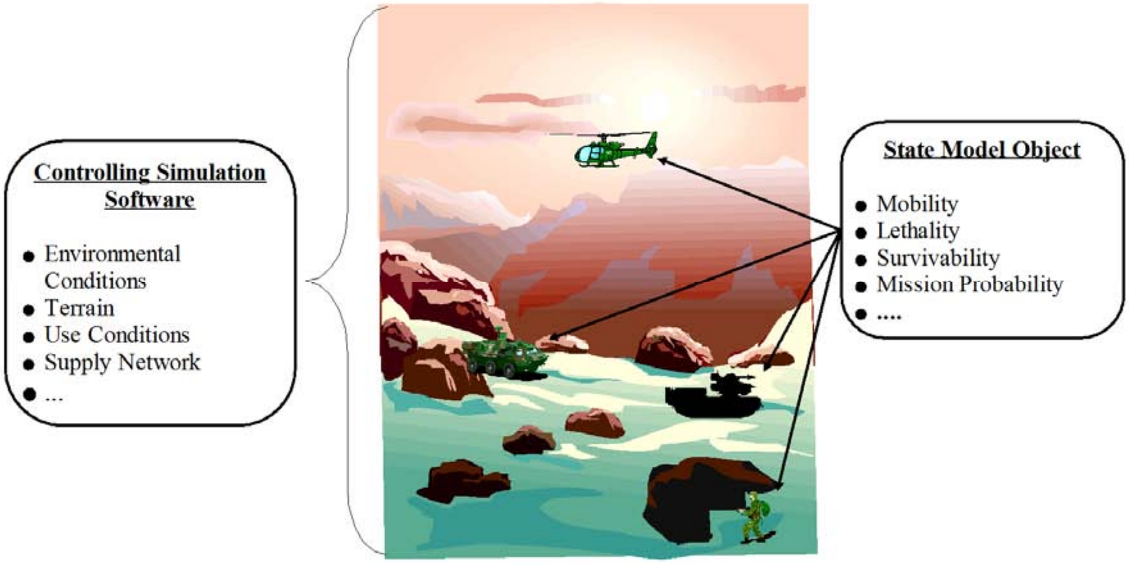


Figure 1.1. Multi-System Simulation Concept.

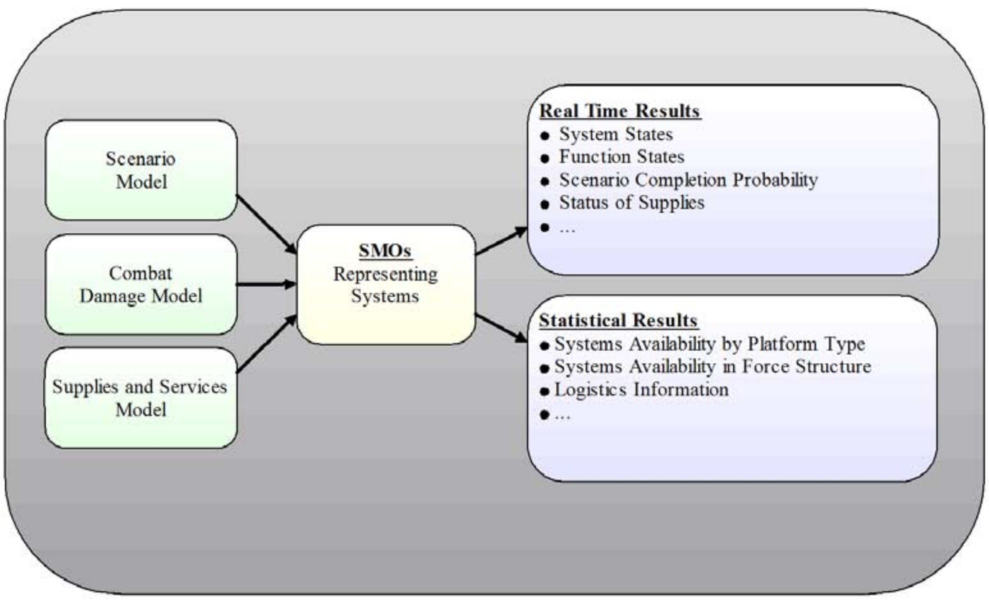


Figure 1.2. SMO Simulation Architecture used in SoSAT.

Key to the multi-system simulation capability has been the development of a State Model Object (SMO) that enables a system, its elements, and its functionality to be encapsulated for use in the simulation. Every system in the simulation is represented by an SMO which has a defined composition of items that help define the system's functionality. SMOs can represent air vehicles, ground vehicles, manufacturing equipment, etc. The systems are the central objects of the model and are the entities that march through the simulation.

SMOs are similar to finite state machines. A finite state machine is a set of states connected by transitions. An SMO is a special form of finite state machine that includes functions, elements, and "goal" states (success and failure). In an SMO, the transitions to goal states are one-way. Figure 1.3 shows a comparison between a finite state machine and an SMO.

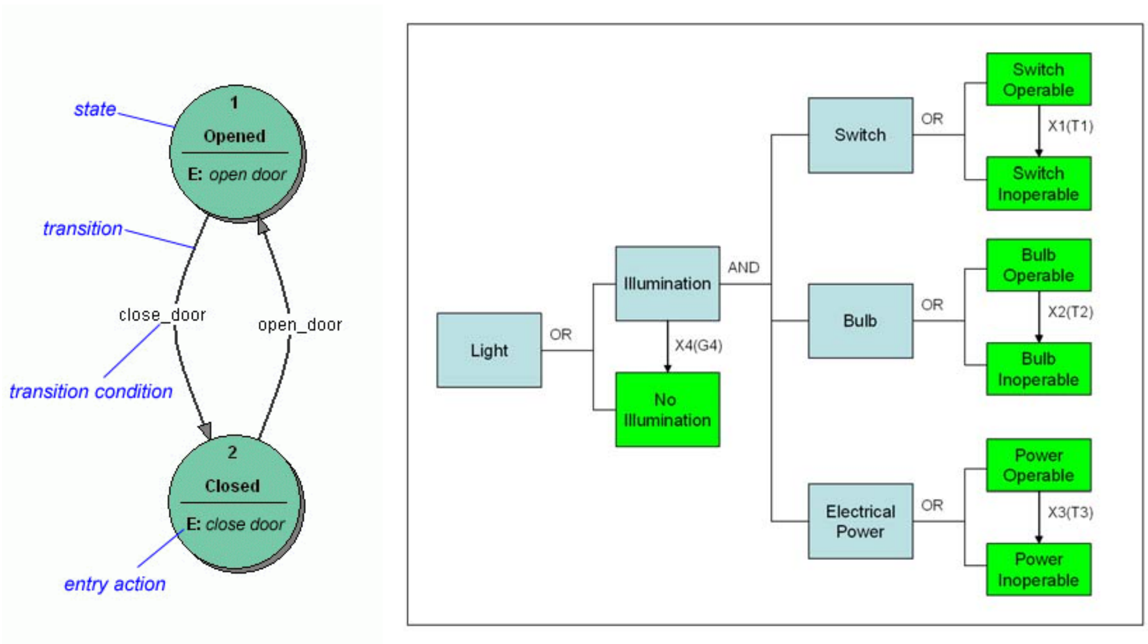


Figure 1.3. Comparison of Finite State Machine (for a Door) and SMO (for a Light).

The basic structure for modeling a system as an SMO in SoSAT is as follows. A system performs functions (e.g., mobility, communications, sensing, lethality, etc.). Functions are supported by elements of the system, including primary elements (engine, instrumentation, sensors, etc.) and consumables (fuel, ammo, etc.). Elements can fail by normal reliability processes, external conditions (combat damage, external elements—e.g. severe weather, hilly terrain, etc.), and the failure of other systems (e.g., logistics). Failure of an element affects system function. Failure of a function can affect other systems and system availability.

Implementation of probability-based HPMs in SoSAT can occur in two ways: (1) a human can be defined as a system, and (2) a human can be defined as an element of a system. The first way is applicable to humans that are not assigned to a single system, and whose activities might have influence over a number of systems, e.g., a platoon leader. The second way is applicable to humans that are assigned to or do not have direct effects on a single system, e.g., a truck driver. Implementation of cognitive HPMs can occur through an interface to allow the HPM to affect one or more systems.

2. Human Performance Modeling Based on Human Reliability Analysis

2.1. Concept

Swain (1963) laid out the basic concept of Human Reliability Analysis (HRA). Examples of HRA models include THERP (Swain and Guttmann, 1983), SLIM (Embrey et al., 1984), and HEART (Williams, 1986). Briefly, HRA is based on the ideas that a human job can be divided into individual tasks, failure of successful completion of an individual task can be quantified by a probability (called a Human Error Probability or HEP), and failure of successful completion of the job can be determined by combining the probabilities (often with the assumption that the tasks are independent).

Modeling humans in a SoS environment presents difficulties not addressed by HRA, and thus the probability-based modeling reported here differs from typical models used in HRA. HRA models are task-specific; i.e., they model the likelihood of a human making an error while performing a sequence of tasks in a given situation. For example, an HRA model might calculate an overall probability of error of a nuclear-reactor controller performing a sequence of tasks during an emergency reactor shut down. The tasks are well-known, and error probabilities can be well-defined (given appropriate information) for each step in the shut-down process.

On the other hand, the HPM designed for implementation in SoSAT, here called a probability-based method, is meant to deal with more general behavior (here called an "activity" to differentiate it from the HRA tasks) in more ambiguous situations. Sequences of specific tasks cannot be described in an analysis being performed at the SoS level, where perhaps thousands of individuals are being tracked, and these thousands of individuals are not necessarily engaged in well-defined tasks or even tasks that we can know in advance. For example, the SoSAT HPM might calculate the overall time that it takes to repair the engine in an Infantry Carrier Vehicle during a sustained operation. In this case, the engine could have any of a number of problems, and the repair could encompass any of a multitude of tasks. Further, even if the sequence of tasks were well-known, e.g., replacing an alternator, the error probabilities and the time to recover from an error are poorly defined, given that the repair might be in the field, late at night, with any number of distractions.

The SoSAT HPM is therefore a top-level description of how humans perform activities in a range of situations. In particular, the model incorporates parameters for expected error rates and times to recover from errors (called time-to-reset) for humans under nominal conditions. To continue with our example, a repairman will make a mistake a certain fraction of the time when replacing an alternator or performing any repair, so that the time it takes to perform the repair will be the nominal time to do the job plus the time to recover from the mistake. Modeling difficult conditions uses the concept of performance shaping factors (PSF). The SoSAT HPM also incorporates parameters that degrade performance when a PSF applies by increasing the failure rate.

2.2. Implementation of Probability-Based Models in SoSAT

SoSAT is designed around systems and their elements. The elements that affect a system can be primary elements (parts or subsystems), consumables, external elements, and reference elements. Humans have been included as a fifth element type. For humans to affect an analysis, they must be defined as an element and be assigned to a SoSAT system. A driver is assigned to an infantry carrier vehicle (ICV) or a repairman is assigned to a mechanics pool.

A human can also be defined as a system in SoSAT. Currently a human system consists of a single element, that being a human element. In this way humans can be included that do not have specific duties for a nonhuman system. A platoon leader serves several functions but, unlike a driver, may not be responsible for the performance of a particular system.

At any point in time an element is either up or down in SoSAT. Humans are down if they are recovering from a mistake (reliability error) or if they have suffered combat damage. The input and implementation for reliability errors are described in Section 2.2.1 Human Error Rates. Combat damage is treated as a PSF in SoSAT, as discussed in Section 2.2.3.4 Combat Damage. The duration of time that elapses when humans are down depends on the reason for being down. The two downtimes are discussed in Section 2.2.2 Human Downtime.

The PSFs implemented in SoSAT are described in Section 2.2.3 Modeling PSFs. Primarily their occurrence modifies the error frequency for humans. The exception is combat damage. SoSAT assumes that any combat damage is sufficiently serious to warrant evacuation of the individual. Thus, minor combat damage that does not warrant evacuation but could adversely impact the performance of the human is not currently implemented in SoSAT.

Human mistakes and human absence adversely impact the performance of the force according to the duties they are assigned. Section 2.2.4 Human Impacts on the Performance of the Force describes how to assign these duties and how to measure the impact on the force when humans fail to perform. Briefly, human involvement fits one of three categories:

- Direct impact – the performance of a driver affects the mobility of a vehicle. The driver is included as an element in the Boolean expression (union of cutsets) that describes the mobility function for the system.
- Logistics authority – the failure of an individual to authorize replacement of parts and consumables in a timely fashion can cause or extend vehicle downtime. Authorities are granted when the human is first defined.
- Repair – a mistake made by a mechanic during a repair job extends repair time for primary elements. Repair personnel are identified when humans are first defined.

2.2.1. Human Error Rates

2.2.1.1. Basic Error Rate

When a human (element) is assigned to a SoSAT system type, properties include a probability distribution to describe basic error rate for the human. SoSAT assumes that in the absence of any PSFs the error rate for an individual would be constant in time. The reason for a distribution here is to encompass both the uncertainty and the human-to-human variability of the constant error rate. Prior to the first simulation, SoSAT samples the distribution N times, where N is the number of instances of the system, hence the number of human elements, using stratified median sampling. Each of the N humans is then assigned one of the sampled error rates.

In keeping with the treatment of parts and subsystems, SoSAT requires a time-to-failure (TTF) distribution for humans. The appropriate distribution for a constant failure rate model is the exponential distribution. Thus, the sampled error rate, , defines the required parameter for the density function, f, and the cumulative distribution function F,

$$f(t) = \lambda e^{-\lambda t} \quad \text{and} \quad F(t) = 1 - e^{-\lambda t} \quad \lambda > 0, t \geq 0 \qquad \textbf{(2-1)}$$

At each time step in a simulation SoSAT samples the TTF cumulative distribution function to determine if the human fails during that time step. The sampling is random, but conditioned on survival to the current simulation time, S. With a constant failure rate model and in the absence of PSFs the calculation is effectively unconditional. That is, it is equivalent to unconditionally sampling the exponential distribution and adding S to the result. This time-independent model would apply throughout a simulation if not for the presence of PSFs.

2.2.1.2. Catastrophic Error Probability

SoSAT distinguishes human errors as recoverable and catastrophic. The human resets after a prescribed time following a recoverable error. If the human commits a catastrophic error to a system, the system is disabled for the remainder of the simulation (nonhuman system) or until a replacement system arrives (human system).

The probability of catastrophic error is conditional. It the human fails during a time step in SoSAT (2.2.1.1 Basic Error Rate) the possibility of catastrophic error is checked. Specifically, if a uniformly generated random value in the interval (0, 1) is less than the catastrophic error probability, the error that the human has committed is catastrophic. If the error is not catastrophic, the error is recoverable.

The effects of catastrophic errors are exemplified as follows:

- When an NCO commits a catastrophic error to his/her own (human) system, it is treated the same as combat damage – evacuation and replacement. SoSAT completes the replacement after a time sampled from the replacement time distribution (see 2.2.2.2 Replacement Time).
- When a driver commits a catastrophic error to his/her assigned (nonhuman) system, the system is disabled for the remainder of the simulation. This effectively removes the driver and any other human assigned to that system for the remainder of the simulation.
- A mechanic can only commit a catastrophic error to the system he/she is currently repairing. SoSAT disables the system which effectively removes the humans assigned to that system for the remainder of the simulation. However, SoSAT assumes that the mechanic and any other mechanics temporarily assigned to that system are unharmed and are returned to their home system.

2.2.2. Human Downtime

2.2.2.1. Reset Time

Reset time is the time required to recover from a non-catastrophic mistake. The time is defined by a probability distribution when the user assigns a human element to a SoSAT system type.

Each instance of the system type means another instance of that human element. Every such human element uses the same reset time distribution.

When the human makes a reliability error, the reset time distribution is randomly sampled. The sampled value is used as follows.

- If human performance directly affects performance of the system (e.g., driver), it is the time required for the human to reset. So, the human (and possibly the system) is down for that time.
- If the human has authority to order parts or consumables for systems, one of those systems requests that the human place an order, and the human is experiencing reset time, the human does not place the order until the reset time has elapsed.
- If a mechanic makes an error during a repair job, the time required to finish the repair is extended by the reset time.

2.2.2.2. Replacement Time

SoSAT replaces a primary element with an identical part or subsystem. The time required is potentially an accumulation of the time to acquire the spare and services, and to perform the services.

Following this model a human is also replaced by an identical human element. With humans the replacement time is sampled from a single probability distribution, defined when the user assigns a human element to a SoSAT system type. As with the reset time each instance of the human element uses the same distribution.

A human is replaced in two instances:

- The human suffers combat damage or
- A human (element) commits a catastrophic error to the human (system).

If a human is not to be replaced during a simulation, assign a fixed probability distribution with a value that exceeds simulation time.

2.2.3. Modeling PSFs

2.2.3.1. Training, Experience, Perceptual Skills

The first three PSFs modeled in SoSAT are independent of time and are defined prior to simulation of the mission. The idea is that an individual with increased training, with longer experience, or with greater perceptual skills is less likely to commit an error than someone with less of these attributes. The user inputs an adjustment factor for each of the three PSFs. SoSAT assumes that the factors are multiplicative and takes the product of the three factors.

The adjustment factors can be defined for the entire force or for human types. To calculate the final adjustment factor for a human type, SoSAT multiplies the product defined for the force by the product defined for the human type. So, it is good practice

- If the entire force is subject to adjustments, to assign values at the force level and set all values for human types to 1.0 or
- If different human types are to have different adjustments, to assign their values accordingly and set the values at the force level to 1.0.

SoSAT divides the adjustment factor into the basic error rate for the affected humans. In this way, improvements should have adjustment factors greater than 1.0 to decrease the error rate.

2.2.3.2. Fatigue+Cognitive Fatigue

Fatigue and cognitive fatigue are not distinguished in SoSAT. Their combined effect is to increase the error rate with time and SoSAT assumes that the increase is linear with time. Rather than prompt the user for the rate of increase (slope), SoSAT prompts for an error-rate-multiplier that is valid at a future point in time. We have chosen 24 hours for that point in time and the user supplies a distribution for the multiplier.

