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An Emerging Methodology: The System Capabilities Analytic Process (SCAP)

by Kevin S. Agan

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14. ABSTRACT

To determine whether or not a system has sufficient capability to complete a mission following a damaging event is part of the evolution of combat. This problem cannot be easily answered using traditional methods and metrics within the live-fire analysis community. As traditional analysis efforts have focused on qualitative metrics, a need for a quantitative methodology and metric was identified. To fill this need, the System Capabilities Analytic Process (SCAP) was developed. SCAP quantitatively and logically links the functional states of a system's components to the capabilities of the system, which are expressed in terms familiar to the military user of the system.
The primary product generated by SCAP is the functional skeleton (FS), which is a map between a system's components and its capabilities. The FS includes both the material components of the system as well as the personnel operating the system. It will be shown how the FS can be used to link the capabilities between individual systems into system array capabilities, and also how the FS can be used to determine the performance of systems in an interacting system-of-systems. Methods for representing the FS mathematically are also discussed.

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1. Introduction

1.1 Background

The complex decision-making problem of determining whether or not a system has sufficient capability to complete the mission following a damaging event is part of the evolution of combat. This problem cannot be easily answered using traditional methods and metrics within the live-fire analysis community. Traditional analysis efforts have been focused on an aggregated qualitative metric called loss of function (LOF) which has a number of drawbacks (*1*, *2*). The first is that many of the consumers of the LOF metric do not have a good understanding of what it means. For example, if a system has received a 50% loss of mobility, what will that mean in a combat situation? A common misinterpretation is that it is a probability of "killed" or "not-killed," when it is really a qualitative measure of how many missions a system will be unable to perform (*3*). In combination with this ambiguity is the fact that a LOF metric cannot be empirically observed in any test used for U.S. Army live-fire test and evaluation (LFT&E). All data in a test that can be measured is fundamentally quantitative—such as the speed a vehicle can attain after a damaging event—which is not represented in an LOF.

Due to these drawbacks, the need for a quantitative methodology and metric was identified. To fill this need, the System Capabilities Analytic Process (SCAP) was developed. This methodology quantitatively and logically links the functional states of a system's components to the capabilities of the system. These capabilities are reported in terms that are shared with the military user of the combat system, which provides the decision-maker with the information that is required to determine a course of action following a damaging event.

1.2 A New Product for System Analysis: The Functional Skeleton

The primary product generated by the application of SCAP is the creation of a functional skeleton (FS) which is a map between a system's components and its capabilities. The FS includes the contributions of all components of a system, including the hardware, the software, and the personnel operating the system. The FS can be used to link capabilities within a system-of-systems (SOS) so that an analyst can know how the loss of critically important hardware on one system will affect the performance of a networked or interacting system. Because of the quantitative nature of the FS, it can be utilized by a number of analytic domains. Some of these domains are reliability, automotive performance, personnel interactions, and live-fire analysis. Because the cause of the component failure is not critical to the FS, it allows failures from several forms to be applied to a single evaluation. For example, a component can suffer a reliability failure which makes a system vulnerable to an attack. The attack occurs and hardware is damaged, at which time the functional skeleton considers both failures in determining the remaining capabilities.

1.3 The Outline of This Report

This report details the fundamentals of SCAP and displays only generalized examples of its use. Specific examples of applications will be published in follow-up documentation as they are developed.

A brief review of the concepts of a criticality analysis (CA) is presented followed by an explanation of fault-tree analysis as used in SCAP. A large section of this report is focused on the four levels of the FS, and on how the FS relates to standardized U.S. Army mission tasks. After a discussion of several example uses of the FS, attention is given to how to construct the FS. The mathematical representation of the functional skeleton will conclude the technical portion of this report.

SCAP is an evolving methodology and has only recently been integrated into U.S. Army analysis efforts. Existing voids in the process and a path for filling these voids is presented near the end of the report.

2. Criticality Analysis

A criticality analysis is the process of examining a system to determine which components of that system are required for the system to perform as intended. A component is considered critical when damage to, or failure of, the component can affect the performance of one or more of the system's primary mission functions. The results of component dependency in a criticality analysis are presented in diagrams known as fault trees.

The methods used to identify which components are critical are not covered in this report. These methods are well documented in other publications; therefore the focus of this report will be on how to structure a functional framework once the critical components have been identified.

3. Fault Tree Analysis

The fault tree—both graphically and mathematically—is a fundamental tool for defining the relationships between the components and the capabilities of a system. The fault trees are graphical representations of a methodology known as fault tree analysis (*4*). A fault tree is a logic diagram that reports the state of a system/group in the terms of the functional states of the inclusive elements. The elements in each tree are connected by series and/or parallel paths. SCAP uses a modified form of fault tree analysis, in that the graphical conventions are much simpler than the industry standards (*5–7*). The beginning of the fault tree is denoted by a single "x"; the end of the fault tree is denoted by a double "x." Each element in a fault tree is considered to be either fully functional or fully dysfunctional. The fault tree is functional only if an unbreakable path through a sequence of functional elements can be traced from the single "x" to the double "x" in the fault tree.

A sample fault tree for a generic sub-system is depicted in figure 1. The relationship between element 1 and element 2 is a series relationship. A series relationship is functional only if all elements of the series portion of the tree are functional. If, for any reason, any element in a series tree is dysfunctional, then the entire tree is considered dysfunctional. The branching relationship from element 2 to elements 3 and 5 is a depiction of a parallel relationship. For parallel relationships, only one branch is required to be functional for the tree to be considered functional. Figure 2 depicts how a fault tree can be a further decomposition of an element in another, higher-level fault tree.