The information is used as follows. First, the sampled error rate assigned to the human (2.2.1.1 Basic Error Rate) is treated as an initial rate ($\lambda_0 = \lambda(0)$). Second, the fatigue multiplier distribution is sampled and the sampled value (v) is assumed to be a multiplier of the initial rate that is valid after 24 hours of operating time ($\lambda(24) = v\,\lambda_0$). SoSAT uses this information to define a constant slope m.

$$m = \lambda_0 (v - 1)/24 \qquad \textbf{(2-2)}$$

The error rate then increases linearly with time according to $\lambda(t) = \lambda_0 + m\,t$. If the fatigue multiplier is fixed at 1.0, then the slope m = 0.0 and the constant error rate model from Equation (2-1) applies.

For the general case (m > 0) the effects of fatigue are used to define a modified TTF distribution function

$$F(t) = 1 - e^{-(\lambda_0 + mt)t} \qquad \lambda_0 > 0, m > 0, t \geq 0 \qquad \textbf{(2-3)}$$

An example comparison of cumulative distribution functions (CDFs) with $\lambda_0 = 0.04$ is shown in Figure 2.1. The no fatigue case uses Equation (2-1). The fatigue case uses Equation (2-3) with m = 0.000833 derived from multiplier v = 1.5 in Equation (2-2). At any given time the cumulative probability of error to that time is greater with fatigue. Of greater interest note that time differences increase with increasing probability. For example at the median there is a 50% chance that the human has made an error by 17.4 hours with no fatigue, but with fatigue there is a 50% chance by 13.6 hours, or 3.8 hours earlier. The difference grows to 14.2 hours (40.3 – 26.1) at the 80^{th} percentile.

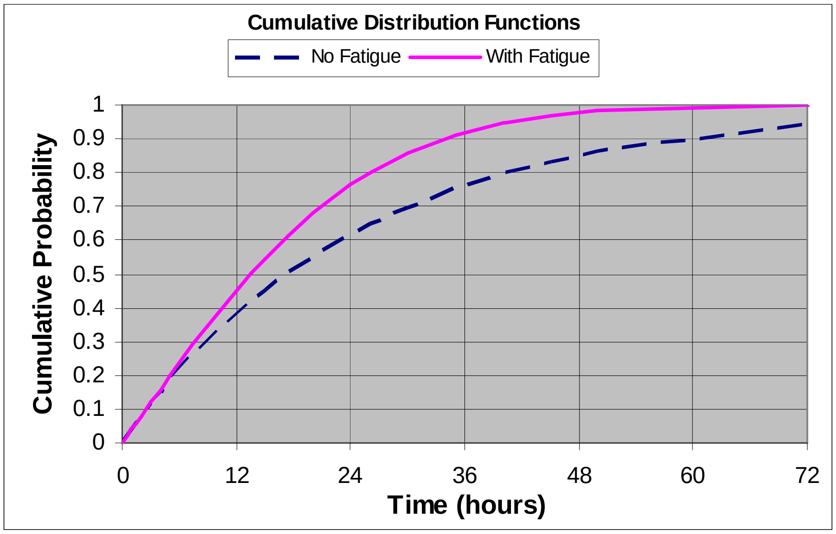


Figure 2.1. Fatigue Distribution Example.

The modified TTF distribution is referred to as the linear rate exponential in SoSAT. For m > 0, its mean ( ) and variance (^{2}) are stated in terms of the complementary error function (erfc).

$$\mu = \frac{e^{\lambda_0^2/4m}}{2}\sqrt{\frac{\pi}{m}}\ \mathrm{erfc}\left(\frac{\lambda_0}{2\sqrt{m}}\right) \quad \text{and} \quad \sigma^2 = \frac{1-(\lambda_0 + m\mu)\mu}{m} \quad \text{where} \quad \mathrm{erfc}(x) = \int_x^\infty \frac{2}{\sqrt{\pi}} e^{-S^2}\, dS \qquad \textbf{(2-4)}$$

For m = 0 (Equation 2-1) they are   = 1/   and ^{2} = 1/ ^{2}.

The linear rate exponential distribution of Equation (2-3) has a t^2 term in the exponent so it somewhat resembles a Weibull distribution with shape parameter equal to two. However, SoSAT does not use the Weibull to model fatigue because regardless of the value of the shape parameter, there is an undesirable crossover behavior that is characteristic of the two-parameter Weibull. Figure 2.2 shows CDFs for the Weibull for shape parameters of 0.5, 1.0, and 2.0. All three curves cross at 1/   (25 hours in this case). The middle blue curve is the exponential (no fatigue) case. The two other curves both have smaller cumulative failure probabilities over some segment of the time range, which does not make sense for fatigue. The linear rate exponential distribution is preferred because it does not suffer from the crossover behavior (Figure 2.1).

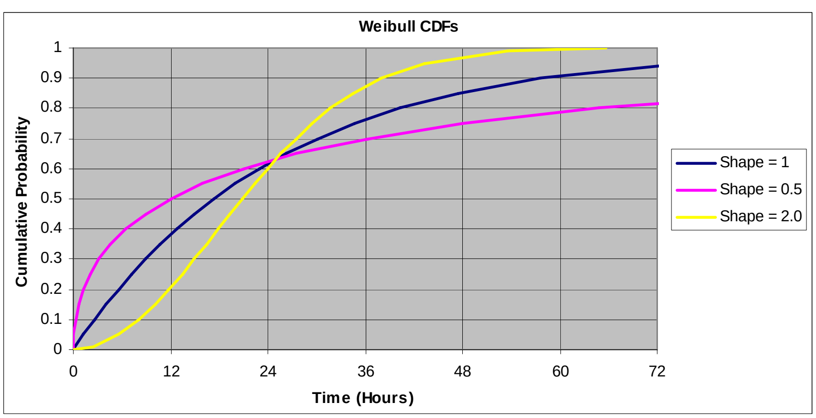


Figure 2.2. Weibull CDFs with Various Shape Parameters.

SoSAT does not use the Weibull for fatigue nor does it use the simple idea of multiplying the error rate by some factor. This simply shifts the CDF from that of Equation (2-1). The time difference at the 50th percentile is the same as the time difference at the 80th percentile, for example. Such a constant shift also is non-intuitive for modeling fatigue.

2.2.3.3. Stress

Stress is modeled in SoSAT through external conditions. An external condition is defined, mapped to segments in a scenario, and given a probability of occurrence. When the scenario is assigned to a system, that system and its elements are subject to the external condition when it occurs.

The effect of the external condition can be applied to humans through one of two multipliers:

- Multiply the initial human error rate for the TTF distribution or
- Multiply the aging rate for the human.

For either case multipliers that exceed 1.0 cause an increase in error probability due to stress.

For the former, the multiplier is applied to the sampled error rate $_{0}$, but the slope is not recalculated (2.2.3.2 Fatigue+Cognitive Fatigue). The assumption is that the basic error rate increases but rate of increase due to fatigue does not.

The latter is applied analogously to aging of primary elements due to stress. The wear and tear on a part operating under stressful conditions for C hours may be equivalent to the wear and tear experienced operating H hours under normal conditions. The multiplier is the ratio H/C. The same reasoning can be applied to humans under stress. Driving a vehicle in the middle of a battle for 2 hours may produce the same wear and tear on the human produced by driving in normal conditions for 5 hours. The multiplier would be 2.5 in this case.

2.2.3.4. Combat Damage

Combat damage models already exist in SoSAT to calculate damage to systems and their primary elements. In general the nodes of a combat damage tree have occurrence probability conditioned on the occurrence of their parent node. The concept has been extended to include humans and humans can appear in two different ways:

- Human elements can be inserted as leaf nodes in the tree the same way that primary elements can and
- Combat damage models can be designed for and assigned to human systems.

SoSAT assumes that in all cases if a human suffers combat damage, that individual is evacuated and replaced. The time required to replace the human is sampled from the replacement time distribution (2.2.2.2 Replacement Time). In the case of a combat damage to a human system, the treatment is the same whether the system is disabled or the human element is damaged.

2.2.4. Human Impacts on the Performance of the Force

2.2.4.1. Direct Impact

Direct impact of humans on a system is modeled in the same way as the impact of all other elements. To have impact the human must be included in cutsets that define the Boolean expressions for functions of the system. In this way the state of a driver can help determine the mobility function, or more generally the operability function, for a system. If the driver is the only element in a simple cutset, when the driver is down the system is down.

A driver can be down for two reasons: he/she makes a mistake or he/she suffers combat damage. For the former the driver is down for the time sampled from the reset time distribution (2.2.2.1 Reset Time). For the latter the driver is down for the time sampled from the replacement time distribution (2.2.2.2 Replacement Time).

Because there are two reasons for the driver to fail, there is an issue regarding backup drivers.

1. Realistically a backup driver would not often be able to prevent the primary driver from making a mistake, so the backup is not redundant in this case. The system should fail when the primary driver fails and should be down for the reset time.
2. On the other hand, if the primary driver suffers combat damage and there is a backup driver present, the backup driver should be able to take over almost immediately, thereby providing redundancy in the mobility function.

Case 1 suggests that the primary driver ought to be in a singleton cutset for mobility of the system. Case 2 suggests that the backup driver be placed into a doubleton cutset with the primary driver (or more accurately in a standby arrangement). Then they would both have to fail for the system mobility to fail.

To resolve this conflict we recommend that backup drivers should not be explicitly introduced into the model. The primary driver should be placed in a singleton cutset so that reliability errors are properly handled. The replacement time for combat damage should be short to simulate immediate replacement. SoSAT "replaces" the driver with an identical copy in this case much like it replaces failed parts with identical parts.

Although much of the discussion and the example problem (2.4 Example Problem) focus on drivers, other individuals can also have direct impact on systems. The failure of a gunner can cause loss of lethality and the failure of a radio operator can cause loss of communications, for example.

2.2.4.2. Supply Orders

When a system requires a consumable or part, it requests that an order be placed. SoSAT now offers the option to require that someone with authority actually place the order. Authorities are assigned to human elements when the humans are first introduced in the input. Humans can have authority for only their system or for a group of systems. The group always consists of systems at the same level of the force structure, and below.

For each system SoSAT examines the input to populate a collection of individuals that has authority over that system.

- If a system has no one in authority (the collection is empty), then SoSAT assumes that no authority is required and all requests to order parts or consumables are immediately placed.
- If a system falls under the authority of a single individual, its collection has a single human element. If the system requests that an order be placed and the human is down due to a reliability failure, then the order will not be placed until the human has reset. If the human is down due to combat damage, then the order will not be placed until the human has been replaced.

- If a system falls under N > 1 humans with authority, its collection has N human elements. For example both a platoon leader and NCO may have authority for all vehicles in their platoon. Thus, each system in the platoon has N = 2 members in its collection. When a system requests that an order be placed, it selects the first member of its collection.
  - If that member is up the order is placed.
  - If that member is down due to reliability error, the order is delayed until the member resets.
  - If that member is down due to combat damage, the system repeats these steps for the next member of its collection.

  With this process SoSAT allows for reliability errors to occur but the requesting system has redundant authorities in case of combat damage. This avoids the issue discussed for backup drivers (2.2.4.1 Direct Impact).

2.2.4.3. Repairs

Individuals that are qualified to perform repairs are identified when humans are first defined. Like other elements they must be attached to a SoSAT system to be included in the analysis. Usually they do not serve a function for the system so they would not normally be included in any cutset. They are the only re-assignable elements in SoSAT. They are temporarily assigned to other systems on an as needed basis. For the failed system to access the mechanics there must be a supply connection from the failed system to the mechanics' system.

Historically the repair of a primary element in SoSAT could require a spare or not and services or not. Now the repair can also explicitly require mechanics or not. If the repair requires mechanics, the mechanics can be accessed directly or via a service that has mechanics included. SoSAT searches supply connections for the requesting system for the spare part, the required number of mechanics, and/or the services.

Generally speaking a repair without services is easier to input because it requires less detailed information. The spare name, the number of mechanics, and the repair time are all defined when the primary element is assigned to a SoSAT system type.

When the primary element fails (without services)

- SoSAT searches supply connections for a provider system for the spare part.
- Only after a provider of the spare is located (or immediately if no spare is required), does SoSAT begin the search for a provider for the mechanics, again searching the supply connections. Currently if multiple mechanics are required for the repair, all must come from a single provider.
- If the two provider systems are not the same, the one with the longest delivery time determines the delay time. Both the spare and mechanics must arrive before the actual repair can begin.

For a more detailed analysis, a repair can require multiple services that must be performed in a given order. Moreover, there can be more than one basic service having the same order number; in which case those services are all performed simultaneously before those of the next higher order number can begin. A service that does not require mechanics (e.g., towing) is called a non-repair service in SoSAT. One that requires mechanics is called a repair service.

When the primary element fails (with services)

- SoSAT examines the services of order 1 to determine if any are of repair type.
  - If so, SoSAT begins searching supply connections for the spare part, if a spare is needed. Only after a provider is found for the required spare does SoSAT begin searching for services.
  - If not, SoSAT immediately begins the search for order 1 services. The search for the spare is postponed until an order is reached that contains a repair type service. Once the non-repair services of order 1 are completed, SoSAT returns to the first step to examine services of order 2, and so on.
- The search for mechanics is part of the search for services. The provider service must be available and it must have a sufficient number of free mechanics. Again if multiple mechanics are required, all must come from a single provider.
- The actual repair begins after the spare and mechanics arrive.

Using services or not, the availability of repair personnel can impact the time required to complete repairs. When SoSAT pings a provider, each of its mechanics is in one of three states:

1. Not present because they are on temporary assignment to another system,
2. Present but down due to reliability error or combat damage, or
3. Present and up.

Only in case 3 are they free to be assigned. If the provider has fewer free mechanics than called for, the provider is passed over. Thus, there can be a delay until a provider is found that has a sufficient number available. Presently SoSAT does not queue the systems for the mechanics search. At each time step it is first come first served.

SoSAT records the time spent awaiting free mechanics to help the analyst determine if there are sufficient mechanics planned for the mission. In some specific instances is not clear when to accumulate this time. Suppose there are two services having the same order number – one repair type and one non-repair type. At some point in the simulation SoSAT is trying to locate a provider for each.

- If the repair type service can be found but the non-repair type cannot, no time delay is accumulated for insufficient mechanics.

- If the non-repair type service can be found but the repair type cannot, candidate providers are disqualified for one of two reasons:
  - The provider system is occupied or
  - The provider system is free but has insufficient mechanics.

  In the first case there is no time delay attributable to insufficient mechanics. If the second case is true for any candidate provider, SoSAT assumes the time delay is caused by insufficient mechanics and is accumulated.

- If neither type of service can be found, SoSAT implements the previous bullet assuming that the non-repair service is available (only for the purpose of time accounting).

Mechanics also directly impact the repair time. The time (T) that mechanics are required to spend on the job is either defined for the primary element or for the service. If a mechanic makes a mistake it requires some time to recover. The time is sampled from the reset time distribution (2.2.2.1 Reset Time). If multiple mechanics are involved simultaneously SoSAT assumes that each one must spend time T on the job. If one or more mechanics fail during time T, the net effect is that the repair time is extended by the maximum reset time amongst the mechanics that failed.

If a system that requires repair is in the field, the mechanic is sent to the field. The mechanic is then subject to the conditions encountered by the system and can therefore be subject to added stress or be injured by combat damage. The added stress enhances the probability of reliability error (2.2.3.3 Stress). If there is combat damage SoSAT assumes that the mechanic must be replaced and the replacement time is sampled from the replacement time distribution (2.2.2.2 Replacement Time).

It is possible in SoSAT for a mechanic to commit a catastrophic error. In that case the system being repaired becomes disabled for the remainder of the simulation. SoSAT assumes that the offending mechanic, and any other mechanics that happen to also be working on the system, are unharmed. They are returned to their home system.

2.3. Parameters and Parameter Values

A number of parameters are discussed above in the implementation of the proability-based HPMs in SoSAT. Here the parameters are described and default parameter values are justified. These defaults are meant to apply to any human, and any activity that this generic human performs. Table 2.1 contains a summary of the parameters and parameter values for the proability-based HPM.

Table 2.1. Basic Error and Recovery Parameters and Parameter Values for the Probability-based HPMs in SoSAT.

Parameter	Value	Notes
Basic Error Rate	E(0.04/hr)	Exponentially distributed; parameter for time-to-failure (TTF) distribution (see Eq. 2-1)
Catastrophic Failure Probability	0.001	Single value; based on the probability that an error committed while driving a car will result in an injury
Time-to-Reset	E(0.5 hr)	Analogous to time-to-repair (TTR)
Replacement Time	—	No default; depends on specific situation (see Section 2.2.2.2)

2.3.1. Definition of Human Base Error Rate

Human Error Probabilities (HEPs) for HRA are defined as the probability of an error occurring when a given task is performed (Swain and Guttman, 1983), where the task could be reading a dial or closing a valve. The task can also be thought of as an opportunity for error. Sometimes HEPs are thought of in terms of rates, e.g., the rate of errors during performance of a number of the same tasks (Wincek and Haight, 2007).

To apply these data to SoSAT, we need to generalize the concept of a task or an opportunity for error. The first generalization is to have the term opportunity apply to any individual activity. Thus, to change the oil in an engine, a mechanic must first remove old oil and then put in the new oil. In an HRA, each of these tasks would be considered to be different, and each would be given a different error probability. Here we generalize them into two equal tasks with two equal opportunities to make an error. We further generalize that the time to perform these tasks is equal. If one of the tasks actually takes approximately twice as long, then we generalize that there are twice as many opportunities to make an error when performing that task.

With these generalizations, we can specify an error rate for all of the tasks that a mechanic must perform, no matter what the tasks are or how long they take. Because this is a general purpose error rate for the mechanic, SoSAT allows the user to specify a probability distribution that encompasses the uncertainty, and human-to-human variability, in this generalized estimate.

Although there are many sources of HRA-type parameter values, to determine basic error rates we use those from Williams (1988) and Wincek and Haight (2007). Note that we intend to define error factors separately, so we want baseline error rates here—error rates unaffected by performance-shaping factors (PSF), e.g., stress, fatigue, etc. Williams offers the following values for "human unreliability" that fall in the category of being unaffected by PSFs. (Values in parentheses are the 5^{th} to 95^{th} percentile bounds.)

- Routine, highly-practiced, rapid task involving relatively low level of skill—0.02 (7E-3 to 4.5E-2)
- Restore or shift a system to original or new state following procedures, with some checking—3E-3 (8E-4 to 7E-3)
- Completely familiar, well-designed, highly practiced, routine task occurring several times per hour, performed to highest possible standards by highest-motivated, highly-trained and experienced person, totally aware of implications of failure, with the time to correct potential error, but without the benefit of significant job aids—4E-4 (8E-5 to 9E-3)
- Respond correctly to system command even when there is an augmented or automated supervisory system providing accurate interpretation of system state—2E-5 (6E-6 to 9E-4)

Wincek and Haight offer base error rates for a number of task types that are unaffected by PSFs. They range from a value for simple arithmetic error (without redoing calculation on separate paper) of 3E-2 per opportunity to a value for the upper limit of credibility of 1E-5 per opportunity. Ten task types apply to mechanical activities (e.g., read instructions, install nuts and bolts, solder connector, etc.), and the values range from 1E-4 to 6.67E-2 errors per opportunity.

Although the Williams values and the Wincek and Haight values exhibit a wide range of variability, a typical intermediate value is approximately 5E-3 errors per opportunity. To err on the side of caution, we assume here a typical value of 1E-2 errors per opportunity.

Most of the task types listed by Wincek and Haight take from a few minutes to a few tens of minutes to perform. This assessment also could hold for the tasks listed by Williams. If we assume that the task durations are uniformly distributed between 1 minute and 30 minutes, the mean duration would be approximately 15 minutes (this number is sensitive to the upper bound of the uniform distribution). Therefore, we assume here that an opportunity takes 15 minutes. And therefore, we assume that the median error rate for a human, generalized to apply to any set of tasks of any duration, is 1E-2 per 15 minutes, or 4E-2 errors per hour.

Given that all that is known is a single value from a distribution, the principle of maximum entropy suggests that the best estimate of the distribution is an exponential distribution (Jaynes, 1957). Here we specify E(4E-2) to describe generalized human error rate. Sampling from the exponential distribution would produce most error rates at around 4E-2/hr or less; however, some error rates could be much greater.

SoSAT actually uses a time-to-failure (TTF) distribution—calculation of a TTF from the basic error rate is discussed in Section 2.2.2.1.

2.3.2. Determination of Catastrophic-Error Probability

The catastrophic-error probability is the fraction of the human basic error rate that results in incapacitating failure, either of the human or the system with which the human working. An example of a catastrophic failure is a mechanic improperly securing engine mounts, with the consequence that the engine comes loose and damages the vehicle to the extent that it is not repairable in the timeframe of the operations.

Catastrophic errors can occur in many military endeavors, from tactical emplacement to weapon maintenance. Here we use data from traffic accidents to represent typical catastrophic-error probabilities.

Data from 2006 indicate that 2,575,000 persons were injured in traffic accidents in the U.S. (RITA, no date). The total vehicle-driven miles that year was 3.0×10^{12}. Assuming an average vehicle speed of 45 miles/hour, we calculate that the traffic-injury rate was approximately 4×10^{-5} injuries/hour. The catastrophic-error probability is then calculated as the quotient of the traffic-injury rate and the human basic error rate, as follows:

$$\mathrm{Pr_C} = \frac{\mathrm{R_{TI}}}{\mathrm{R_{BE}}} = \frac{4\times10^{-5}}{4\times10^{-2}} = 10^{-3} \tag{2-3}$$

where $\mathrm{Pr_C}$ is the catastrophic-error probability, $\mathrm{R_{TI}}$ is the traffic-injury rate, and $\mathrm{R_{BE}}$ is the human basic error rate. This probability can be interpreted to mean that, on average, one error out of a thousand errors will result in incapacitating failure. It is not possible at this time to justify this probability further. One would need to know more; for instance, one would need to know how many driver errors occur before one results in an injury. However, these errors include not only accidents, but other errors for which no statistics are taken, such as making wrong turns or not using a turn signal before a turning.

2.3.3. Determination of Human Time-to-Reset

Little to no data exists in the scientific literature concerning human time-to-reset. For one reason, HRA is not typically concerned with recovery from an error. With the time-to-reset parameter, we want to capture how long will it take to notice and correct the error, and how long will the human continue to make similar errors involving similar situations.

Here we note that the time to recover from an error is often the amount of time that it took to perform the task in the first place, and thus the task ends up taking twice as long. Consider the following logic. During performance of a task, an error is made. For example, while adding oil to an engine, the oil is spilled. In this case, the error must be first addressed—e.g., the oil must be cleaned up—and then the task must be performed again—e.g., new oil must be added to the engine. However, not all errors are as obvious as spilling oil. An arithmetic error might never be caught. To error on the side of caution, we assume that the typical time to recover from an error is twice the amount of time that it takes to perform the task in the first place.

Note that the time to perform a typical task was assumed to be 15 minutes, based on Wincek and Haight (2007) as discussed above. Therefore, the time to recover from an error is assumed to be approximately 30 minutes. Again, the exponential distribution is applicable in this regard. Here we specify an exponential distribution with a mean of 0.5 hr (E(0.5 hr)) to describe the human time-to-reset.

2.3.4. Determination of the Performance-Shaping-Factors Parameter Values

Performance-shaping factors (PSFs) are conditions that contribute to human performance. In HRA modeling, PSFs are used to increase or decrease standard or normal rates of occurrence of human errors. Preliminary values for the PSF parameters are specified in this section. In the probability-based HPM, these values are only used to decrement performance, so they are called impairment values. How these parameters are used is discussed in Section 2.2. The PSF values are intended to apply to a generic human.

In the probability-based HPM, PSFs are used to modify only the human base error rate. (No data exist to support also modifying the human time-to-reset, although it is plausible that PSFs might impact reset time.)

Miller and Lawton (2007) defined 11 PSFs for consideration in this effort. The PSFs fall into four categories, as shown in Table 2.2. The PSFs of Thirst and Chemicals/NBC were not considered in the probability-based HPM. The three time-independent PSFs were treated in the same way in the HPM. The Immobilized, Can't Communicate, and Casualty PSFs were treated the same as combat damage in the HPM.

Table 2.2. PSFs for the Probability-Based HPM (Miller and Lawton, 2007).

Category Name	PSFs
Time Independent	Inadequate Perceptual Skills Inadequate Experience Inadequate Training
Consumable-Related	Thirst
Combat Damage	Immobilized Can't Communicate Casualty
Time Dependent	Stress Cognitive Fatigue Chemicals/NBC Fatigue

Table 2.3 shows the impairment values suggested for the different categories of PSFs. The Fatigue and Cognitive Fatigue and the Stress PSFs in the time-dependent category are separated because they are treated differently in the HPM. The data used to derive the impairment values comes from Lieberman et al. (2007). Lieberman et al. administered batteries of cognitive and mood tests to Ranger officers undergoing training and to enlisted men attempting to qualify as SEALs. The Rangers averaged 9 years of experience; the SEAL aspirants averaged 3 years of experience. The training in both cases was physically and mentally draining. It lasted approximately three days with little chance for rest. The tests were administered before and after the training. Determination of the impairment value for a given PSF is based on the decrement in the test scores.

Table 2.3. PSF Categories and Impairment Values for the Probability-Based HPMs in SoSAT (based on Lieberman et al., 2005).

PSF Category Name	Impairment Values	Notes
Time Independent	U(0.63,1)	Uniformly distributed; the distribution applies to each PSF; the distribution is based on the difference between the test results of the Ranger and the SEAL trainees
Consumable-Related	—	Not considered in this effort
Combat Damage	—	See Section 2.2.3.4
Time Dependent—Fatigue and Cognitive Fatigue	U(1.07,2.57)	Uniformly distributed; see text
Time Dependent—Stress	3.46	Single value; based on the average of the extremes of the decrements in test scores—i.e., (1.22+5.70)÷2

2.3.4.1 Time-Independent PSFs

Inadequate experience, inadequate training, and inadequate perceptual skills are assumed to be represented in the differences in test scores between the Ranger officers and the SEAL enlisted-men trainees, as reported by Lieberman et al. (2007). Reported differences are between a factor of 0.25 and 1, where the smaller number indicates that the SEAL candidates performed 0.25 as well as the Rangers.

The testing did not distinguish between experience or training or perceptual skills. In the probability-based HPM, entries for inadequate experience, inadequate training, and inadequate perceptual skills are multiplied to determine the total effect. We assume that these three PSFs are represented in the data, so we assume that the lower value for each PSF is 0.63 (note that 0.63*0.63*0.63 = 0.25). Thus, considering these PSFs separately, the range of the difference in the test scores would be from 0.63 to 1. Based on the principle of maximum entropy (Jaynes, 1957), a uniform distribution between these endpoints is assumed.

(Although a piecewise distribution based on the reported differences could be constructed, it is not obvious how much information this would contribute, because all of the tests are different, and the testing situations were different.)

Most of the tests administered by Lieberman et al. measure time (response and reaction time), and thus relate more to reset time than to basic error rate. The one test that relates to the error rate is four-choice visual reaction time, specifically hitting the wrong key. In this test, the SEAL candidates performed worse than the Rangers by approximately a factor of 0.25, which is at the lower end of the range of possibilities, suggesting that experience and training might better reduce errors rather than the duration of tasks. This effect should be investigated further.

2.3.4.2 Consumable-Related PSFs

Although the Thirst PSF is not being considered here, Lieberman et al. (2007) report that Rangers lost about 4kg of body weight during their training. It is likely that the physiological degradation is implicit in the test scores.

2.3.4.3 Combat-Damage PSFs

Combat-damage PSFs are handled through the Combat Damage Model in SoSAT. It is assumed that in all cases if a human suffers combat damage, that individual is evacuated and replaced (2.2.3.4 Combat Damage). The time required to replace the human is sampled from the replacement time distribution (2.2.2.2 Replacement Time). In the case of a combat damage to a human system, the treatment is the same whether the system is disabled or the human element is damaged.

2.3.4.4 Time-Dependent PSFs

Two categories of time-dependent PSFs are recognized in the probability-based HPM modeling: fatigue+cognitive fatigue and stress. These two categories are treated differently (Sections 2.2.3.2 and 2.2.3.3), with fatigue+cognitive fatigue continuously increasing over time, until rest and recuperation, and with stress being assigned for a given scenario. Fatigue+cognitive-fatigue is parameterized by a slope, which is determined by sampling a distribution. Stress is parameterized by a single value. The same data from Lieberman et al. are used here to calculate both PSF values, which could be double-counting the affects. However, overestimating these affects is preferred to underestimating them. Also, the Rangers and the SEAL aspirants were only training and not in actual combat. In actual combat, the fatigue and stress could be worse.

In the battery of tests administered by Lieberman et al., the least decrement in performance was 22% in the test for scanning visual vigilance; the greatest decrement was 470% in one of the categories in the profile of mood (fatigue). These bounds are taken as representative of the range of possible impairment for all time dependent PSFs. Again, the four-choice-visual-reaction-time test shows greater degradation in performing correctly than in performing quickly. This effect is apparent for Rangers and SEAL aspirants and thus exists beyond the effect of the time-independent PSFs.

Fatigue+cognitive fatigue. The performance deficits have a range of 0.22 to 4.7. Assuming that the deficit increases linearly over 3 days (the approximate length of the training), after 1 day the deficit delta would range from 0.07 and 1.57. Converting these numbers into multipliers of the basic error rate, a slope parameter of between 1.07 and 2.57 is achieved. As no overriding tendency is apparent in the data, a uniform distribution is assumed between these endpoints: U(1.07,2.57).

Stress. Again, the performance deficits have a range of 0.22 to 4.7. Converting these numbers into multipliers of the basic error rate, we have a range of 1.22 to 5.7. As only a single value is allowed for this parameter, we take the average of the endpoints: 3.46. Here it is assumed that (1) the onset of stress is abrupt, (2) the magnitude of stress is constant, and (3) all humans experience the same magnitude of stress. These assumptions should be revisited in the future.

2.3.4.3 Combining PSFs

The literature reports several different methods of combining the effects of PSFs. Swain and Guttman (1983) define uncertainty bounds to encompass the effect of multiple PSFs (propagating the uncertainty bounds across multiple tasks). Wincek and Haight (2007) take the product of their error rate multipliers to combine them. Williams (1988) multiplies his error producing conditions (ECPs), times the assessed proportion of the ECP (a fraction of the total effect), times the nominal human unreliability to achieve a weighted average of effects. In the IMPRINT application (IMPRINT, 2005), multiple degradation factors (DFs) are ordered and reduced by the exponent of the reciprocal of the ordering number, before taking their product.

One might assume that multiple PSFs would cause greater impairment than a single PSF, and three of the four references cited above are designed to produce this effect. Apparently little evidence supports or discounts this idea. Here we follow Wincek and Haight: in the probability-based HPM, the affect of multiple PSFs is the product of their individual affects.

2.4. Example Problem

2.4.1. Introduction

The force structure for the example problem contains a company that has two platoons and three separate support vehicles. The force also has a repair facility and a consumables depot that are independent of the company. Key systems of the platoons are

- Their own water supply (CAMEL)
- Command vehicles (CV)
- Sandia all purpose vehicles (SAPV)
- Platoon leaders (Platoon Leader)
- Senior NCOs (NCO)

The company's three support vehicles are trucks for supplying fuel, ammunition, and spare parts. The repair facility has a parts depot and a pool of mechanics.

Personnel include the aforementioned platoon leaders and NCOs. Also, the mechanics pool consists of three repair personnel. These are generic mechanics that are qualified to make any kind of repair that systems may require. The only other humans modeled in this problem are the drivers of the vehicles.

Systems have primary elements that can fail and require spare parts and mechanics for their repair. Systems can also fail if they run out of consumables. Systems must access someone with authority to request that spares and consumables be ordered. The persons of authority for the systems of a platoon are their platoon leader and NCO.

All mechanics are initially assigned to the mechanics pool. They are temporarily reassigned as needed to systems that require repair. Drivers are permanently assigned to systems. Their performance directly impacts the performance of their system.

The mission for the company includes a 72-hr stretch in the field, a 24-hr break at the repair facility, and another 72-hr stretch in the field. During each period in the field there could be a 12-hr battle. The 3-day stretches in the field cause fatigue for the humans, which increases their error rates. The battle causes stress which also causes humans to make errors more frequently. In addition the probability of combat damage to humans increases with battle.

Each human is assigned a basic error rate distribution. The sampled error rate can be influenced by several performance shaping factors (PSFs). Miller and Lawton, 2007 discussed 11 PSFs of interest. This example problem deals with fatigue+cognitive fatigue, stress, and indirectly with combat-damage-related PSFs (casualty, immobilized, and can't communicate). Capability of dealing with time-independent PSFs (inadequate training, inadequate experience, inadequate perceptual skills) is discussed but not exercised. PSFs not addressed are chemicals/NBC and thirst.

Section 2.4.2 Problem Input describes the input for the example problem. Each branch of SoSAT's input navigation tree is covered in a subsection. The problem is run for 200 trials and selected results are shown in Section 2.4.3 Problem Results. There is a general summary in Section 2.2.4 Conclusions. It is stated in the input discussions that many of the input values are arbitrary. So even though the impacts of human errors on the performance of the force are measurable with this problem, these results may or may not be realistic.

2.4.2. Problem Input

2.4.2.1. Basic Definitions – Settings

Simulation Parameters

The simulation parameters are shown in Figure 2.3. The simulation duration is set to 168 hours, which is the total mission time. The numerical simulation will use 0.1-hr time steps.

The last three items are new adjustment factors for the assigned personnel. The factors provide a means for quickly simulating what-if questions concerning three time-independent PSFs – training, experience, and perceptual skills – for the entire force. If additional training could reduce errors by 25%, enter 1.25 for the training adjustment.

Simulation Parameters

Simulation Parameters

Settings	Value
Number of Simulation Trials	200
Random Seed	71408
Simulation Duration (hr)	168
Simulation Time Step (hr)	0.1
Training Adjustment	1
Experience Adjustment	1
Perceptual Skills Adjustment	1

Figure 2.3. Simulation Parameters.

When an individual is assigned to a system type, that person is assigned a probability distribution for basic error rate. SoSAT will divide each sampled error rate by the product of adjustment factors before using the rate. For this problem we are using all default values (1.0), which means no adjustment. Note that these adjustment factors can also be assigned when an individual is attached to a system type, so that these PSFs can vary across the force.

External Elements

There are no external elements in this problem.

Primary Elements

The primary elements are typically parts or subsystems that could fail for the systems. We use the simplified set of elements shown in Figure 2.4. There is no attempt to diagnose potential failures and fix them before they occur in this example problem, so Prognostics and Health Management (PHM) of parts is not modeled. Thus, the relevant input here is the list of primary element names.

Primary Elements

Define the primary elements that will be used in a system

Name	PHM Enabled	Inspection Interval	False Positive Probability	False Negative Probability
Engine	☐	1	0	0
Fuel System	☐	1	0	0
Machine Gun	☐	1	0	0
Radio	☐	1	0	0
Suspension	☐	1	0	0
Wheels	☐	1	0	0

Figure 2.4. Primary Elements.

Personnel

The initial input for personnel includes a name and the various tasks that the person could perform as shown in Figure 2.5.

Personnel

Give a title and authorities for every type of human to be included in the analysis

Name	Can Order Consumables	Can Order Parts	Authority At Level	Can Do Repairs
Driver	☐	☐	☐	☐
Mechanic1	☐	☐	☐	☑
Mechanic2	☐	☐	☐	☑
Mechanic3	☐	☐	☐	☑
NCO	☑	☑	☑	☐
Platoon Leader	☑	☑	☑	☐
Supplier Driver	☑	☑	☐	☐

Figure 2.5. Personnel Names and Tasks.