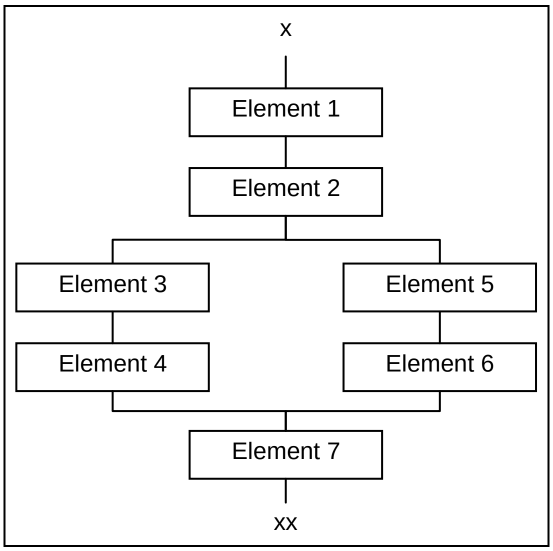


Figure 1. A sample fault tree.

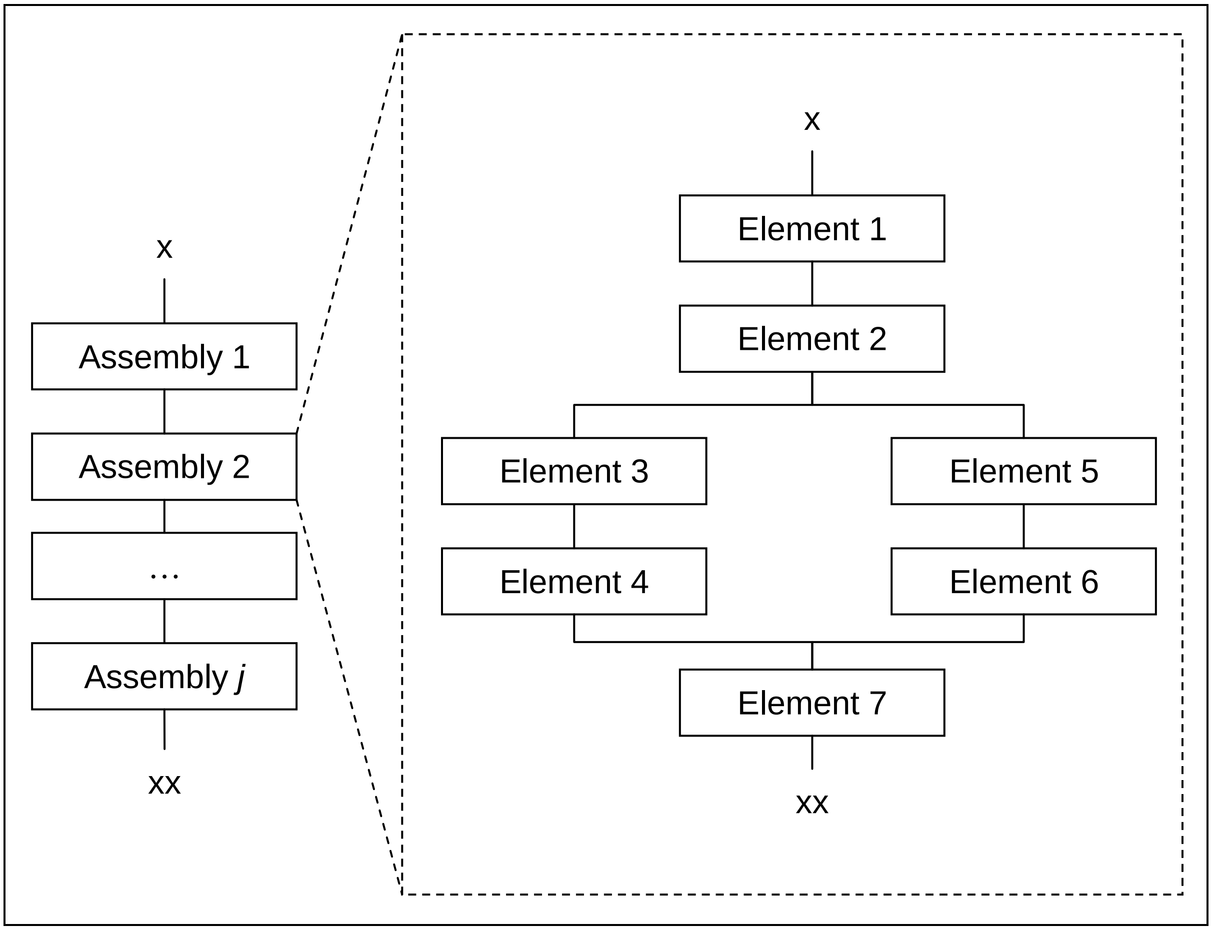


Figure 2. A fault tree for an element of a higher-level fault tree.

A fault tree can be represented mathematically (*8*). The mathematics for fault tree analysis is based on the current functioning state of the system. Assume that the functional state of a component is represented by a binary set: a “1” represents an element is functional, while a “0” represents an element that is dysfunctional. Assume the element of interest is element 3 in figure 2, hence forth denoted as E_3. Therefore, E_3 is mathematically represented as:

$$\mathrm{E}_3 = \begin{cases} 0, & \text{dysfunctional} \\ 1, & \text{functional} \end{cases} . \tag{1}$$

It is possible to evaluate the total function or dysfunction of the entire fault tree by evaluating the functional state of all elements within the fault tree. For a series relationship, the functional state of the tree—and therefore the higher-level assembly—is represented by the product-sum of all the elements in the series, as shown in equation 2.

$$A_j = \prod\nolimits_i^n (E_i). \tag{2}$$

If $A_j = 1$, then the assembly A_j is considered functional. If $A_j = 0$, then the assembly A_j is considered dysfunctional.

For a parallel relationship, the functional state of the tree—and therefore the higher-level assembly—is represented by equation 3, where B_i is the functional representation of each independent branch of the parallel tree.

$$A_j = 1 - \prod_i^n (1 - B_i). \tag{3}$$

If $A_j = 1$, then the assembly A_j is considered functional. If $A_j = 0$, then the assembly A_j is considered dysfunctional.

It is possible to combine the mathematics of series and parallel relationships. If a branch of a parallel tree is composed of a series relationship of elements, then the equation for a series relationship would be substituted for the variable representing the function of the branch. If a parallel relationship exists within a series tree, then the mathematical representation of the parallel branches would be included as one of the elements in the series product sum. There is no limit to complexity of these combinations, so long as the analyst can maintain the record-keeping. As an example, recall the fault tree for A_2 depicted in figure 2. In this case, the equation representing the functional state of A_2 can be constructed by combining the mathematical relationships for both series and parallel. The resulting equation is:

$$A_2 = E_1 \cdot E_2 \cdot \left\{1 - \left\{\left(1 - \left(E_3 \cdot E_4\right)\right) \cdot \left(1 - \left(E_5 \cdot E_6\right)\right)\right\}\right\} \cdot E_7. \tag{4}$$

---

4. SCAP Defined

4.1 An Overview of the SCAP and the FS

When analyzing a system using SCAP, a map is created to define the relationship between components of the system and the system's capabilities. The map of these relationships is known as the FS. The levels of the FS are depicted in figure 3. Throughout the FS, all data is explicit and quantitative; in other words, it defines what is functional or what can be accomplished by the system. The mission task is analyzed or evaluated using the FS, and is the actions that are employed to utilize the system. The map between the system capabilities (SC) and the mission tasks are not entirely scientific and fall more into the "art of war." The FS will tell you what SC's are functional, and the analyst decides if and how these SC allow you to accomplish the mission using the commander's intent. The FS will be discussed in sections 4.4.1–4.4.4. Mission tasks will be discussed in section 4.4.5.

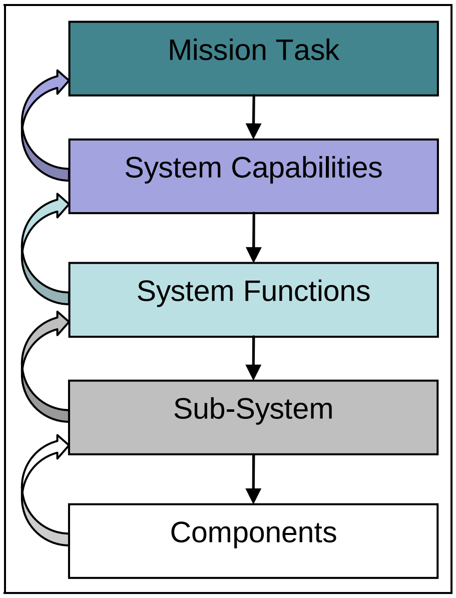


Figure 3. The levels of the FS.

A mnemonic to understand how the FS relates to the system's hardware and the actions defined by a mission task is: "When components are grouped into sub-systems, they will produce functions that will provide the capability to complete the mission task."

4.2 Potential Lexicon Conflicts

SCAP has potential applications in multiple other government agencies and analysis domains, in which particular lexicon may have a unique meaning. Therefore, a possible conflict in lexicon between SCAP and these other government agencies has been identified. In fact, there are multiple military definitions for the same words which may represent fundamentally different concepts to different government agencies.

The definitions of terms generally used in the T&E community are derived from military application. However, since SCAP has possible application across more than the Department of Defense (DOD), the definitions presented in this document are derived from industrial standards of systems and reliability engineering.

4.3 Definitions of Dysfunction

In all levels of the FS, the concept of dysfunction will be the same. An element or assembly is considered to be "functional" if it is performing as it was intended by the system's designers without any measurable degradation. An element is considered to be "dysfunctional" if it is not performing as intended or if it is entirely absent. A "transient dysfunction" is when an element is not performing as it was intended due to some influence, but will return to full functionality when the influence is either compensated for or removed. Transient dysfunctions are most commonly associated to the non-destructive dysfunctions, which includes electronic warfare, personnel actions or status, or issues with networked communications. All three of these dysfunctions are discussed in the following sections.

4.4 The Functional Skeleton

Each level of the FS is explained in detail in the next few sections. The partial decomposition of a commercially-available light-duty truck will be used to help explain the four levels of the FS. It is assumed that an analyst has acquired the information for this light-duty truck—depicted in figure 4—and is compiling the FS for this vehicle. Recalling the explanations of fault tree analysis in section 3, the FS will be considered an aggregated fault tree of the components of the truck up, through the capabilities of the vehicle.

Figure 4. A commercially available light-duty truck.

4.4.1 Components

The components are the lowest level of the FS and are the physical parts of the system that is being analyzed. Components can be either individual parts, such as a drive shaft, or they could be a functional sub-assembly that is considered a line-replaceable unit in the field, such as a fuel pump. Or they can even be a human interacting with the system, which will be discussed in section 4.5.

A component is considered dysfunctional when some interaction has rendered it unable to function as designed. For the case of ballistic vulnerability, this occurs when some threat has damaged the component to the point that it will no longer function properly, which is defined in traditional methodologies as "killed." In addition to ballistic vulnerability, any form of insult can be applied to render a component dysfunctional (*9, 10*). Some of these insults can be, but are not limited to environmental effects or contamination, reliability failure, chemical attack, or system abuse. A component can also be considered dysfunctional in the simple case of it not being powered on, such as a radio that is unintentionally left off.

By default all components are assumed to be functional ($C_i = 1$) when the FS is constructed. A component is dysfunctional when some interaction or insult has either deactivated it or sufficiently damaged the material to cause it to fail to function. A component can also be subject to a transient dysfunction. One simple example is a machine gun that has been rendered dysfunctional because the barrel (the component) has overheated due to duration of fire in excess of the time-threshold the barrel was designed to sustain. Once the barrel cools, it is theoretically possible for the gun to be functional again.

A partial component dysfunction—a component that is performing somewhere between fully dysfunctional and fully functional—is not currently modeled with the FS. Theoretically, an infinite scale of partial dysfunctions exist, therefore it is not possible to quantitatively map every possibility. Therefore, if a component has been sufficiently damaged to affect its function, it is considered "killed" or dysfunctional.

For the case of the light-duty truck, assume that one of the components of interest is the front tire on the left (driver's side) of the vehicle. As long as the tire holds air and has sufficient tread to maintain traction, the component is considered functional. If we are to assume a hole has been placed in the tire and it is flat, then it is considered "killed" or dysfunctional. As partial component dysfunctions are not represented, a hole in the tire that does not release all the air pressure would be considered "functional."