The generic driver has no authorities here but must be given a name for use in other parts of the input. The difference between the generic Driver and the Supplier Driver is that the latter will be attached to a supply type vehicle that does not fall under the command of the platoon leaders or NCOs. So they are given the authority to order parts and consumables for their own systems. If systems assigned to a platoon require parts or consumables, those systems must make their request through the platoon leader or NCO. Checking the Authority At Level column means that the human has authority to place such orders for every system at their same level in the force structure, and below. We will insert a platoon leader and NCO into each platoon.

Checking the Can Do Repairs column identifies those personnel as qualified repair personnel. For this problem we will assign these personnel to the mechanics pool. During a simulation they can be temporarily reassigned to systems needing repair, either in the field or at the repair facility. Once the repair is complete they are returned to the pool.

2.4.2.2. Basic Definitions – Parts

Parts Definition

Four of the primary elements entered above (see Figure 2.4) will require spares if they fail. They are listed in Figure 2.6. The values for weight, volume, and cost are arbitrary.

Parts Definition

Define all the spare parts that will be used in the simulation

Name	Weight	Volume	Cost
Engine	1000	3	1500
Machine Gun	50	1	500
Radio	5	1	200
Wheels	150	2	250

Figure 2.6. Parts Definition.

Parts Grouping

The parts grouping defines the inventories for the parts truck and the depot. The input for the part truck inventory shown in Figure 2.7 lists which parts and their quantity that a parts truck could carry. The count and other values are arbitrary. The part depot has the same list of spares but with large inventories so that the probability of total depletion is small. Again, the values are arbitrary.

Parts Grouping

Define a parts group

Name
Part Depot
Part Truck

Part Inventories

Define the spare part(s) that belong to the selected group

Spare	Count	Reorder Level	Maximum Level	Lot Size
Engine	1	0	2	1
Machine Gun	2	0	4	1
Radio	5	1	10	1
Wheels	8	2	8	1

Parts Grouping

Define a parts group

Name
Part Depot
Part Truck

Part Inventories

Define the spare part(s) that belong to the selected group

Spare	Count	Reorder Level	Maximum Level	Lot Size
Engine	50	3	50	1
Machine Gun	50	4	50	1
Radio	50	6	50	1
Wheels	200	8	200	1

Figure 2.7. Parts Grouping.

2.4.2.3. Basic Definitions – Consumables

Consumables Definition

The three consumables treated in this problem are listed in Figure 2.8. The values for weight, volume, and cost per unit are arbitrary.

Consumables Definition

Define the consumables that are supplied and consumed by systems during the simulation

Name	Units	Weight per Unit	Volume per Unit	Cost per Unit
Ammunition	Rounds	20	50	10
Fuel	Gallons	7	1	4.5
Water	Gallons	5	1	1

Figure 2.8. Consumables Definition.

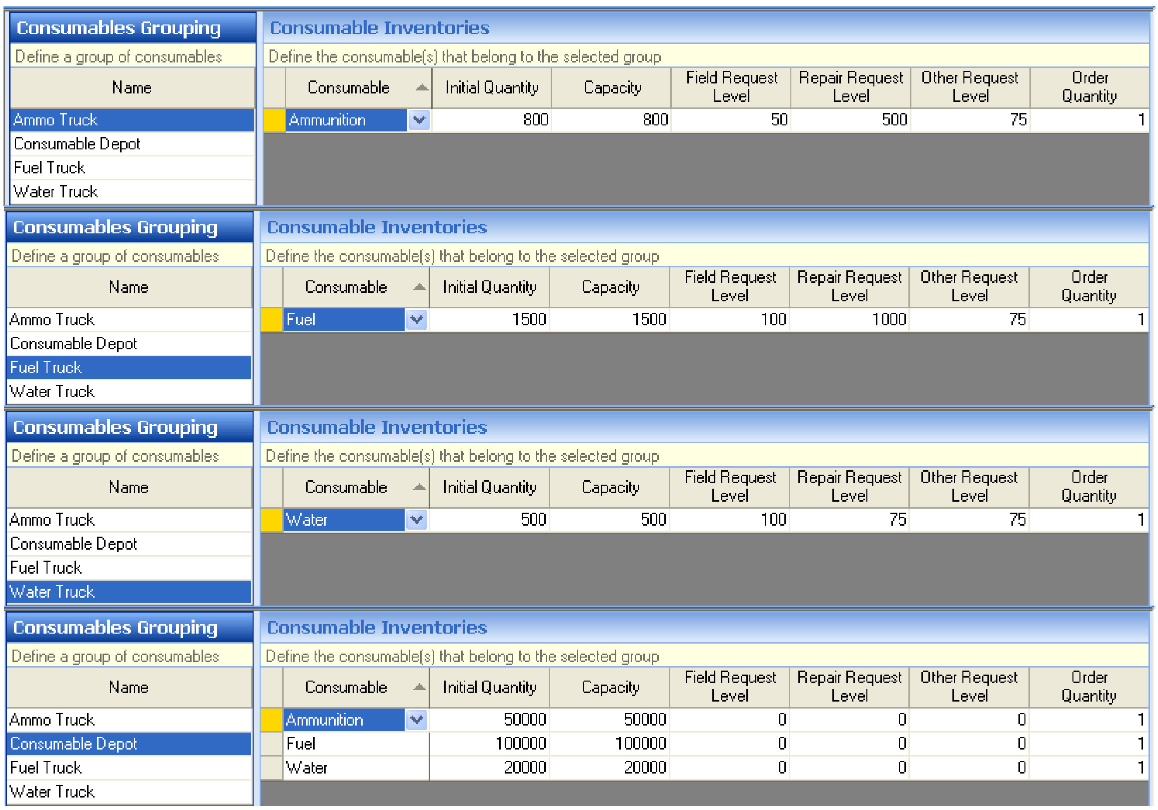
Consumables Grouping

The consumables grouping defines the inventories for the supply trucks and the depot, as shown in Figure 2.9. Each of the ammo, fuel, and water trucks carry only one type of consumable, as indicated by their name. The depot carries large quantities of each consumable. All values are arbitrary. There are additional columns, not shown in Figure 2.9, that describe how systems generate consumables. Consumable generation is not included in the example problem.

2.4.2.4. Basic Definitions – Services

Although services have a broader meaning, in SoSAT services are only used for performing system repairs. A repair can require multiple services that must be performed in a given order. Moreover, there can be more than one basic service having the same order number; in which case those services are all performed simultaneously before those of the next higher order number can begin.

A service that does not require mechanics (e.g., towing) is called a non-repair service in SoSAT. One that requires mechanics is called a repair service. If a failed element requires a spare, the spare must arrive, the mechanics must arrive, and any lower order non-repair services must be complete before the actual repair can begin.



Consumables Grouping — Define a group of consumables

Name
Ammo Truck
Consumable Depot
Fuel Truck
Water Truck

Consumable Inventories — Define the consumable(s) that belong to the selected group

Group (selected)	Consumable	Initial Quantity	Capacity	Field Request Level	Repair Request Level	Other Request Level	Order Quantity
Ammo Truck	Ammunition	800	800	50	500	75	1
Fuel Truck	Fuel	1500	1500	100	1000	75	1
Water Truck	Water	500	500	100	75	75	1
Consumable Depot	Ammunition	50000	50000	0	0	0	1
Consumable Depot	Fuel	100000	100000	0	0	0	1
Consumable Depot	Water	20000	20000	0	0	0	1

Figure 2.9. Consumables Grouping.

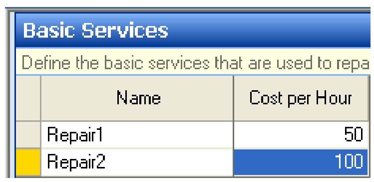
Using this design a detailed sequence of services can be defined for the repair of an element. On the other hand, a repair can also be done without the use of any services, which is simpler to define. The example problem includes repairs that require service and repairs that do not for three reasons:

1. It illustrates how mechanics are included in the input both with and without services.
2. It points out when (some) input for primary elements will be used and when it will not.
3. It demonstrates the new SoSAT feature that uses a service time distribution rather than the element's time-to-repair distribution.

Referring back to the primary elements defined in Figure 2.4, repair of the engine and suspension will require two mechanics, repair of the fuel system, wheels, and radio will require one mechanic, and the repair of the machine gun will require no mechanics. Repair of the radio and machine gun are done without using services. Repair of the other four elements will each require a single service.

Basic Services

One basic repair service requires a single mechanic and the other requires two mechanics. To this end we define two basic services: Repair1 and Repair2. Their costs in Figure 2.10 are arbitrary.



Basic Services

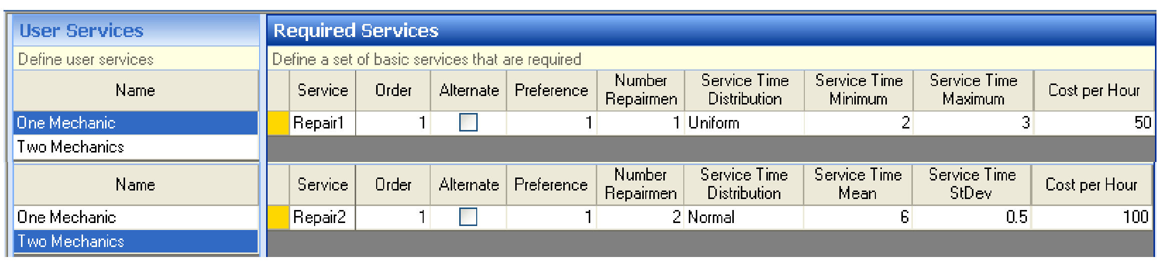
Define the basic services that are used to repa

Name	Cost per Hour
Repair1	50
Repair2	100

Figure 2.10. Basic Services.

User Services

Four of the primary element failures require a user service. Failure of the engine or the suspension requires a service that provides two mechanics. A single mechanic is required for repair of the wheels and fuel system. In this simple example of a single user service for a repair, the service is first and last, so it has order number 1. The values shown for service time in Figure 2.11 are arbitrary.



User Services

Define user services

Name
One Mechanic
Two Mechanics

Required Services

Define a set of basic services that are required

Service	Order	Alternate	Preference	Number Repairmen	Service Time Distribution	Service Time Minimum	Service Time Maximum	Cost per Hour
Repair1	1	☐	1	1	Uniform	2	3	50

Name
One Mechanic
Two Mechanics

Service	Order	Alternate	Preference	Number Repairmen	Service Time Distribution	Service Time Mean	Service Time StDev	Cost per Hour
Repair2	1	☐	1	2	Normal	6	0.5	100

Figure 2.11. User Services.

When we attach primary elements to system types (2.4.2.5 Basic Definitions – System Types, subheading Primary Elements) there are input items for the name of a user service, the number of repairmen required, and the repair time. The latter two items are used only if a service is not specified. The rule for their use by SoSAT is as follows.

- If a user service is selected for the element, that service defines both the number of repairmen required and the repair (service) time as in Figure 2.11. Any values entered for these items at the primary element level are ignored. This will be the case for repair of the engine, fuel system, suspension, and wheels in the example problem.
- If the user service entry is left blank for the element, SoSAT uses both the number of repairmen required and the repair time distribution entered for that element. This will be the case for repair of the radio and machine gun.

One additional important consideration that is related to the above rule is: if there are any non-repair type services (e.g., towing) involved in the repair of a primary element, the actual repair must also be defined as a service. There are no such non-repair services defined for this example problem so this consideration does not apply.

Provider Services

The mechanics pool provides both basic services, as shown in Figure 2.12.

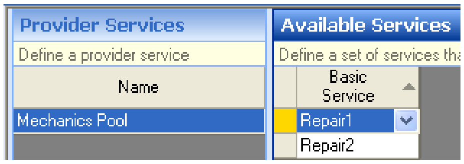


Figure 2.12. Provider Services.

2.4.2.5. Basic Definitions – System Types

System Types

There are two new features for defining system types. First, the new supply category of type Pool is assigned to the mechanics pool, as shown in Figure 2.13. SoSAT treats a pool just like any other system with one minor but important difference.

- When a system is providing a service to a requesting system, the providing system is unavailable for use by any other system. A parts truck or a tow truck cannot be in two places at once.
- When a pool is providing a service, it is providing its elements (mechanics are the only current possibility in SoSAT) to another system. But as long as the pool has adequate free elements, the pool itself should be available to be used by several other systems simultaneously. So SoSAT does not lock the pool from use by other systems.

The second new feature identifies some systems as being human. SoSAT treats humans much like it treats primary elements – they can fail and require a repair or reset time. And like primary elements, the only way to include humans in the analysis is to assign them to a system. Typically we assign a driver to a specific vehicle and a mechanic to a pool. However an NCO may ride on several systems and be on foot part of the time. Because he/she is not tied to a single system, we create a system for the NCO. In this problem we do the same for the platoon leader. Designate human systems by checking the box in the IsHuman column (Figure 2.13).

System Types

Define the system templates used when creating an instance of a system

Name	Is Human	Random Seed	Supply Category	Number of Copies
Ammo Truck	☐	347308	Supply Vehicle	1
CAMEL	☐	433782	Supply Vehicle	2
Consumables Depot	☐	433789	Supply Vehicle	1
CV	☐	433784	Other	3
Fuel Truck	☐	345421	Supply Vehicle	1
Mechanics Pool	☐	425282	Pool	1
NCO	☑	401061	Other	2
Parts Depot	☐	433786	Supply Vehicle	1
Parts Truck	☐	433794	Supply Vehicle	1
Platoon Leader	☑	415422	Other	2
SAPV	☐	433812	Other	5

Figure 2.13. System Types.

Primary Elements

Figure 2.14 displays the primary elements for the SAPV system type. The elements for the CV are the same; except it does not have a machine gun. The elements for the ammo truck, CAMEL, fuel truck, and parts truck are the same as the CV; except the failure rate parameter for the exponential time-to-failure distribution for the engine is lower, 0.0001. Neither depot nor the mechanics pool has any primary elements. Also, because the human systems cannot have primary elements, they are not listed here.

System Types

Select a System Type

Name
Ammo Truck
CAMEL
Consumables Depot
CV
Fuel Truck
Mechanics Pool
Parts Depot
Parts Truck
SAPV

Primary Elements

Define the primary elements that belong to the system and which are subject to normal reliability processes

Element	Initial Age	Repair when Operating	Repair when Operable	Repair when Inoperable	Age when Operating	Age when Operable	Age when Inoperable	Repair at Field	Repair at Facility
Engine	0	☐	☑	☑	☑	☐	☐	☑	☑
Fuel System	0	☐	☑	☑	☑	☐	☐	☑	☑
Machine Gun	0	☐	☑	☑	☑	☐	☐	☑	☑
Radio	0	☐	☑	☑	☑	☐	☐	☑	☑
Suspension	0	☐	☑	☑	☑	☐	☐	☑	☑
Wheels	0	☐	☑	☑	☑	☐	☐	☑	☑

Element	Repair at Other	Required Spare Part	Required Service	Diagnostic Error	No. required Repairmen	Time-to-Fail Distribution	Time-to-Fail Parameter
Engine	☐	Engine	Two Mechanics	0	0	Exponential	0.0025
Fuel System	☐		One Mechanic	0	0	Exponential	0.00065
Machine Gun	☐	Machine Gun		0	0	Exponential	0.0052
Radio	☐	Radio		0	1	Exponential	0.006
Suspension	☐		Two Mechanics	0	0	Exponential	0.00048
Wheels	☐	Wheels	One Mechanic	0	0	Exponential	0.0015

Element	Time-to-Repair Distribution	Time-to-Repair Value	Time-to-Repair ---	Time-to-Repair ---	Multiplier Distribution	Multiplier Value	Multiplier ---
Engine	Fixed	8			Fixed	1	
Fuel System	Fixed	3			Fixed	1	
Machine Gun	Fixed	1			Fixed	1	
Radio	Fixed	1			Fixed	1	
Suspension	Fixed	4			Fixed	1	
Wheels	Fixed	1			Fixed	1	

Figure 2.14. Primary Elements for SAPV System Type.

As mentioned in the section 2.4.2.4 Basic Definitions – Services subheading User Services, repair of the engine, fuel system, suspension, and wheels require services. The number of repairmen and the time to repair shown here are ignored because they are specified in the input for the service.

The two elements whose repair does not require a service are the radio and the machine gun. The radio requires a mechanic for the repair but the machine gun does not. They are each given a one hour fixed repair time. All of the values in Figure 2.14 are arbitrary.

Consumables

Figure 2.15 displays the consumables used by the SAPV system type. It is the only system type that consumes ammunition. The values for fuel and water are the same for the ammo truck, CAMEL, CV, fuel truck, and parts truck – with the exception of the multiplier distribution. This distribution is fixed at 1.0 for those systems not in a platoon; ammo truck, fuel truck, and parts truck. Neither depot nor the mechanics pool uses any consumables. Human systems are not listed here. A future version of SoSAT may address the human need for water or nourishment, but it is not currently implemented.

System Types

Select a System Type

Name
Ammo Truck
CAMEL
Consumables Depot
CV
Fuel Truck
Mechanics Pool
Parts Depot
Parts Truck
SAPV

Consumables

Define a set of consumables that are used by the system type

Consumable	Capacity	Initial Quantity	Request Level in Field	Request Level in Repair	Request Level in Other	Order Quantity	Use when Operating
Ammunition	200	200	50	100	20	1	☑
Fuel	50	50	20	15	15	1	☑
Water	50	50	20	15	15	1	☑

Consumable	Use when Operable	Use when Inoperable	Usage Rate	Multiplier Distribution	Multiplier Minimum	Multiplier Best Estimate	Multiplier Maximum
Ammunition	☐	☐	5	Triangular	0.75	1	1.25
Fuel	☐	☐	2.2	Triangular	0.75	1	1.25
Water	☐	☐	0.6	Triangular	0.75	1	1.25

Figure 2.15. Consumables for SAPV System Type.

External Elements

There are no external elements in this problem.

Personnel

Individuals are assigned to systems on the input form shown in Figure 2.16, which shows a supplier driver being assigned to an ammo truck.