4.4.2 Sub-Systems

A sub-system (SS) is a collection of components assembled and functioning together to perform a specific purpose. For the example of the light-duty truck, we will compose the front-left wheel sub-system. This subsystem is composed of the tire, the wheel, and the hub.

In some cases, a sub-system is composed of a single component, such as a portable global positioning system (GPS) unit. There are also times when a subsystem is a complex assembly of other smaller sub-systems. A sub-system fault tree can contain both components and other sub-systems. This is the only level of the FS where elements from two levels are allowed to be in the same fault tree.

4.4.3 System Functions

The system function (SF) is an observable, repeatable, and measurable performance of a sub-system or a collection of sub-systems. When the sub-systems are functioning as intended, their successful operations and actions are the observed system functions. Some examples of SF's are: maintain engine lubrication, maintain proper operating temperature, maintain traction, generate energy from fuel, aim weapon, and so on.

4.4.3.1 Fault Tree Representation of SF's. The complexity of the SF determines the choice of the elements for the fault tree when it is constructed. For the majority of cases, the SF will be a simple tree to represent operation such as "maintain lubrication." For cases of this nature, the elements of the SF fault tree are the sub-systems that produce these functions. Some less-common forms of SF's are ones that represent relatively complex performances—such as calculating the trajectory of an attack. In cases like this, the elements of the SF will be lower-order SF's, such as: determine location of weapon, determine range to target, compute ballistic path, and so on. An example of this kind of relationship is depicted in figure 5.

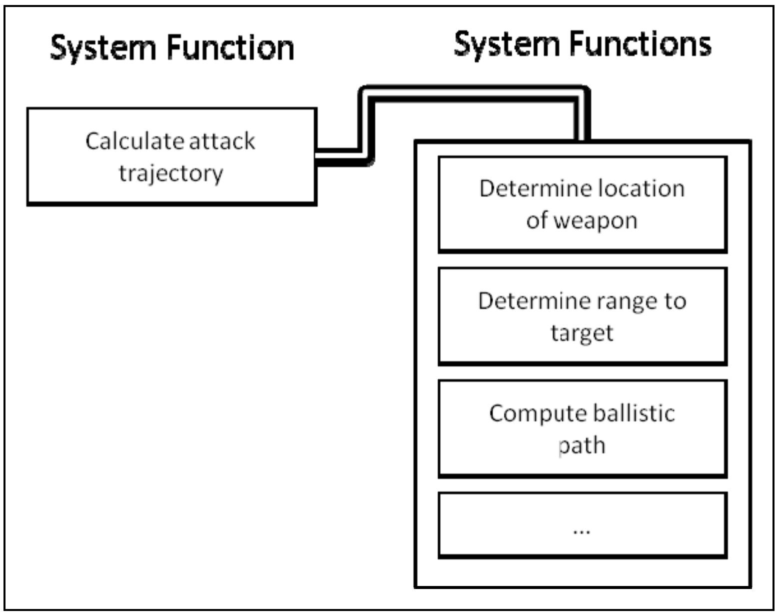


Figure 5. An SF with other SF's as its elements.

When composing the SF's fault trees, the elements will be either sub-systems or other system functions, but never both in a single tree. If we were allowed to mix the levels, then we could have a fault tree that could contain both the physical hardware of a system and a measure of a system performance. As both of these levels are fundamentally different concepts, there is no quantitative way to aggregate these into a single answer. The only option is to keep them separated so that SF can aggregate into other SF or that a SS can produce a SF. If this rule were violated in the example of the light-duty truck, then an analyst would be able to construct a fault-tree with both the SF "maintain lubrication" and a SS of "engine system" on the same level with each other. An example of this improper mixing is depicted in figure 6.

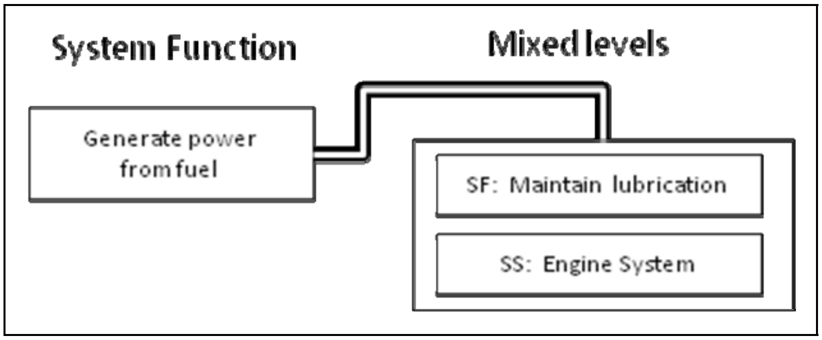
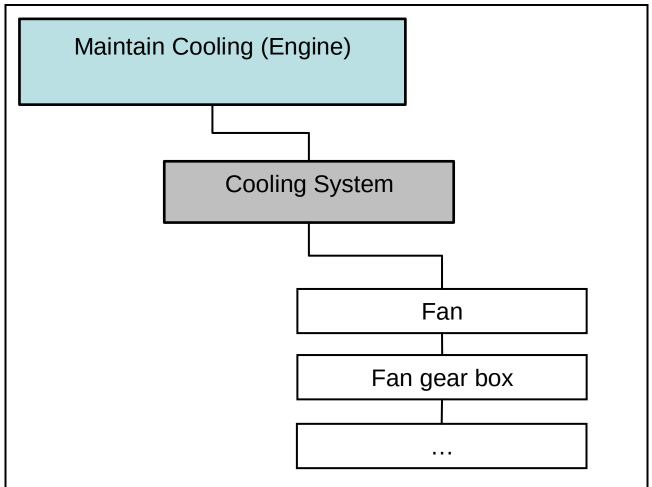


Figure 6. An example of an improper mixing of SF and sub-system elements.