System Types

Select a System Type

Name
Ammo Truck

Personnel

Attach personnel to systems

Human Title	Training Adjustment	Experience Adjustment	Perceptual Adjustment	Util if System Operating	Util if System Operable	Catastrophic Probability
Supplier Driver	1	1	1	1	0	0.001

Human Title	Error-Rate Distribution	Error-Rate Parameter	Error-Rate ---	Error-Rate ---	Time-to-Reset Distribution	Time-to-Reset Parameter
Supplier Driver	Exponential	0.04			Exponential	0.5

Human Title	Fatigue Distribution	Fatigue Minimum	Fatigue Maximum	Fatigue ---	Replacement Time Dist	Replacement Value
Supplier Driver	Uniform	1.07	2.57		Fixed	4

Figure 2.16. Personnel for SAPV System Type.

The supplier driver was introduced in the subsection Personnel under 2.4.2.1 Basic Definitions – Settings. The adjustment factors implement time-independent PSFs as discussed in the section Simulation Parameters under 2.4.2.1 Basic Definitions – Settings. Again we use the default adjustments (no modification) for this problem. We assume that the driver is 100% utilized when the ammo truck is operating and is not utilized at all when the ammo truck is operable (or inoperable).

The catastrophic probability is the probability that when the driver makes an error, it is severe enough to disable the ammo truck. The driver could drive off a bridge, for example. The probability entered here is conditioned on the occurrence of an error and its value was discussed in 2.3.2 Determination of Catastrophic-Error Probability.

The frequency of driver error is given by the error-rate distribution. When sampled, this distribution should produce values that have units errors/hour. In this case we use the maximum entropy distribution for our best estimate of 0.04 errors/hour (an exponential distribution, see 2.3.1 Definition of Human Base Error Rate).

The error rate will increase with fatigue as described in Section 2.2.3.2 Fatigue+Cognitive Fatigue. In this case the fatigue distribution is uniform on [1.07, 2.57], so the drivers of ammo trucks have a 7% to 157% increase in error rate after 24 hours (2.3.4.4 Time-Dependent PSFs).

The time to reset and replacement time distributions are typically applied in case of error and combat damage, respectively. The reset time is the time required to catch and correct the error. In this case we use the maximum entropy distribution for our best estimate of 0.5 hours (2.3.3 Determination of Human Time-to-Reset). The replacement time is the time required to replace an individual that has been injured and evacuated, 4 hours for the supplier driver. This varies by personnel in the example problem.

The remaining assignments and the data that varies for the humans are given in Table 2.4. All other values are as given in Figure 2.16.

- Although Table 2.4 only shows one mechanic assigned to the mechanics pool, all three are assigned.
- The replacement time value is used as the single parameter of a fixed distribution.
- The only other input difference is that mechanics have no utilization when at their home pool, whether the pool is operable or operating, so those utilization fractions are zeroes.

We assume that drivers of vehicles in the platoons are the first to transport over hostile ground and know less of the road conditions and hazards. So, their probability of catastrophic mistake is 5 times more likely than supplier drivers. The probability of a mechanic disabling a system while attempting to repair it is assumed to be about the same as a supplier driver.

Table 2.4. Other Personnel Assignments to Systems.

System	Human	Catastrophic Probability	Replacement Time
CAMEL	Driver	0.005	0.5
CV	Driver	0.005	0.5
Fuel Truck	Supplier Driver	0.001	4.0
Mechanics Pool	Mechanic*	0.001	6.0
NCO	NCO	0.001	8.0
Parts Truck	Supplier Driver	0.001	4.0
Platoon Leader	Platoon Leader	0.001	8.0

SAPV	Driver	0.005	0.5

SoSAT treats catastrophic errors committed on human systems differently from those on nonhuman systems. SoSAT does not replace disabled nonhuman systems during the remainder of a simulation. For human systems, it assumes that humans are evacuated but can be replaced. The probability of catastrophic error is given as 0.001 for the platoon leaders and NCOs.

We assume that there is someone in the platoon that is capable of taking over driving duties for the driver, so replacement time in case of combat damage is short (0.5 hours). Because they may not be readily available, it takes longer to find a replacement for a supplier driver, longer yet for mechanics, and longer yet for NCOs and platoon leaders. Note that the replacement time distribution for NCOs and platoon leaders is used for both combat damage and catastrophic errors.

Functions

SoSAT assumes that errors made by humans can affect the performance of the system to which they are assigned. In this example problem the drivers can cause their systems to fail when they make a mistake. When a driver makes a wrong turn it requires some time to catch the error and return the system to where it is intended to be. While the system is not in proper position, its usefulness to the force is diminished. SoSAT assumes that the system is effectively down (unavailable) during that time.

Each system has only one function in this problem – the default SoSAT-generated operability function. The cutsets are all simple and contain primary elements, consumables, and humans. The largest set of cutsets is for the SAPV, shown in Figure 2.17, where the driver has been included.

None of the consumables depot, parts depot, or mechanics pool has any cutsets. The other vehicles have the same cutsets as shown in Figure 2.17 except for Machine Gun and Ammunition. Neither the platoon leader nor the NCO is shown here. SoSAT automatically generates a single, simple cutset for each. The member of the cutset is the human element Platoon Leader and NCO, respectively.

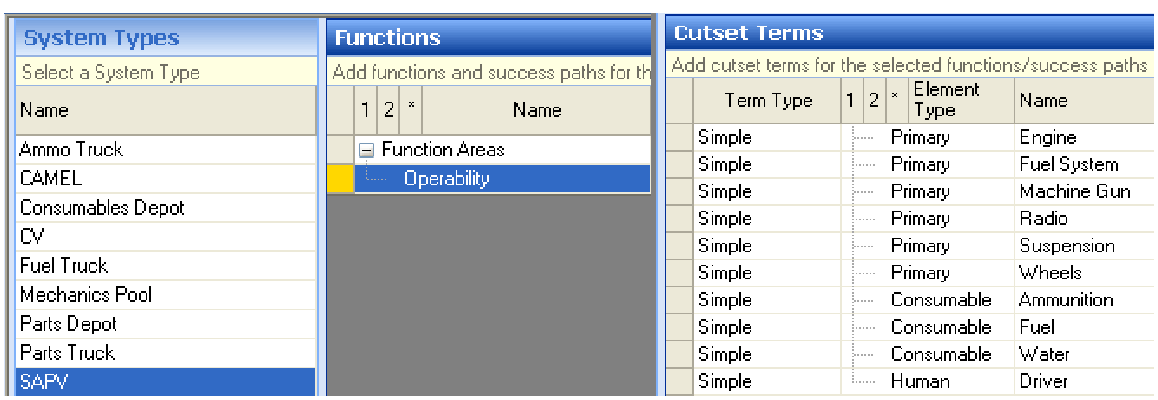


Figure 2.17. Cutsets for System Type SAPV Operability.

2.4.2.6. Scenario Definitions – Combat Damage

Combat damage trees are defined here and later assigned to systems. Historically in SoSAT, combat damage could fail primary elements of the system or the entire system. Combat damage can now also apply to humans. The example problem focuses on that new feature.

We define three different combat damage models: Action, Supply, and Human System. The idea behind the models is as follows:

- Combat damage frequency ought to be greater for vehicles that are at the front lines most of the time. The Action model will be assigned to vehicles that belong to each platoon.
- Combat damage frequency ought to be somewhat less for supply vehicles. The Supply model will be assigned to supply vehicles.
- Because the platoon leader and NCO are not attached to a nonhuman system, the human systems are given a separate combat damage model, Human System.

The Action model is shown in Figure 2.18. The arbitrary values indicate that the rate of occurrence of combat damage to a system (to which this model is assigned) is 0.002 occurrences per hour. If damage occurs there is a 0.25 probability that the damage is severe enough to disable the system. If the damage occurs and the system is not disabled, there is a 0.5 probability of damage to humans assigned to the system. If there is damage to humans, there is a 0.2 probability of damage to the driver, and also to the mechanics. The latter will only apply if there are mechanics working on the system when the damage occurs. As the wording suggests, probabilities at nodes are conditioned on the occurrence of their parent node. The time to replace is given by the human's replacement time distribution (Figure 2.16).

The Supply model is nearly identical to the Action model. The damage frequency is less (0.001) and the Supplier Driver is entered in place of the generic Driver.

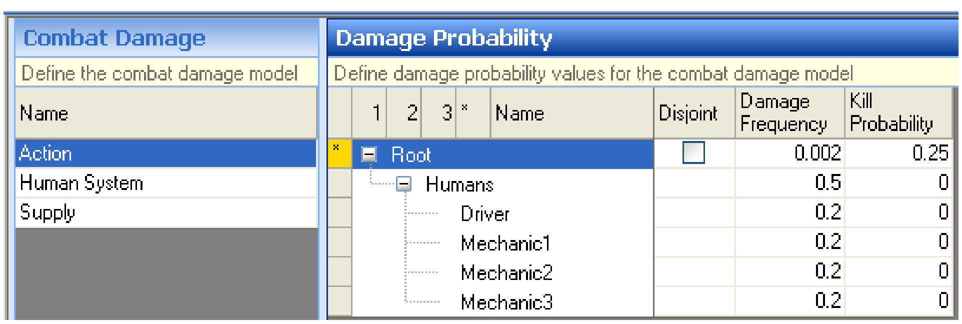
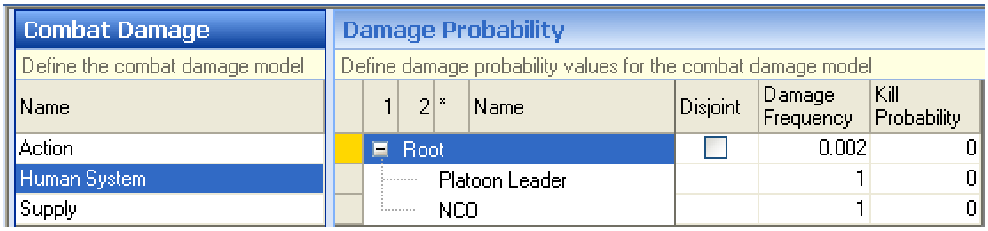


Figure 2.18. The Action Combat Damage Model.

The Human System model is shown in Figure 2.19. The rate of occurrence of combat damage is the same as that for the Action model. Currently in SoSAT, it makes no difference whether a human "element" is damaged or its human "system" is killed. In either case SoSAT evacuates and replaces the human element.



Combat Damage — Define the combat damage model

Name
Action
Human System
Supply

Damage Probability — Define damage probability values for the combat damage model

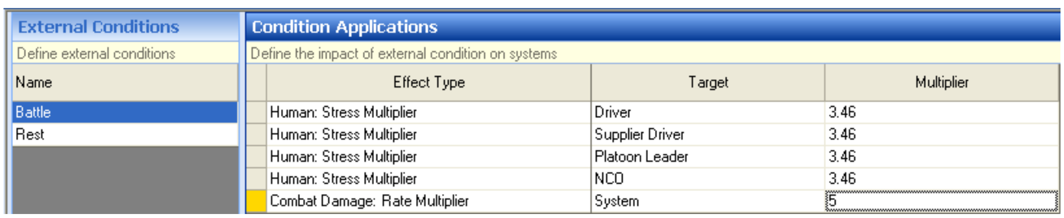
Name	Disjoint	Damage Frequency	Kill Probability
Root	☐	0.002	0
Platoon Leader		1	0
NCO		1	0

Figure 2.19. The Human System Combat Damage Model.

External conditions and scenarios are defined in the next two subsections. We will use the concept of an external condition to model the possibility of battle. Systems will be subject to one of three conditions: positioning, battle, and rest phases. The combat damage trees defined here will be used for the positioning phases. If battle occurs we will increase the Damage Frequency. During rest, we will set the frequency to 0.

2.4.2.7. Scenario Definitions – External Conditions

The possibility of battle is simulated as an external condition. The effect of battle on human performance is shown in Figure 2.20.



External Conditions — Define external conditions

Name
Battle
Rest

Condition Applications — Define the impact of external condition on systems

Effect Type	Target	Multiplier
Human: Stress Multiplier	Driver	3.46
Human: Stress Multiplier	Supplier Driver	3.46
Human: Stress Multiplier	Platoon Leader	3.46
Human: Stress Multiplier	NCO	3.46
Combat Damage: Rate Multiplier	System	5

Figure 2.20. The Battle External Condition.

We assume that a battle increases stress on the humans much like rough terrain could stress axles or turbulence could stress an air frame. Implementing stress as a PSF in SoSAT is done through the use of an external condition. The probability of human mistakes increases according to the multipliers shown in Figure 2.20, which was discussed in 2.3.4.4 Time-Dependent PSFs.

Logically the incidents of combat damage to systems will also increase during a battle. The rate of occurrence for combat damage increases by a factor of 5 in this example problem. The multiplier is applied to Damage Frequency (see Figures 2.19 and 2.20) whenever a battle occurs.

The external condition named Rest is quite simple and is not shown here. It has one effect in this problem and that is to reduce Damage Frequency to zero. So, the combat damage rate multiplier is set to 0.

2.4.2.8. Scenario Definitions – Scenarios

There are two scenarios defined in the example problem. Scenario Mobile (Figure 2.21) is designed for systems that operate in the field. Scenario Static (Figure 2.22) is for the stationary systems at the repair facility.

For mobile systems each 72-hr stretch in the field is partitioned into three segments of 30, 12, and 30 hours. During the 12-hr segments the external condition named Battle can occur. The probability of occurrence in segment 2 is 0.8, as shown in Figure 2.21, and in segment 6 is 0.6 (not shown). The positioning segments of the mission (1, 3, 5, and 7) have no external conditions. Segment 4 at the repair facility has the external condition named Rest. Its probability of occurrence is 1.0.

While in the field all systems are intended to be operating, at 100% utilization. Systems are intended to be operable but with no utilization while at the repair facility.

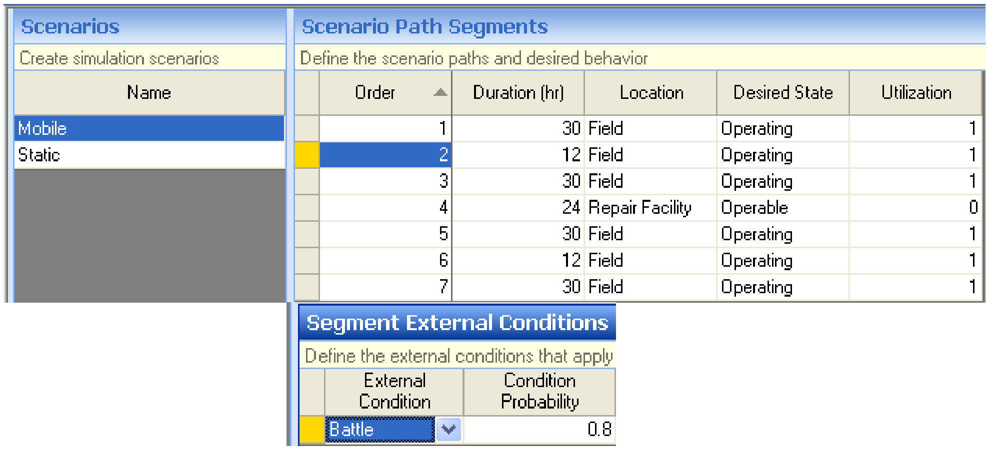


Figure 2.21. Scenario Mobile.

The systems that do not leave the repair facility (parts depot, consumables depot, and mechanics pool) will be assigned the Static scenario (Figure 2.22). There are no external conditions included.

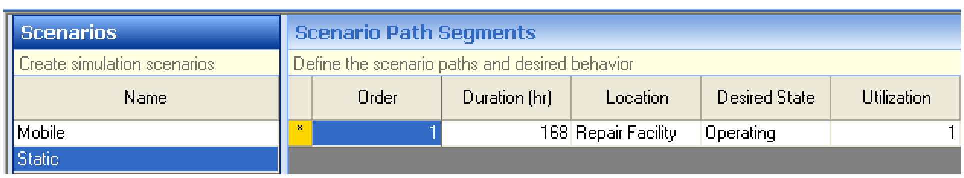


Figure 2.22. Scenario Static.

2.4.2.9. System of System Definitions – Structures

The force structure was described in 2.4.1 Introduction. Figure 2.23 shows how system types fit into the structure. There is one instance of each system type for most systems. The exceptions are SAPV (SAPV-001 and SAPV-002 in Platoon A and SAPV-003, SAPV-004, and SAPV-005 in Platoon B) and CV (CV-002 and CV-003 in Platoon B).

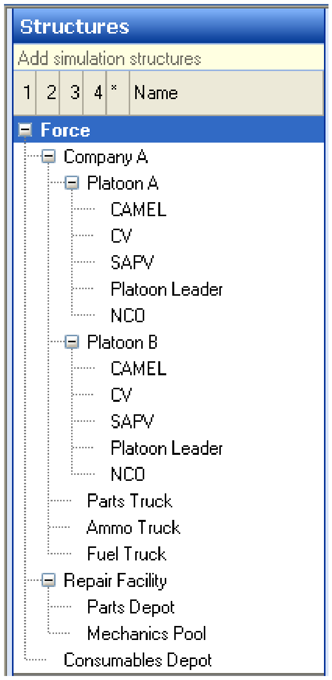


Figure 2.23. Force Structure Showing System Types.

Instances of system types and their properties are prompted by SoSAT on a form placed to the right of Figure 2.23. To consolidate the input data in this discussion, the properties for the assigned systems are displayed in Tables 2.5, 2.6, and 2.7. The names of the scenarios, combat damage models, and logistics definitions and providers were defined in previous sections.

Table 2.5. Systems of Platoon A.

System	Scenario	Combat Damage	Provider Service	Spare Group	Consumable Group
CAMEL-001	Mobile	Action			Water Truck
CV-001	Mobile	Action			
SAPV-001	Mobile	Action			
SAPV-002	Mobile	Action			
Platoon Leader-001	Mobile	Human System			
NCO-001	Mobile	Human System			

Table 2.6. Systems of Platoon B.