There are cases where a SF can be present in the FS without any elements to define the function. This occurs when a system function is required for the successful operation of a system but no feature of the design is able to perform this function. One example is a heavy machine gun that has no cooling-system. The SF of "maintain proper operating temperature" is present in the FS, but if the gun relies on ambient-air convective cooling then no elements are assigned to the SF fault tree. When the gun overheats, a transient dysfunction occurs on this SF until the system cools down to operating temperatures. If the system is unable to return to a normal operating state, then a permanent dysfunction occurs.

4.4.3.2 Binary and Probabilistic System Functions. In most mechanical systems, the representation of the SF is a binary set—either functional ($SF_i = 1$) or dysfunctional ($SF_i = 0$)—based on the functionality of the elements in the fault tree, which is depicted in figure 7.

Early in the development of SCAP, a situation was discovered where the elements of an SF were all functional, but it was possible for an SF to sometimes perform successfully and sometimes perform unsuccessfully based on conditions acting on the sub-systems. If a SF has a probability of being successful versus unsuccessful based on conditions acting on functional sub-systems, then it is defined to be a probabilistic system function (PSF). A PSF is best modeled mathematically as a Bernoulli trial where the criteria for a success is the probability mass function that contains the requirements for success, as will be seen in the following example.



State:	System Function Value:
All parts functional	1.0
Fan failed	0.0

Figure 7. Binary system function.

In the example of a simplified infrared (IR) sensor depicted in figure 8, assuming all components are fully functional, the IR signal detection sub-system is at full performance, and therefore fully functional. To determine if the performance of the SF “detect IR signal” is successful or unsuccessful, conditions such as the strength of the source signal and distance between the source of the signal and the sensor determines the performance thresholds, and therefore determines the probability the SF is indeed functional. If a signal is too weak to be detected the SF “detect IR signal” would be dysfunctional even if all the components are functioning correctly. In the example shown, a “maximum” signal is detected about 60% of the time for a given distance from the sensor of interest. Therefore, about 60% of the time, when these conditions are present, the “detect IR signal” SF is functional and about 40% of the time it is dysfunctional.

The probability of functional for a PSF can be modified if the conditions affecting the PSF are changed. For example, the presence of flares could provide a stronger IR signal than the source signal. In this case, the probability of correctly detecting the source signal would decrease as the sensor may detect the wrong signal, thus rendering a SF as dysfunctional even though all components are functioning as intended.

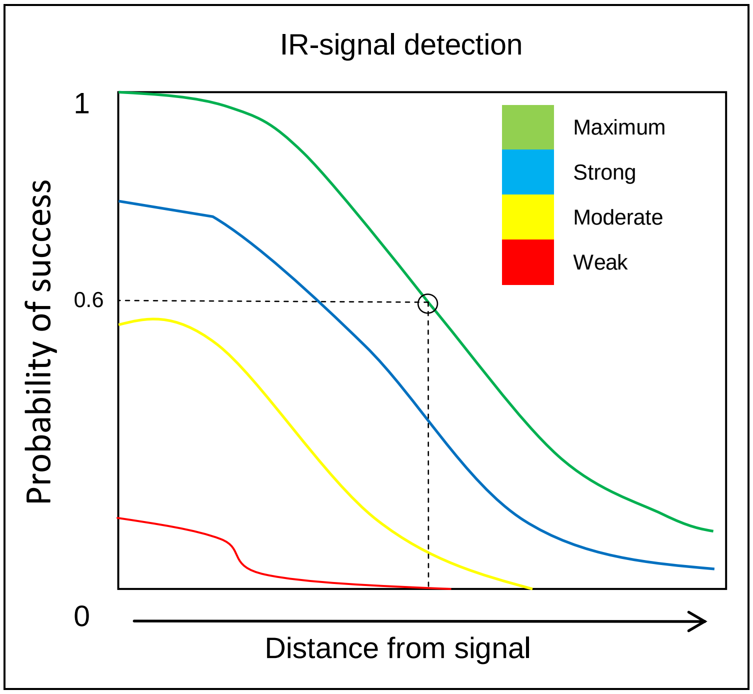


Figure 8. Probabilistic SF.

To determine if a PSF is functional, an analyst will need to examine the conditions and criteria in the probability mass function and find the conditions that most closely match the ones that currently exist on the sub-systems in the PSF. Once the probability of the PSF being functional is determined, a random draw on the probability occurs to see if the PSF is assessed as functional.

4.4.4 System Capabilities

The SC is an independent and measurable performance of the system which is an aggregation of relevant system functions. All SC are observable, measurable, and repeatable. Examples of SC are: travel on roads, fire main gun, and send/receive short-range communications. These capabilities are used to evaluate whether or not the system can accomplish the mission. For example, if the system loses the ability to travel off-road but the mission being evaluated is to conduct a raid in an urban environment, then the loss of this capability would not deter the system from being able to accomplish the mission. The elements of the SC fault trees are the SF that are required to perform the identified capability.

4.4.4.1 Bins. Multiple levels of remaining capability may exist for each SC. These levels of remaining capability are known as "bins." These bins contain all the available levels of performance a SC can have as the system is degraded due to component, sub-system, or SF dysfunction. These bins can be either linearly related, as is the case for attainable speed on roads, or categorical, such as the types of communication that can be sent/received. Both of these forms of SC bins are depicted in figure 9.

Travel on Roads	Damage state
Can travel 31 to 50 mph	Undamaged
Can travel 11 to 30 mph	Two flat tires, on run-flats
Can travel 1 to 10 mph	Four flat tires, on run-flats
NOT possible	Tires completed destroyed

Linear System Capability bins

Communicate short-range	Damage state
Data and voice	Undamaged
Data only	Hand-mike failed
Voice only	Radio computer failed
NOT possible	Radio failed

Categorical System Capability bins

Figure 9. The two forms of the SC bins.

The values assigned to the bins are dependent on the design of the system and on the context of the capability. For example, the speed of a wheeled vehicle is dependent on whether it is designed with either a four- or eight-cylinder engine and in the context of either on- or off-road. In reality, the SC bins are continuous from not capable to max capability. A small to moderate number of discrete bins are chosen as it is theoretically impossible to map the fully inclusive distribution of available bins based on all conditions, contexts, and levels of dysfunction.

A system can exist in only one bin at any given time since the nature of the bins is to be mutually exclusive from each other. If a system if fully functional then it is assigned the highest performance bin within the system function. It cannot also exist in the lower bins because each bin is a representation of the “best” capabilities of the system. If a system were in the top-performance bin and a minimal-performance bin, then it is impossible to determine if the system is fully functional or degraded in some way. In the case of a light-duty pickup truck, the system can lose the ability to travel at a maximum off-road speed if it loses any of the critical system functions, as depicted in figure 10. Either losing a SF or the presence of a lesser (degraded) SF will put the system into a lower-performance SC bin.

4.4.4.2 Categories and Classes. System Capabilities are described in two different contexts: the type of action the SC represents and the temporal nature of the SC of interest. To describe the type of action the SC represents, we group the SC into six distinct categories for ground-combat systems:

- Movement – these are the capabilities that represent the ability for system to move from one location to the next.
- Firepower – these are the capabilities that determine which offensive and/or defensive weapon performances are present for the system.
- Communications.
- Survival – these are the capabilities that determine how well the system will protect both the system and the Warfighter.

- Observations – these are the capabilities that allow the system to determine information such as GPS location, identification of airborne chemicals, sensors, etc.
- Special – these are SC that are unique to a system and are not common, such as “treat critical casualties” for an ambulance vehicle.

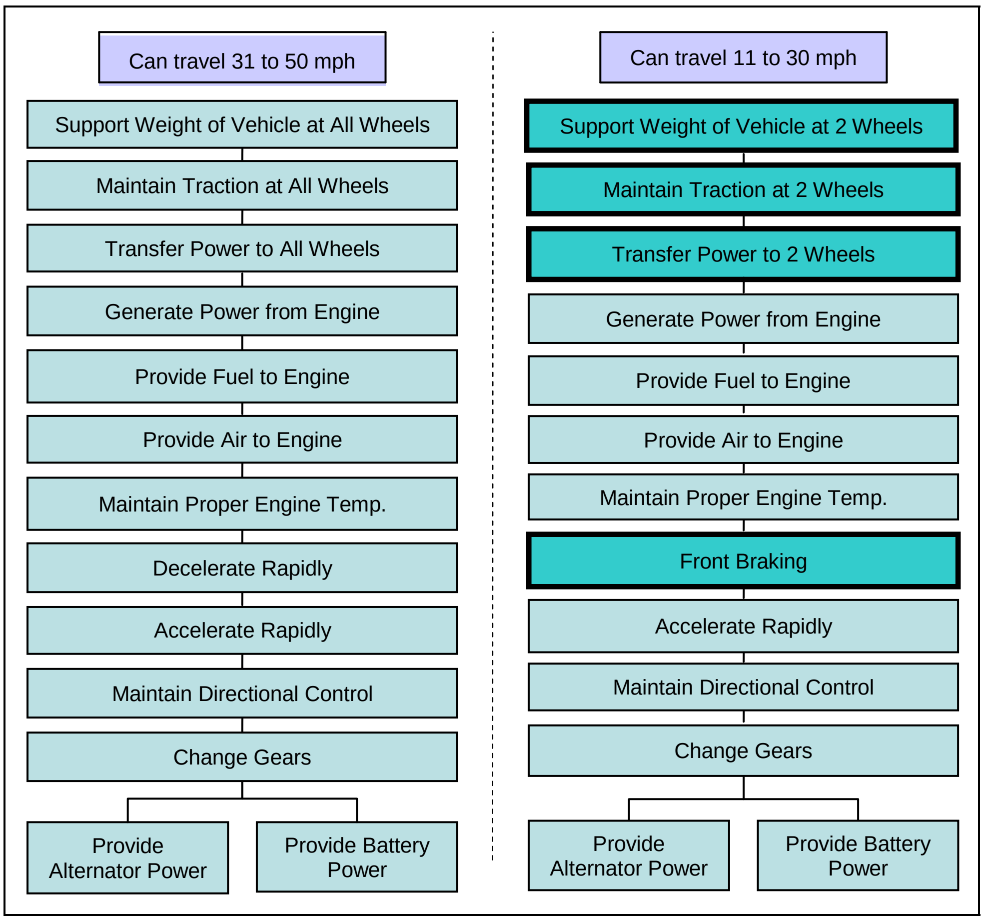


Figure 10. Degraded bins for system capability travel off-road.

Depicted in figure 11 is a sample grouping of system capabilities by category.