System	Scenario	Combat Damage	Provider Service	Spare Group	Consumable Group
CAMEL-002	Mobile	Action			Water Truck
CV-002	Mobile	Action			
CV-003	Mobile	Action			
SAPV-003	Mobile	Action			
SAPV-004	Mobile	Action			
SAPV-005	Mobile	Action			
Platoon Leader-002	Mobile	Human System			

NCO-002	Mobile	Human System			

Table 2.7. Other Systems.

System	Scenario	Combat Damage	Provider Service	Spare Group	Consumable Group
Parts Truck-001	Mobile	Supply		Part Truck	
Ammo Truck-001	Mobile	Supply			Ammo Truck
Fuel Truck-001	Mobile	Supply			Fuel Truck
Parts Depot-001	Static			Part Depot	
Mechanics Pool-001	Static		Mechanics Pool		
Consumables Depot-001	Static				Consumable Depot

2.4.2.10. System of System Definitions – Supply Connections

This example problem defines the 13 different supply connections named in Figure 2.24. Rather than show the properties of each in the format prompted by SoSAT, we condense the input with a description of each connection and then give a table of remaining input.

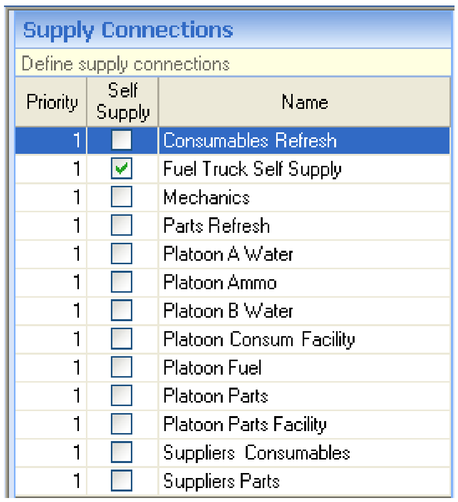


Figure 2.24. Supply Connections.

Consumables Refresh – this connection defines where the consumable supplier vehicles go to replenish their inventories. The ammo truck, the fuel truck, and both CAMELs are connected to the consumables depot.

Fuel Truck Self Supply – this connection enables the fuel truck to fuel itself while in the field. It is marked as self supply.

Mechanics – this connection defines where all vehicles need to obtain mechanics. The ammo, fuel, and parts trucks, and all platoon vehicles are connected to the mechanics pool.

Parts Refresh – this connection defines where the parts truck goes to replenish its inventory. The parts truck is connected to the parts depot.

Platoon A Water – this connection defines where the vehicles of Platoon A obtain water. The CV-001, SAPV-001, and SAPV-002 vehicles are connected to CAMEL-001.

Platoon Ammo – this connection defines where vehicles go to acquire ammunition. All five SAPVs are connected to the ammo truck.

Platoon B Water – this connection defines where the vehicles of Platoon B obtain water. The CV-002, CV-003, SAPV-003, SAPV-004, and SAPV-005 vehicles are connected to CAMEL-002.

Platoon Consumables Facility – this connection allows all vehicles that are assigned to a platoon to acquire consumables while not in the field. All such vehicles are connected to the consumables depot.

Platoon Fuel – this connection defines where all vehicles that are assigned to a platoon should go to acquire fuel while in the field. All such vehicles are connected to the fuel truck.

Platoon Parts – this connection defines where all vehicles that are assigned to a platoon should go to acquire parts while in the field. All such vehicles are connected to the parts truck.

Platoon Parts Facility – this connection allows all vehicles that are assigned to a platoon to acquire parts while not in the field. All such vehicles are connected to the parts depot.

Suppliers Consumables – this connection defines where the supplier vehicles go to acquire consumables. The ammo truck, the fuel truck, the parts truck, and both CAMELs are connected to the consumables depot.

Suppliers Parts – this connection defines where the supplier vehicles go to acquire parts. The ammo truck, the fuel truck, the parts truck, and both CAMELs are connected to the parts depot.

Table 2.8 shows the properties for each connection. The Apply At Other column is omitted because it is never checked in this example problem. The Time-to-Supply in the table is used as the single parameter for a Fixed distribution type. The values are arbitrary.

Table 2.8. Supply Connection Data.

Connection Name	Supply Category	Apply At Field	Apply At Repair Facility	Time-to-Supply (hrs)
Consumables Refresh	Replenish Consumables	X	X	8
Fuel Truck Self Supply	Acquire Consumables	X		0.1
Mechanics	Obtain Repair Personnel	X	X	2
Parts Refresh	Replenish Parts	X	X	8
Platoon A Water	Acquire Consumables	X		0.5
Platoon Ammo	Acquire Consumables	X		0.5
Platoon A Water	Acquire Consumables	X		0.5
Platoon Consum Facility	Acquire Consumables		X	0.5
Platoon Fuel	Acquire Consumables	X		0.5
Platoon Parts	Acquire a Spare	X		0.5
Platoon Parts Facility	Acquire a Spare		X	0.5
Suppliers Consumables	Acquire Consumables	X	X	5
Suppliers Parts	Acquire a Spare	X	X	5

In SoSAT a system can obtain mechanics either directly (e.g., radio in the example problem) or by requesting a service that requires mechanics (e.g., engine in the example problem). Because SoSAT offers a Supply Category named Access Services, one can use that category for obtaining mechanics through a service. However to avoid a potential error, it is recommended that you always use the category Obtain Repair Personnel when connecting to mechanics providers (line 3 of Table 2.8).

If there are any repairs that (1) do not require any services but (2) do require mechanics, then the Obtain Repair Personnel category *must be* used in a supply connection to obtain the mechanics. If no such connection exists SoSAT will be unable to locate mechanics.

2.4.2.11. System of System Definitions – External References

There are no external references included in this example problem.

2.4.2.12. System of System Definitions – Systems

Systems

The individual systems and their properties are automatically generated by SoSAT. SoSAT uses the data contained in Tables 2.5, 2.6, and 2.7 combined with the system instances defined in the force structure to display the form shown in Figure 2.25. The data can be edited, but there is no need to in the example problem.

Systems

Modify the system name and/or assignment

Name	System Type	Combat Damage	Provider Service	Spare Group	Consumable Group	Scenario
Ammo Truck-001	Ammo Truck	Supply			Ammo Truck	Mobile
CAMEL-001	CAMEL	Action			Water Truck	Mobile
CAMEL-002	CAMEL	Action			Water Truck	Mobile
Consumables Depot-001	Consumables Depot				Consumable Depot	Static
CV-001	CV	Action				Mobile
CV-002	CV	Action				Mobile
CV-003	CV	Action				Mobile
Fuel Truck-001	Fuel Truck	Supply			Fuel Truck	Mobile
Mechanics Pool-001	Mechanics Pool		Mechanics Pool			Static
NCO-001	NCO	Human System				Mobile
NCO-002	NCO	Human System				Mobile
Parts Depot-001	Parts Depot			Part Depot		Static
Parts Truck-001	Parts Truck	Supply		Part Truck		Mobile
Platoon Leader-001	Platoon Leader	Human System				Mobile
Platoon Leader-002	Platoon Leader	Human System				Mobile
SAPV-001	SAPV	Action				Mobile
SAPV-002	SAPV	Action				Mobile
SAPV-003	SAPV	Action				Mobile
SAPV-004	SAPV	Action				Mobile
SAPV-005	SAPV	Action				Mobile

Figure 2.25. Individual Systems.

Primary Elements

The primary elements for systems are as they were assigned to the system type.

Consumables

The consumables for systems are as they were assigned to the system type, with the exception of usage rates. For the nonhuman system types that have multiple instances (CAMEL, CV, and SAPV), triangular distributions (0.75, 1.0, 1.25) were assigned for the multiplier distribution. Usage rates are therefore sampled by SoSAT to be applied to instances of those system types. SoSAT uses stratified median sampling for this exercise.

External Elements

There are no external elements for the example problem.

External References

There are no external references for the example problem.

Functions

The cutsets for systems are as they were assigned to the system type. SoSAT automatically generates a single, simple cutset for each human system.

2.4.3. Problem Results

2.4.3.1. Human Performances – System Human Delays

Figure 2.26 shows the effects of humans on system performance lined out by the force structure. To save space only system types and the mean results are shown here. The mean delay time in ordering consumables for the SAPV systems of Platoon B is shown to be 4.021 hours. Because the mean results are additive, this is the sum of the mean delay times for SAPV-003, SAPV-004, and SAPV-005. If desired, those individual times are available in SoSAT by expanding the node.

System Human Delays - By Structures

1 2 3 4 * System	Delay Ordering Consumables	Delay Ordering Parts	Insufficient Mechanics Delay	Mechanic Error Delay	Catastrophic Error Time
⊟ Force	7.420	0.916	1.691	4.386	76.107
⊟ Company A	7.420	0.916	1.691	4.386	76.107
⊟ Platoon A	0.785	0.098	0.482	2.366	27.376
⊞ CAMEL	0.139	0.016	0.120	0.046	12.600
⊞ CV	0.163	0.004	0.244	0.685	3.398
⊞ SAPV	0.483	0.078	0.118	1.635	11.258
⊞ Platoon Leader	0.000	0.000	0.000	0.000	0.080
⊞ NCO	0.000	0.000	0.000	0.000	0.040
⊟ Platoon B	6.635	0.808	0.692	1.021	46.364
⊞ CAMEL	1.078	0.131	0.106	0.452	2.926
⊞ CV	1.536	0.220	0.267	0.240	24.392
⊞ SAPV	4.021	0.458	0.320	0.329	18.311
⊞ Platoon Leader	0.000	0.000	0.000	0.000	0.320
⊞ NCO	0.000	0.000	0.000	0.000	0.415
⊞ Parts Truck	0.000	0.000	0.073	0.679	0.618
⊞ Ammo Truck	0.000	0.005	0.029	0.288	0.879
⊞ Fuel Truck	0.000	0.005	0.416	0.033	0.871
⊟ Repair Facility	0.000	0.000	0.000	0.000	0.000
⊞ Parts Depot	0.000	0.000	0.000	0.000	0.000
⊞ Mechanics Pool	0.000	0.000	0.000	0.000	0.000
⊞ Consumables Depot	0.000	0.000	0.000	0.000	0.000

Figure 2.26. Human Delays by Structure.

The columns can be described as follows:

Delay Ordering Consumables – when a system has reached its reorder level for a consumable, it notifies an individual with authority for that system to place an order. If that individual fails to immediately place the order, there is a delay time.

Delay Ordering Parts – when a primary element fails on a system and the element requires a spare, the system notifies an individual with authority over it to place an order. If that individual fails to place the order immediately, there is a delay time.

Insufficient Mechanics Delay – when a repair for a primary element of a system requires mechanics, SoSAT searches the supply connections for the system to locate a provider of mechanics. If the mechanics of a provider are currently assigned to work on other systems, the next connected provider is pinged. If no provider can be found, there is a delay time until one becomes available.

Mechanic Error Delay – during the course of a repair a mechanic can make a mistake. The repair of the element is then delayed by the time required for the mechanic to detect and recover from the mistake.

Catastrophic Error Time – when a human makes a catastrophic error on a nonhuman system, SoSAT disables the system for the remainder of the mission. The time remaining in the mission is called catastrophic error time. When a human makes a catastrophic error on a human system, SoSAT replaces the system following elapsed replacement time. This is also included in catastrophic error time

From Figure 2.26 it is evident that the catastrophic error time dominates all other human-induced time delays. The catastrophic error probability assigned to drivers of the platoon vehicles was 0.005, which may be too high. Compared to catastrophic error time, the time delays appear to be minor for this problem. Figure 2.26 does not show information about humans assigned to cutsets that determine system functionality. In this problem setup this means failures of drivers, which are included in the next result.

2.4.3.2. System Details – Elements – Element Details

The element details result shows six measures of performance for 121 elements including the 20 human elements. To focus on the humans we culled those 20 records and created Table 2.9. Only the mean results are shown.

Table 2.9. Element Details for Humans.

System	Name	Up Time	Down Time	Random Failures	Combat Damage Failures	Total Number of Failures	Availability
Ammo Truck-001	Supplier Driver	152.3	9.0	16.1	0.03	16.1	0.944
CAMEL-001	Driver	125.0	20.3	36.0	0.05	36.1	0.863
CAMEL-002	Driver	148.5	2.8	4.7	0.04	4.7	0.982
CV-001	Driver	150.7	4.4	8.0	0.05	8.0	0.971
CV-002	Driver	120.4	16.0	29.3	0.04	29.4	0.884
CV-003	Driver	146.8	3.2	5.6	0.05	5.6	0.979
Fuel Truck-001	Supplier Driver	153.9	7.7	14.0	0.03	14.0	0.952
Mechanics Pool-001	Mechanic1	164.6	3.4	0.5	0.00	0.5	0.980
Mechanics Pool-001	Mechanic2	164.6	3.4	0.5	0.00	0.5	0.980
Mechanics Pool-001	Mechanic3	163.5	4.5	0.6	0.01	0.6	0.973
NCO-001	NCO	160.4	7.6	5.1	0.61	5.7	0.955
NCO-002	NCO	141.2	26.8	41.7	0.45	42.1	0.840
Parts Truck-001	Supplier Driver	150.1	8.7	15.6	0.01	15.7	0.946
Platoon Leader-001	Platoon Leader	160.7	7.3	5.3	0.56	5.8	0.957
Platoon Leader-002	Platoon Leader	140.8	27.2	41.3	0.49	41.8	0.838
SAPV-001	Driver	128.1	18.8	33.8	0.04	33.9	0.869
SAPV-002	Driver	154.0	1.1	1.8	0.03	1.8	0.993
SAPV-003	Driver	154.2	2.0	3.5	0.06	3.6	0.987
SAPV-004	Driver	141.8	6.8	12.4	0.04	12.4	0.954
SAPV-005	Driver	128.4	14.8	26.6	0.04	26.6	0.896

The drivers and supplier drivers are elements of simple cutsets for the operability function for their system. Thus, their mean downtime is the mean time their system is down due to their failure. These downtimes range from 1.1 hours (SAPV-002) to 20.3 hours (CAMEL-001). Judging from the ratio of random (reliability) failures to combat damage failures, the downtime primarily arises from reliability failures.

Note that the sum of up time and downtime is mission time (168 hours) for the NCOs, platoon leaders, and mechanics. This is not the case for either type of driver. The reason for this is that SoSAT discontinues time accounting for elements when a system becomes disabled. So by subtracting the sum of up time and downtime from mission time we can know the average time lost due to system disabling.

Doing the subtraction the disabled time for Ammo Truck-001 is 6.7 hours on the average. Of that time the portion attributable to combat damage and to catastrophic error by the driver it is not known. Separation and display of these two values could be a future enhancement of SoSAT. The worst system for average disabled time is CV-002 (31.6 hours).

2.4.3.3. Summary Statistic – Functional Availability by Structure

Figure 2.27 shows the performance of the force in terms of operational availability. The impact of human performance on system performance is not evident here, so we modify the input and make a second run without the influence of humans.

Rather than explicitly removing the humans from the input, we can remove their impact.

- Humans will not fail if their failure rate is zero. We can model this by setting one of the time-independent PSFs to a large number. Under 2.4.2.1 Basic Definitions – Settings subheading Simulation Parameters set the Training Adjustment to 1.0E30 (refer to Figure 2.3). Recall that the basic error rate is divided by this number, so we are effectively setting all human error rates to zero.
- Change the input so that no mechanics are required. The user services named Repair1 and Repair2 required one and two mechanics, respectively. Change both of these to zero (refer to Figure 2.11). Also, the radio was repaired (without using a service) by one mechanic. Under 2.4.2.5 Basic Definitions – System Types subheading Primary Elements set the number of required repairmen to zero for each occurrence of the radio (6 system types). Figure 2.14 shows the radio attached to the SAPV system type. Change it there and for the other 5 system types.
- Do not allow humans to suffer combat damage. Under 2.4.2.6 Scenario Definitions – Combat Damage set the damage frequency to zero for each of the three combat damage models (refer to Figures 2.18 and 2.19 and text).

The same set of availability results are generated and displayed in Figure 2.28. Comparing Figures 2.27 and 2.28, there is general degradation of availability when humans are included. There are instances, however, where availability improves with the addition of humans. This is an artifact of the statistics. Presumably if more trials were run, this behavior would not appear.

Functional Availability Rollup by Structure

System	Operability Mean	Operability 5th	Operability 95th
Force	0.800	0.671	0.899
Company A	0.759	0.606	0.878
Platoon A	0.782	0.607	0.909
CAMEL	0.687	0.182	0.864
CV	0.755	0.306	0.966
SAPV	0.689	0.315	0.900
Platoon Leader	0.952	0.882	0.991
NCO	0.949	0.872	0.995
Platoon B	0.725	0.556	0.879
CAMEL	0.831	0.209	0.988
CV	0.659	0.371	0.886
SAPV	0.684	0.415	0.899
Platoon Leader	0.813	0.744	0.887
NCO	0.816	0.744	0.884
Parts Truck	0.824	0.292	0.939
Ammo Truck	0.843	0.547	0.935
Fuel Truck	0.773	0.256	0.954
Repair Facility	1.000	1.000	1.000
Parts Depot	1.000	1.000	1.000
Mechanics Pool	1.000	1.000	1.000
Consumables Depot	1.000	1.000	1.000

Figure 2.27. Operational Availability.

Functional Availability Rollup by Structure

System	Operability Mean	Operability 5th	Operability 95th
Force	0.857	0.744	0.944
Company A	0.828	0.691	0.933
Platoon A	0.827	0.652	0.991
CAMEL	0.857	0.261	1.000
CV	0.727	0.102	1.000
SAPV	0.689	0.285	0.986
Platoon Leader	1.000	1.000	1.000
NCO	1.000	1.000	1.000
Platoon B	0.809	0.650	0.966
CAMEL	0.859	0.173	1.000
CV	0.750	0.317	0.995
SAPV	0.705	0.393	0.972
Platoon Leader	1.000	1.000	1.000
NCO	1.000	1.000	1.000
Parts Truck	0.843	0.153	0.999
Ammo Truck	0.845	0.205	0.993
Fuel Truck	0.948	0.875	1.000
Repair Facility	1.000	1.000	1.000
Parts Depot	1.000	1.000	1.000
Mechanics Pool	1.000	1.000	1.000
Consumables Depot	1.000	1.000	1.000

Figure 2.28. Operational Availability without Human Influence.