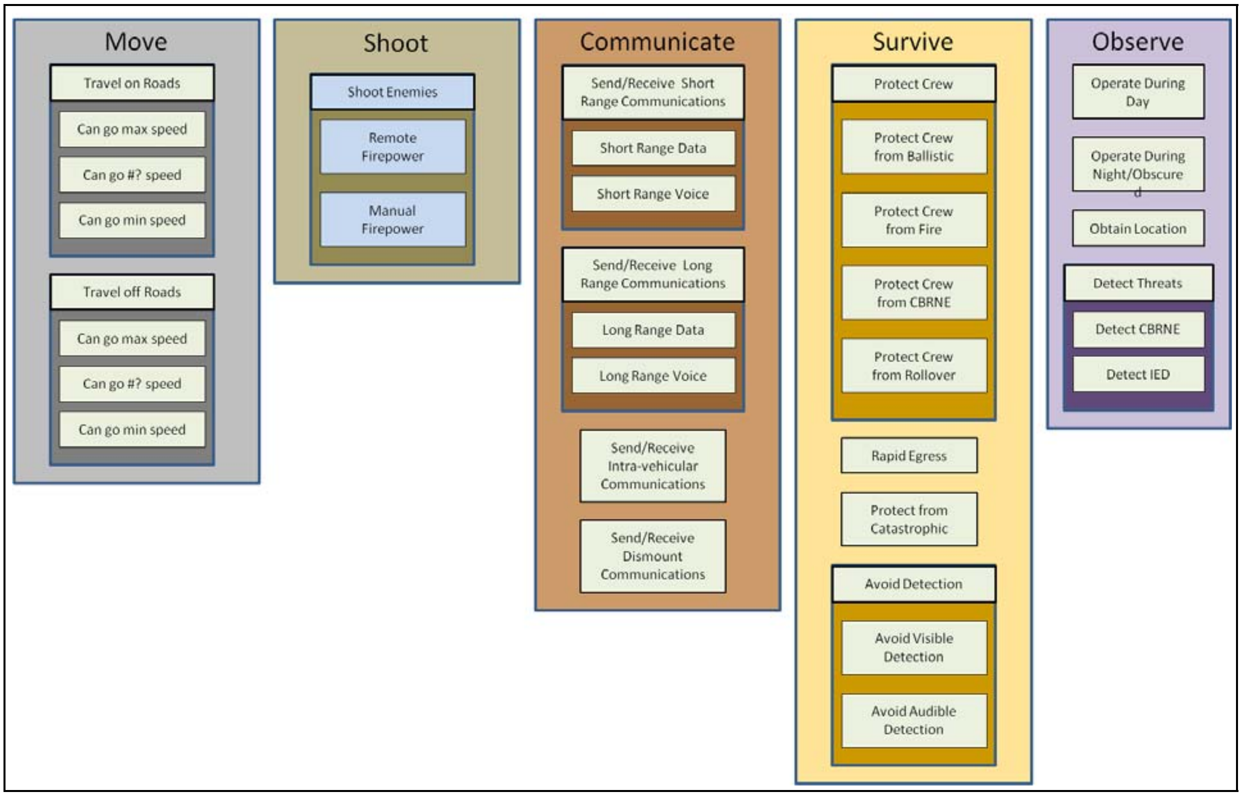


Figure 11. A sample categorical grouping of system capabilities.

To describe the temporal nature of the SC or interest, the SC are grouped into one of two classes: persistent and transitional. The "persistent" class contains SC that are performing continuously for a given context. These are either employed for a sustained period or can be called upon without the system or the performances of the system being modified in some way. Examples of persistent SC are:

- Travel on roads (movement)
- Shoot main weapon (firepower)
- Send/receive short-range communications (communicate)
- Protect crew (survival)
- Detect CBRNE (observations)

Transitional SC are used to change the conditions or state of a system. These SC are usually employed as a single action and would change the performance of the system from one persistent SC to a different SC that is mutually exclusive. Examples of transitional SC are:

- Start engine – transition from "not possible" to "travel on roads at xx-mph."

- Emplace – for a howitzer, this SC allows the system to transition from the inability to fire the main cannon to a state where it can fire the main cannon.

4.4.4.3 Capabilities Common to a Family of Vehicles (FOV) and Variant Specific Capabilities. For an FOV, such as a series of light duty tactical trucks, most of the capabilities will be common across the whole family, as can be seen in figure 12. These common SC include, but are not limited to, capabilities for travel on roads, operate during daytime, protect crew, and communication short range. When special variants exist within the FOV—such as a command and control (C2) variant, or an ambulance variant—then special, variant specific capabilities are defined. For the C2 variant, a special system capability of "maintain satellite communication" is defined which is unique to that variant because it is the only one with a satellite communication requirement. For the ambulance variant, the special system capability of "treat critical casualties" is defined, which includes all of the advance life support equipment and stretcher racks.

	System Capability	**Weapons Carrier**	**Reconnaissance**	**Command and Control**	**Ambulance**
common capabilities	travel on roads	•	•	•	•
	travel off-road	•	•	•	•
	operate during day	•	•	•	•
	operate at night	•	•	•	•
	protect crew	•	•	•	•
	commo long range	•	•	•	•
	commo short range	•	•	•	•
variant specific capabilities	commo satellite			•	
	engage enemies	•	•		
	observe long range		•		
	treat casualties				•

Figure 12. System capabilities grouped by family-common and variant-specific.

Since the variants across the FOV will share the common system capabilities, this significantly reduces effort to analyze these systems. It also allows for a robust analysis across the variants as they jointly execute various missions and tasks.

4.4.5 Mission Task

The mission task (MT) is the operational task that can be achieved when the Warfighter and the system, or the SoS, work in concert. For the U.S. Army, the mission tasks are defined in Field Manual (FM) 7-15: "Army Universal Task List" (*11*). Each MT as defined in FM 7-15 is not tied to any specific system or armed conflict. They are intentionally general so they can be employed using any active system with the required SC in any conflict. Specific examples of mission tasks are:

- Conduct a raid.
- Conduct direct fires.
- Hold an objective position.

The MT is not a level in the functional skeleton but is at least one level above the FS. This is because it is not possible to create an entirely scientific/quantitative map between the SC and the MT. A scientific map can be constructed between the MT and the SC only in the presence of an explicit military doctrine. However, an evaluator or battle commander will determine which doctrine and/or actions are required to complete an objective, and then employ the systems and Warfighters as desired to achieve that objective. This is done based on the current context of the operation, the acceptable risk, and the available resources. The FS will define for the commander or evaluator what systems have particular capabilities and then the commander/evaluator will determine which actions to take based on those capabilities.

This is where the art of warfare comes into play. The ways the task can be executed based on the available capabilities of the systems can change regularly based on the changing/evolving context. In fact, the application of capabilities into mission tasks has been studied as it has evolved over generations of warfare and is expected to change as technology and civilizations adapt. As such, there is no “right” answer for how to employ a system, only the ones that may have a greater chance at success (*12*).

4.5 Including the Warfighter

Every military system consists of the hardware and the personnel that are operating the system. To show how the performance of the system is affected by the performance of the crew, the following two sections will detail how to include personnel in the FS.

4.5.1 Incorporation of the Warfighter Into the Functional Skeleton

With the FS, each person that interacts with the system will be considered a unique and independent sub-system. This allows the personnel to be associated with their respective SF’s in the fault tree. For example, one of the SF for the system capability set of “travel on roads” is “maintain directional control.” For the hardware of the system, the appropriate sub-system is the steering controls. For the crew, the driver is in series with the steering controls, as depicted in figure 13. If for any reason the driver is unable to perform his task, the system will be incapable of traveling on roads regardless of the functional status of the hardware. This highlights the fact that if the Warfighter is able to perform a particular system function, then the Warfighter is considered to be “operationally available.” If the Warfighter is not operationally available, then s/he is considered incapacitated.