To facilitate comparison at the command level we copied each grid into a spreadsheet and generated the plot shown in Figure 2.29. The decrease in availability due to the actions of humans is evident for the force, the company, and both platoons.

Figure 2.29. Operational Availability Comparison.

2.4.4. Conclusions

The example problem demonstrates various ways of including humans in SoSAT. Human errors can

- Extend downtimes (mechanic mistakes, platoon leaders not ordering parts in a timely fashion),
- Cause temporary failures (drivers making a wrong turn, platoon leaders not ordering consumables in a timely fashion), or
- Cause catastrophic failures (drivers crashing their vehicle).

We modeled PSFs that increase the likelihood of mistakes.

- Fatigue+cognitive fatigue was accounted for by defining a fatigue distribution that produced values greater than one (uniform on [1.07, 2.57]) and
- Stress was included through the human stress multipliers whenever a battle occurred (3.46).

Although we used the training adjustment factor only as a shortcut to effectively remove humans from the example problem for the second run, it demonstrated how the time-independent PSFs could be used to modify the error rates for the entire force.

Combat damage models were developed that impacted humans. SoSAT assumes that damaged humans are replaced with a time delay defined by the replacement time distribution. Technically the human is replaced by itself, or with an identical human.

The time delays caused by humans are available through new and existing result outputs. In the example problem the largest impacts were driver mistakes causing system downtime and driver mistakes causing catastrophic errors. The input for the former was based on literature values summarized for a generic individual. The input for the latter was entirely arbitrary.

3. Human Performance Modeling Based on Cognitive Modeling

For this effort of the LDRD, we wanted to explore the impacts of cognitive moderators on platoon-level logistics. As such, we created a simple information-processing model of a mechanized infantry platoon sergeant (PSG). The PSG was chosen for this model because the PSG has primary responsibility for managing platoon logistics. To gain insight into the activities, we conducted background research and interviewed a subject-matter expert (SME). For the background research we used publicly available material, as well as OUO reports from the Army Knowledge Online (AKO) Web site. In addition to this background research, we conducted a series of interviews with an SME, a retired Army officer, to get a better sense of the actual roles and responsibilities of the NCO during a relevant scenario. After much discussion, we arrived at a "Hasty Defense" Consolidation and Reorganization Operation (CRO) that would showcase many of the challenges of platoon-level logistics after an engagement with an enemy.

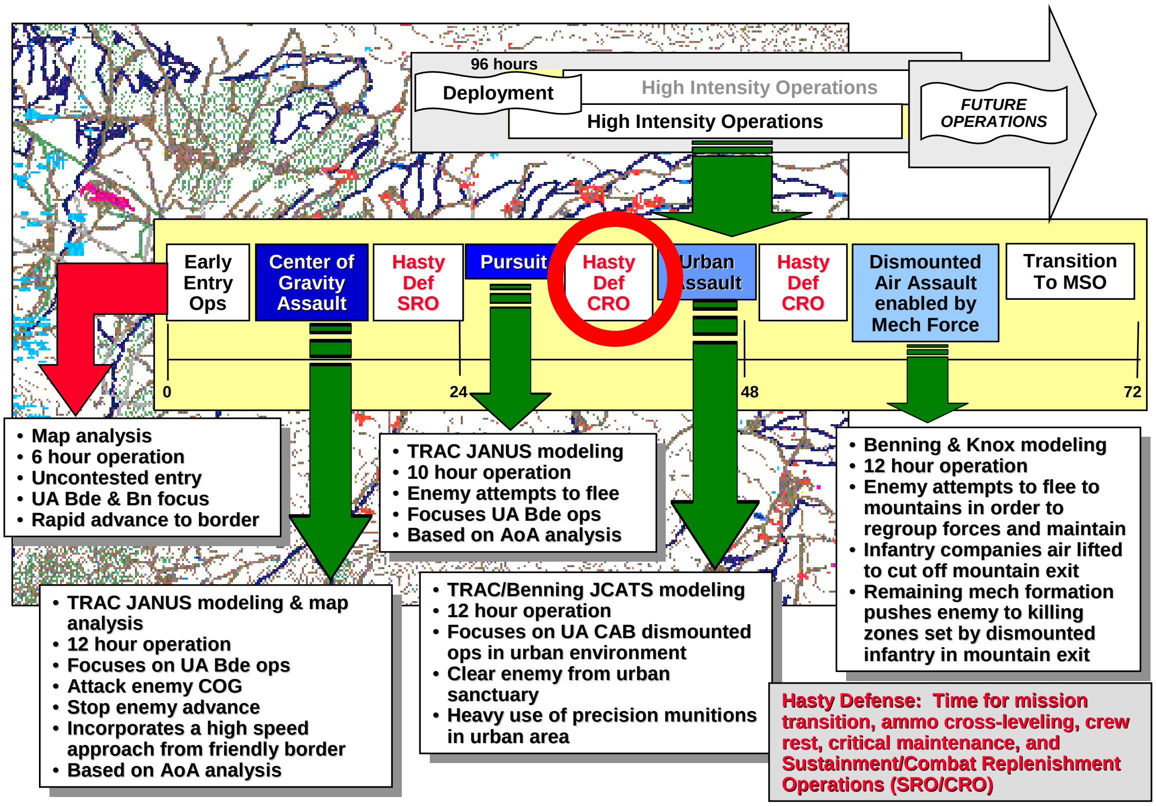


Figure 3.1. Outline of the High-intensity Operations Scenario; Cognitive Modeling was Based on the Actions of a Platoon Sergeant During the Second Hasty Defense CRO (indicted by the red circle).

In the selected scenario, a company is in the middle of a 72-hour high-intensity operation. About 12 hours into the operation, the company makes a center-of-gravity assault on an enemy, performs a Hasty Defense CRO, pursues the enemy, and then performs another Hasty Defense CRO before an Urban Assault Operation. The PSG's cognitive model was based on this second Hasty Defense CRO.

First, we gathered requirements for the PSG during such a Hasty Defense CRO from both the information culled from the background research and the SME. The platoon consolidates and reorganizes as required by the situation and mission:

- Consolidation is the process of organizing and strengthening a newly captured position so that it can be defended.
- Reorganization is the actions taken to shift internal resources within a degraded unit to increase its level of combat effectiveness.

The platoon executes follow-on missions as directed by the company commander. A likely mission may be to continue the attack against the enemy within the Area of Operation. Regardless of the situation, the platoon must posture itself and prepare for continued offensive operations.

From here, we create a reasonable set of assumptions:

- A mounted pursuit
- Intermittent squad- to platoon-sized dismounted operations during pursuit
- Suburban/sparsely populated terrain
- High expenditure of fuel and vehicle weapons-systems ammunition
- Moderate casualties
- Vehicular casualties: IEDs, anti-tank weapons (e.g., RPGs)
- SBCT stops short outside a built-up urban area
- Minimal-to-moderate threat of attack in the defense
- Emphasis is on
    - Consolidating and reorganizing
    - Transitioning/task organizing for an urban assault.

Thus, we created the Hasty Defense CRO as follows. The platoon secures its sector and reestablishes the defense by repositioning forces, destroying enemy elements, processing Enemy Prisoners of War (EPWs), and reestablishing obstacles. The platoon conducts all necessary Combat Service Support (CSS) functions as it prepares to continue defending. Squad and team leaders provide Ammunition, Casualty, and Equipment (ACE) reports. The Platoon Leader (PL) reestablishes the platoon chain of command. The PSG coordinates for resupply and supervises the execution of the casualty- and EPW-evacuation plan. The platoon continues to improve positions, quickly reestablishes operating positions, and resumes security patrolling as directed.

- Consolidation includes organizing and strengthening a position so that it can continue to be used against the enemy. Some platoon consolidation requirements are:
    - Adjust other positions to maintain mutual support.
    - Reoccupy and repair positions and prepare for renewed enemy attack. Relocate selected weapons to alternate positions if leaders believe that the enemy may have pinpointed them during the attack.
    - Repair damaged obstacles and replace mines (Claymore) and booby traps.
    - Reestablish security and communications.
- Reorganization includes shifting internal resources within a degraded unit to increase its level of combat effectiveness. Some platoon consolidation requirements are:
    - Man key weapons, as necessary
    - Provide first aid and prepare wounded soldiers for CASEVAC.

- Redistribute ammunition and supplies.
- Process and evacuate EPWs

We then created a general responsibilities list for the PSG. The platoon sergeant is the senior NCO in the platoon and second in command. He assists and advises the PL and leads the platoon in the PL's absence. He supervises the platoon's administration, logistics, and maintenance. He is a tactical expert in platoon operations to include maneuver of the platoon and employment of all weapons. The platoon sergeant:

- When directed, controls the mounted element when the PL dismounts, or dismounts with the platoon when the platoon is conducting ground operations independent of their organic vehicles or when it is necessary to command and control the platoon controls the platoon when necessary.
- Serves as VC and section leader when the platoon is mounted
- Receives squad leaders' administrative, logistical, and maintenance reports and requests for rations, water, fuel, and ammunition. Coordinates with the company's first sergeant or executive officer (XO) to request resupply.
- Directs the platoon medic and platoon aid and litter teams in moving casualties during mounted or dismounted operations.
- Maintains platoon strength information, consolidates and forwards the platoon's casualty reports, and receives and orients replacements.
- Monitors the morale, discipline, and health of platoon members.
- Takes charge of task-organized elements in the platoon during tactical operations. This can include, but is not limited to, quartering parties, support elements in raids or attacks, and security patrols.
- Ensures ammunition and supplies are properly and evenly distributed after consolidation on the objective and during reorganization.
- Controls digital reports while the platoon is in contact to allow the PL to maneuver the squads.
- Ensures the PL is updated on appropriate reports and forwards those needed by higher headquarters.
- Collects, prepares, and forwards logistical status updates and requests to the company headquarters.

For the particular Hasty Defense CRO, we created the prioritized list of PSG responsibilities:

- Assists PL in establishing security
- Consolidates squad/vehicle - ACE reports
- Advises PL of ACE status – PL adjusts security, as necessary, based on this report (e.g., a vehicle or vehicular weapon system is inoperable).
- Issues orders to cross-level ammunition and personnel based on ACE reports.
- Establishes Casualty Collection Point, supervises medic
- Relays to company 1SG/XO Class I, III, V, VII, and VIII.
- Confirms with company 1SG/XO the plan for CASEVAC.
- Confirms with company 1SG/XO the plan for re-supply (assume "service station" method for this scenario) – disseminates to Squad Leaders

- Supervises movement of casualties to company Casualty Collection Point.
- Details personnel to man EPW collection point.
- Establish EPW collection point.
- Orders movement of EPWs to collection point one squad at a time.
- Adjusts security as necessary.
- Checks with PL about upcoming operations based on his communications with higher.
- Double checks security
- Supervises movement of vehicles (one at a time) through service station—PL adjusts security while this is done.
- If vehicles are inoperable, supervises replacement and removal (in that order).
- Adjusts security as necessary.
- Confirms ACE is green, once all elements have moved through the service station
- Supervises crew-level maintenance on vehicles and key weapons systems, adjusting security as necessary to accomplish this.
- Assists PL in developing Paragraph IV of the OPORD for the next operation

3.1. Proof-of-Concept Implementation in SoSAT

For this project, we used the requirements and task decomposition above to create a simple information-processing model of the Platoon Sergeant. The major decomposition of this problem is that there is:

- Background Events that modulate the tasks required by the PSG
- Discrete events occur in response to stochastic external events and PSG actions

The Background Events are created according to predefined probability distributions. The stochastic external events are also determined by predefined probability distributions. The actions taken by the PSG are based on a limited-attention model of the PSG. First, the PSG must become aware of the event, which moves the event into the PSG's short-term, or working, memory. The PSG will select the single highest task from short-term memory and begin processing that task. This action may, in turn, generate discrete events. If a burst of high-relevance events occur nearly simultaneously, then the PSG model can become overwhelmed and devoted to processing those tasks, rather than the normal information tasks. Likewise, the workload of the PSG can also modulate the probability that the PSG makes an error in a logistics request or some other task. This can also create an information bottleneck, where a particular request may get processed immediately, delayed temporarily, delayed indefinitely (if the task has been "forgotten"), or incorrectly executed. The primary purpose of this cognitive model is to determine how workload affects the delivery of logistic supplies during the Hasty Defense CRO from known principles from cognitive psychology.

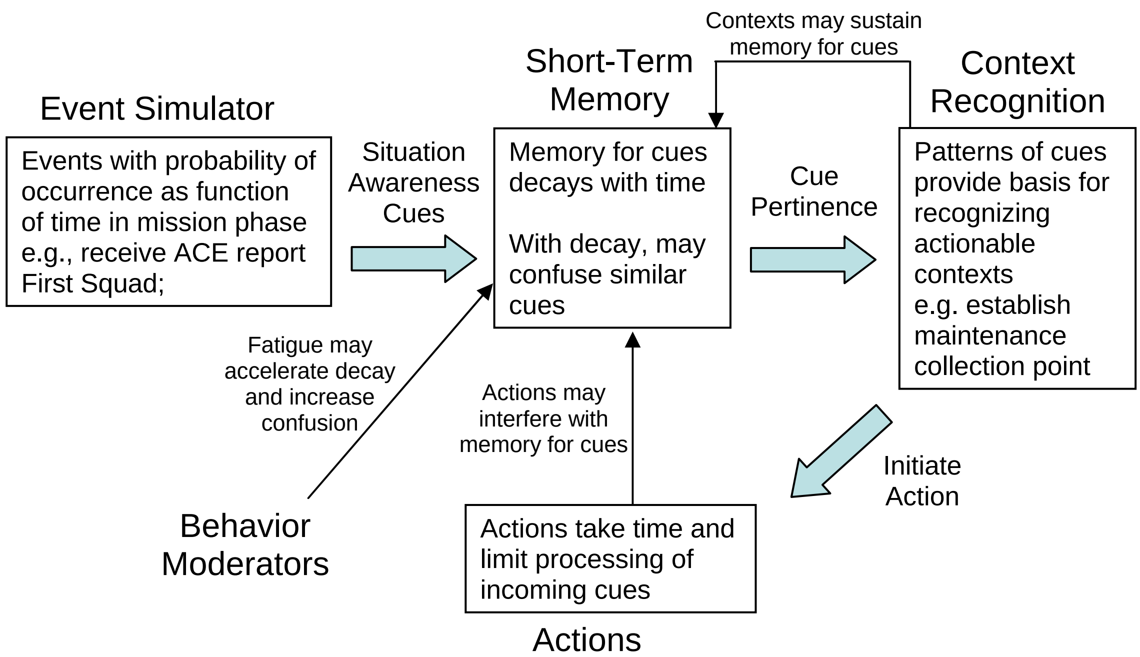


Figure 3.2. Diagram of the Cognitive model.

The Proof-of-Concept implementation for the PSG information-processing was written in Sun Java 1.5 using the specifications provided by cognitive psychologists. The events, event parameters and probabilities, and actions for the model are given in the Appendix. We created a DLL bridge that communicates with SoSAT's Microsoft C# via JNI.

3.2. Simulation Input

The implementation of the Proof-of-Concept cognitive model was meant to take logistic requests from the SoSAT tool and respond at each time step if a particular request has been satisfied or not, and if there was an error in processing the request.

3.3. Parameters and Parameter Values

The Spreadsheet in the Appendix has the detailed parameter values for the model.

3.4. Current Status

The cognitive model has been implemented and runs as described. However, there were some challenges in modifying the existing SoSAT scenarios to push requests into the PSG cognitive model instead of the normal routing. So, we have not been able to obtain specific performance results for this cognitive model on a standardized SoSAT scenario.

4. Conclusions

4.1. Accomplishments

The work performed for this LDRD has led to the following accomplishments:

- We developed and implemented in SoSAT 1.0 a general-purpose, Human-Performance Modeling capability based on Human Reliability Analysis
- This capability is unique and can now be implemented in the most recent version of SoSAT, SoSAT 1.5, where it can be available for use by our customers
- We investigated and performed preliminary cognitive-based modeling of a Platoon Sergeant managing logistics

4.2. Remaining Issues

4.2.1. Current Capability Upgrades for the Probability-Based HPM

Improvements to consider for current capabilities include:

- Mimicking the treatment for failed parts, SoSAT replaces a combat injured human with an identical human after a sampled replacement time. However, there may be an individual available to assume the duties of the injured human almost immediately. But given that he/she is an emergency replacement, he/she may be less qualified to perform the duties – resulting in increased mistakes. Also the permanent replacement may not be assigned until the system is scheduled for rest time, if at all. The treatment of human replacement needs to be made more flexible in SoSAT.

- The evacuation process of combat damaged individuals could have a more detailed treatment. It is currently possible to define systems and personnel to perform medical duties. Vehicles for evacuation can be made subject to reliability issues, consumable depletion, and human performance. To complete the treatment, new capability would include modeling the obtaining of the medical services, which could be done analogously to obtaining repair services. Also, new performance measures would have to be defined for the force which measure the success or failure of the medical service.

- When services are not specified for a repair, mechanics are assumed to be generic. SoSAT only prompts for the number of repairmen required. If a mix of different specialized repairmen is needed, the user has no choice but to define the repair using services. It would be more user-friendly to offer an alternative.

- For more detailed definition of repair jobs it may happen that M different specialized mechanics are required. This can be simulated by defining M different services each with a different named mechanic. However, this approach can narrow the mechanic's capability to one specialization. In reality a mechanic can likely perform many but not all repair tasks. SoSAT should be modified to allow a single mechanic to perform multiple tasks, without assuming he/she can perform all tasks.

- In the example problem (section 2.4 Example Problem) the mechanics pool has three repairmen. We had to give each mechanic a unique name. SoSAT can make multiple instances of systems but does not do so with elements within a system. It could ease the input for mechanics if element duplication was allowed in this case.

4.2.2. Additional Capabilities for the Probability-Based HPM

Additional capabilities to consider for SoSAT include:

- Model the thirst PSF. Presumably a vehicle requires water for cooling and for its personnel. Currently the consumption rate implicitly includes both. We would have to investigate whether it makes sense to separate these two rates to determine when thirst may become a factor. Also, we would have to determine how to model the effects of thirst on human performance in SoSAT.

- Implement the affect of PSFs on human reset time. No data have been found to suggest that such an affect exists; however, an affect is a plausible conjecture. Determining whether the affect exists and the magnitude of the affect would require a research effort. If an affect does exist, the probability-based HPM could be modified to represent it.

- Include the possibility of embedded training. If embedded training was scheduled in advance for a mission, then it could be included in the scenario that systems are to follow. During embedded training presumably the system would be partially operating. The benefit of embedded training would be to reduce mistakes by personnel. The cost includes less rest for the trainees and additional aging of parts of the system that have to be operating during the training. The benefit and part of the cost could be captured by a divisor of the initial error rate. The divisor would be greater than 1.0 for the training benefit. The divisor would be smaller than 1.0 for the increased fatigue. The user would determine the net divisor. The parts and consumables that would be used for training would have to age and be depleted during the training. If their aging and depletion rates are significantly different from those defined when the system is fully operating, an additional set of input would be required.

  On a related note, the training may not be prescheduled. It may occur only if there are lulls in the action. Future versions of SoSAT may be two-dimensional and more focused on positioning and a battle plan, and it may become possible to determine when a lull occurred. It may be appropriate to revisit the concept of unscheduled embedded training when the future version becomes available.

- Define and implement withdrawal points. When a platoon’s effectiveness is reduced to some level, the platoon leader should call for withdrawal. One issue is how to define that level (functionality of the systems, operability of personnel?). The other issue is the consequence of making a wrong decision. If the platoon leader does not withdraw when it is called for, is the platoon subject to increased combat damage or increased stress- or fatigue-driven mistakes? If the platoon leader calls for withdrawal prematurely, how can the costs to the mission be measured?

- A company commander (or higher) is responsible for positioning and repositioning his/her forces. Poor decisions could lead to increased combat damage, including the possibility of friendly fire. Presumably this function will be more readily included into SoSAT in a future version that is two-dimensional.

4.2.3. Release Version

The inclusion of human duties and failures into SoSAT has been implemented into a development version of SoSAT. The capabilities need to be implemented into a release version. The current release version is of sequence 1.5.

4.2.4. Remaining Issues for the Cognitive Modeling

The cognitive modeling has not been fully implemented or tested in a system of systems analysis framework. To complete the work started with this LDRD, the cognitive HPM must generate results that can be compared with the probability-based HPM. An interface with SoSAT has been designed. The example problem used for the probability-based HPM must be modified to allow the following calculations: (1) a baseline run without humans in the problem; (2) extension of the baseline with only the cognitive HPM; (3) extension of the baseline with only an probability-based HPM modeling the Platoon Sergeant in the problem; (4) extension of the baseline with all humans modeled using the probability-based HPM (which is presented in Section 2.4 Example Problem); and (5) extension of the problem to allow all humans modeled using the probability-based HPM, except for the Platoon Sergeant, which would be modeled using the cognitive HPM. Completion of this example problem will allow comparison of the probability-based HPM with the cognitive HPM, as well as a better understanding of what the parameter values should be in the models.

Another remaining issue is the cognitive modeling of other humans in a brigade. What is necessary to model the humans of interest? Is there a subset of behaviors that can lead to a more general cognitive model? The work performed for this LDRD has only scratched the surface of what might be possible with cognitive modeling. But it is still an open question as to whether cognitive HPMs can be used in a system-of-systems environment.

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Appendix: Cognitive Model Parameters

Actionable Contexts

Context	Cues	Action	Time (sec)	Error Mode & Prob	Resulting Event
Receive ACE Report Squad 1	Squad 1 ACE Report Ready	Record ACE Report Squad 1	45	ammo omitted 0.005; erroneous ammo 0.005; casuality omitted 0.005; equip loss omitted 0.005; equip repair omitted 0.005; erroneous equip repair 0.005	Recorded ACE Report Squad 1
Receive ACE Report Squad 2	Squad 1 ACE Report Ready	Record ACE Report Squad 2	45	ammo omitted 0.005; erroneous ammo 0.005; casuality omitted 0.005; equip loss omitted 0.005; equip repair omitted 0.005; erroneous equip repair 0.005	Recorded ACE Report Squad 2
Receive ACE Report Squad 3	Squad 1 ACE Report Ready	Record ACE Report Squad 3	45	ammo omitted 0.005; erroneous ammo 0.005; casuality omitted 0.005; equip loss omitted 0.005; equip repair omitted 0.005; erroneous equip repair 0.005	Recorded ACE Report Squad 3
Receive ACE Report Squad 4	Squad 1 ACE Report Ready	Record ACE Report Squad 4	45	ammo omitted 0.005; erroneous ammo 0.005; casuality omitted 0.005; equip loss omitted 0.005; equip repair omitted 0.005; erroneous equip repair 0.005	Recorded ACE Report Squad 4
Prepare ACE Resupply Request	Recorded ACE Reports Squad 1,2,3,4, (-ACE Resupply Request Ready)	Prepare ACE Resupply Request	450	erroneous ammo 0.005; equip loss omitted 0.005; erroneous equip loss 0.005; equip repair omitted 0.005; erroneous equip repair 0.005	ACE Resupply Request Ready
Ready Submit ACE Resupply Request	ACE Resupply Request Ready, >180 sec since Contact Company XO	Contact Compay XO	20		
Submit ACE Resupply Request	Company XO Available, (-Submit ACE Resupply Request)	Submit ACE Resupply Request	180	erroneous ammo 0.005; equip loss omitted 0.005; erroneous equip loss 0.005; equip repair omitted 0.005; erroneous equip repair 0.005	ACE Resupply Request Submitted
Establish Casualty Collection Point	Casualties, (-Casualty Collection Point)	Establish Casualty Collection Point	180		Casualty Collection Point
Ready Request MedEvac	MedEvac, >180 sec since Contact MedEvac	Contact Request MedEvac			
Request MedEvac	MedEvac Available, (-MedEvac Requested)	Request MedEvac	180		MedEvac Requested
Supervise MedEvac	MedEvac Arrives	Supervise MedEvac	600		

Need to Redistribute Personnel	Casualties, (-Personnel Redistributed), Request Send Personnel to Other Platoon, Platoon attacked	Redistribute Personnel	1200		Personnel Redistributed	
Inform PL Vehicle Casualty	Vehicle Casualty	Inform PL Vehicle Casualty	600		PL Cognizant Vehicle Casualty	
Need Coordinate Vehicle Triage	Squad 1,2,3,4 Equipment Loss, Squad 1,2,3,4 Needs Equipment Repair	Coordinate Vehicle Triage	240		Vehicle Triage Underway	Would not happen
Requested Send Vehicle to Other Platoon	Request Send Vehicle to Other Platoon	Send Vehicle Other Platoon	450	fails to send vehicle 0.005; sends vehicle wrong platoon 0.005		
Requested Send Personnel to Other Platoon	Request Send Personnel to Other Platoon	Send Personnel Other Platoon	450			
Need Send Vehicle Maintenance Section	Determine Vehicle Needs Maintenance Section Repair	Send Vehicle Maintenance Section	600	fails to send vehicle 0.005; sends vehicle wrong place 0.005		
Check Status of Vehicles	Vehicle Triage Underway, Squad 1,2,3,4 Needs Equipment Repair, >300 sec since Check Status	Check Status	180			
Must Destroy Vehicle	Determine vehicle irrepairable damage	Order Destroy Vehicle	60		Beyond the platoon	
Redistribute Weapons/Ammo	Determine Need to Redistribute Weapons, Request Send Vehicle to Other Platoon, Platoon attacked	Order Redistribute Weapons	1800			
Fortify Position	Determine Need to Fortify Position, Platoon attacked	Order Fortify Position	45 min			
Coordinate Security	Forces Not Positioned	Position Forces	600			
Establish EPW Collection Point	EPWs	Establish EPW Collection Point	600		EPW Collection Point	
Assess Response EPW Intelligence	EPW with Good Intelligence	Respond EPW Intelligence	210			Not Pl SGT
Redistribute Class II/VI Supplies	Squad 1,2,3,4 Class II/VI Supply Request	Order Redistribution Supplies	60			
Prepare Class II/VI Resupply Request	Squad 1,2,3,4 Class II/VI Supply Request (-Class II/VI Resupply Request Ready)	Prepare Class II/VI Resupply Request	1200		Class II/VI Resupply Request Ready	
Ready Submit Class II/VI Resupply Request	Class II/VI Resupply Request Ready, >180 sec since Contact Company XO	Contact Compay XO				
Submit Class II/VI Resupply Request	Company XO Available, (-Submit Class II/VI Resupply Request)	Submit ACE Resupply Request	180	omit to request Class II/VI supplies 0.005, erroneous request for Class II/VI supplies 0.001	Class II/VI Resupply Request Submitted	
Advises PL Resource Situation	Squad 1,2,3,4 Equipment Loss, Squad 1,2,3,4 Needs Equipment Repair, Casualty, Request Send Vehicle to Other Platoon, Request Send Personnel to Other Platoon	Advise PL	450			

Respond to attack	Platoon attacked	Respond to Attack	1800
Respond to miscellaneous request from PL	Misc Request PL	Respond to request	180
Respond to miscellaneous request from squad leaders	Misc Request SL	Respond to request	180
Respond to miscellaneous request from company	Misc Request Company	Respond to request	180

Only one context can be recognized at any time

Each context has an associated level of activation that is a product of the activation of the associated cues

The context recognized at any time is the one for which there is the greatest level of activation

Recognition of a context prompts the corresponding action

Once an action is initiated, recognition of the corresponding context persist until the action is complete

The overall level of activation determines an error multiplier that adjusts all error probabilities

Following completion of one action, confusability effects the recognition of the next action.

The level of confusability is based on the level of activation at the time for each context with contexts having high levels of activation being more confusable.

Confusion may be simulated through a probability that the context with highest activation will be confused with another context that is a function of the similarity in their levels of activation.

Confusability may be modified by a multiplier to simulate the effects of fatigue such that it becomes more difficult to suppress competing actions.

Immediate Awareness

Events/Cues	Trigger	Salience (1-10)	Associations
Forces Not Positioned	Preceding events	9	
Squad 1 ACE Report Ready	Event simulator	6	
Squad 2 ACE Report Ready	Event simulator	6	
Squad 3 ACE Report Ready	Event simulator	6	
Squad 4 ACE Report Ready	Event simulator	6	
Recorded ACE Report Squad 1	Action - Recorded ACE Report Squad 1	6	
Recorded ACE Report Squad 2	Action - Recorded ACE Report Squad 2	6	
Recorded ACE Report Squad 3	Action - Recorded ACE Report Squad 3	6	
Recorded ACE Report Squad 4	Action - Recorded ACE Report Squad 4	6	
ACE Resupply Request Ready	Action - ACE Resupply Request Ready	6	
Company XO Available	Action - Contact Company XO (p=0.2 available)	7	

ACE Resupply Request Submitted	Action - Submit ACE Resupply Request	5
Casulaties	Preceding events	7
Casualty Collection Point	Action - Establish Casualty Collection Point	7
MedEvac	Preceding events	8
MedEvac Available	Action - Contact MedEvac (p=0.4 available)	8
MedEvac Requested	Action - MedEvac Requested	8
MedEvac Arrives	Event simulator	8
Personnel Redistributed	Action - Redistribute Personnel	6
Vehicle Casualty	Preceding events	5
PL Cognizant Vehicle Casualty	Action - Inform PL Vehicle Casualty	5
Squad 1 equipment loss	Preceding events	4
Squad 1 needs equipment repair	Preceding events	4
Squad 2 equipment loss	Preceding events	4
Squad 2 needs equipment repair	Preceding events	4
Squad 3 equipment loss	Preceding events	4
Squad 3 needs equipment repair	Preceding events	4
Squad 4 equipment loss	Preceding events	4
Squad 4 needs equipment repair	Preceding events	4
Vehicle Triage Underway	Action - Coordinate Vehicle Triage	4
Request Send Vehicle to Other Platoon	Event simulator	4
Request Send Personnel to Other Platoon	Event simulator	4
DetermineVehicle Needs Maintenance Section Repair	Event simulator	4
Determine vehicle irrepairable damage	Preceding events	3
Determine Need to Redistribute Weapons/Ammo	Event simulator	8
Determine Need to Fortify Position	Event simulator	8
EPWs	Preceding events	5
EPW with Good Intelligence	Event simulator	7
Squad 1 Class II/VI Supply Request	Event simulator	3
Squad 2 Class II/VI Supply Request	Event simulator	3
Squad 3 Class II/VI Supply Request	Event simulator	3
Squad 4 Class II/VI Supply Request	Event simulator	3
Class II/VI Resupply Request Ready	Action - Class II/VI Resupply Request Ready	3
Class II/VI Resupply Request Submitted	Action - Submit Class II/VI Resupply Request	3
Platoon attacked	Event simulator	10
Misc Request PL	Event simulator	1 to 7
Misc Request SL	Event simulator	1 to 7
Misc Request Company	Event simulator	1 to 7

When events/cues occur, there is a corresponding level of activation

Event/Cue activation diminishes over time

The initial activation of a cue will be a product of the salience of the cue

Events/cues may be activated as a product of preceding events indicating that occurred prior to stopping and there is sustained awareness

Events/cues may be activated as a product of the event simulator

Events/cues may be activated as a product of actions

Associations reflect activation of related events/cues that occurs through association with events/cues that have actually occurred.

Event Simulator

Event	Precondition	Minimum Delay (sec)	Average Latency (sec)	Replacement	
Squad 1 ACE Report Ready	none	300	1200	no	
Squad 2 ACE Report Ready	none	300	1200	no	
Squad 3 ACE Report Ready	none	300	1200	no	
Squad 4 ACE Report Ready	none	300	1200	no	
MedEvac Arrives	MedEvac Requested	1800	3000	no	
Request Send Vehicle to Other Platoon	Requested to send vehicle to other platoon	600	1200	yes	
Request Send Personnel to Other Platoon	Requested to send personnel to other platoon	2400	3600	yes	
Determine Vehicle Needs Maintenance Section Repair	Need to send vehicle to maintenance section	3600	7200	yes	
Determine Vehicle Irreapairable Damage	Vehicle irrepairable damage - must destroy	3600	7200	yes	
Determine Need to Redistribute Weapons/Ammo	Need to Redistribute Weapons/Ammo	600	1200	yes	
Determine Need to Fortify Position	none	1800	3600	yes	
EPW with Good Intelligence	EPWs			yes	Beyond scenario
Determine Need to Redistribute Supplies	none			no	Too improbable
Squad 1 Non-ACE Supply Request	Squad 1 II/VI Supplies Deplensihed	900	600	yes	Beyond scenario
Squad 2 Non-ACE Supply Request	Squad 2 II/VI Supplies Deplensihed	900	600	yes	Beyond scenario
Squad 3 Non-ACE Supply Request	Squad 3 II/VI Supplies Deplensihed	900	600	yes	Beyond scenario
Squad 4 Non-ACE Supply Request	Squad 4 II/VI Supplies Deplensihed	900	600	yes	Beyond scenario
Enemy Attack	Platoon is attacked			yes	Montonically increasing from some minimum to a maximum likelihood at end of two hours

Misc Request PL	none	0	900	yes
Misc Request SL	none	0	900	yes
Misc Request Company	none	0	900	yes

At each timestep check to see which events have occurred

Each event has a delay which indicates the earliest timestep at which the event may occur

Each event has an average latency which reflects the most likely timestep at which the event occurs

Probabilities of an event occurring are distributed around the average latency

The probability of an event occuring at the average latency increases as the average latency approaches the delay

Replacement indicates that an event may occur on multiple occasions

Equal occurrence indicates that the event is equally likely at any time during the scenario

Probablistic Events

Condition/event	Precondition	Prob	
Forces not positioned	none	1	
Squad 1 needs ammo replenished	none	0.35	
Squad 2 needs ammo replenished	none	0.35	
Squad 3 needs ammo replenished	none	0.35	
Squad 4 needs ammo replenished	none	0.35	
Squad 1 has casuality	none	0.075 (KIA 0.05, WIA 0.2, MedEvac 0.5)	
Squad 2 has casuality	none	0.075 (KIA 0.05, WIA 0.2, MedEvac 0.5)	
Squad 3 has casuality	none	0.075 (KIA 0.05, WIA 0.2, MedEvac 0.5)	
Squad 4 has casuality	none	0.075 (KIA 0.05, WIA 0.2, MedEvac 0.5)	
Squad 1 equipment loss	none	0.1	
Squad 1 needs equipment repair	none	0.15	
Squad 2 equipment loss	none	0.1	
Squad 2 needs equipment repair	none	0.15	
Squad 3 equipment loss	none	0.1	
Squad 3 needs equipment repair	none	0.15	
Squad 4 equipment loss	none	0.1	
Squad 4 needs equipment repair	none	0.15	
Requested to send vehicle to other platoon	none	0.1	Likelihood would diminish with loss of vehicles
Requested to send personnel to other platoon	none	0.25	
Need to send vehicle to maintenance section	Equipment repair Squad 1,2,3,4	0.4	
Vehicle irrepairable damage - must destroy	Equipment loss Squad 1,2,3,4	0.4	
EPWs	none	0.15 (EPW with Good Intelligence 0.05)	

Need to Redistribute Weapons/Ammo	Needs Ammo Replenished Squad 1,2,3,4 OR Equipment Loss Squad 1,2,3,4 OR Equipment Repair Squad 1,2,3,4	0.4
Squad 1 Non-ACE Supplies deplenished	none	0.05
Squad 2 Non-ACE Supplies deplenished	none	0.05
Squad 3 Non-ACE Supplies deplenished	none	0.05
Squad 4 non-ACE Supplies deplenished	none	0.05
Platoon is attacked	none	0.2

Preceding conditions reflect the likelihood that events have occurred prior to the beginning of the scenario

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