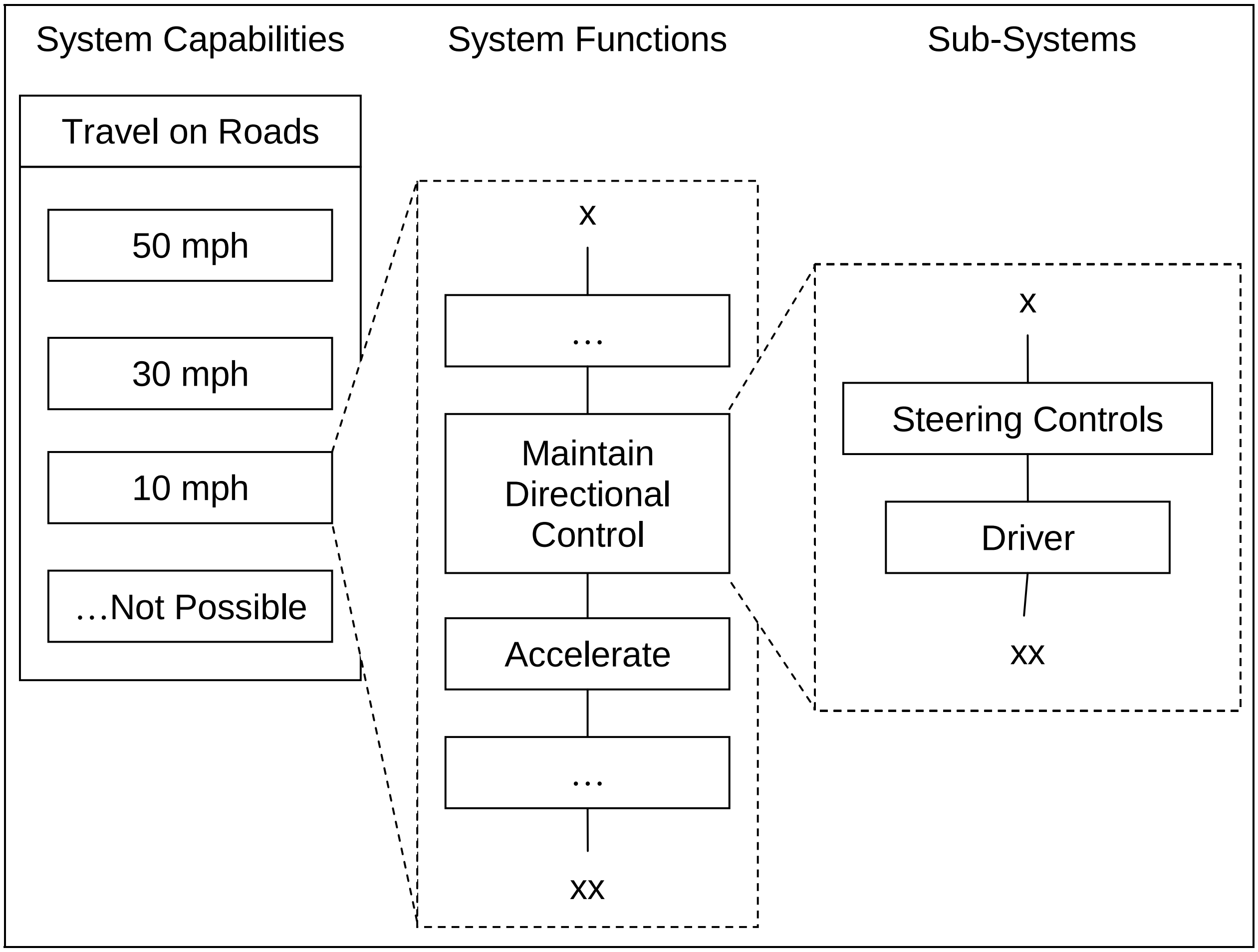


Figure 13. Integration of crew into the FS.

4.5.2 Incapacitation vs. Injury

As described in the previous section, the concept of the driver being a critical element in the capability of the system is a new concept with this methodology. Previous methodologies used injury severity to determine the incapacitation, but these two concepts are different principles. So what is the difference between injury and incapacitation?

Injury simply describes how a human body responds when it is insulted by a threat. In essence, injury is the damage that the human body sustains when attacked, and the severity is rated based on the level of the threat to life on the Warfighter. The scoring system for injury accounts for and assumes the anticipated treatment that would be required in its attempt to quantify the risk to life. Recalling the discussion on the survive category of the system capabilities in section 4.4.4.2, one can see that the injury rating is the metric that is used to determine the bins of how well a system will protect the crew.

Incapacitation is the next evolution of the injury metric, and is considered an additional metric. Incapacitation evaluates the severity and location of the injury and compares it to the performance required to successfully perform the SF or Warfighter task. The Warfighter is considered incapacitated if they are unable to perform the required functions because of their injuries

As the definition of incapacitation is related to injury, it could be easily confused. Two theoretical scenarios are presented to help clarify the difference between the metrics.

- Scenario 1: A Warfighter is assigned the responsibility of guarding a convoy with a heavy machine gun. In this assignment, the ability to "fire M2 machine gun" would have the structure depicted in figure 14 for "engage enemies." As can be seen, the Warfighter must be operationally capable for the "engage enemies" system capability to be available. Assume that the Warfighter receives a "severe" injury to one leg. In this case, the SC of "protect crew" would be in a lower bin of "protect 1," but the gunner is still operationally capable of firing his weapon as their hands and eyes were not injured.
- Scenario 2: The same pre-insult situation exists as in scenario 1. In this case, assume wind-blown sand momentarily blinds the gunner. Even though the gunner is not severely injured, the system capability to engage enemies is unavailable because the gunner is unable to aim the weapon.

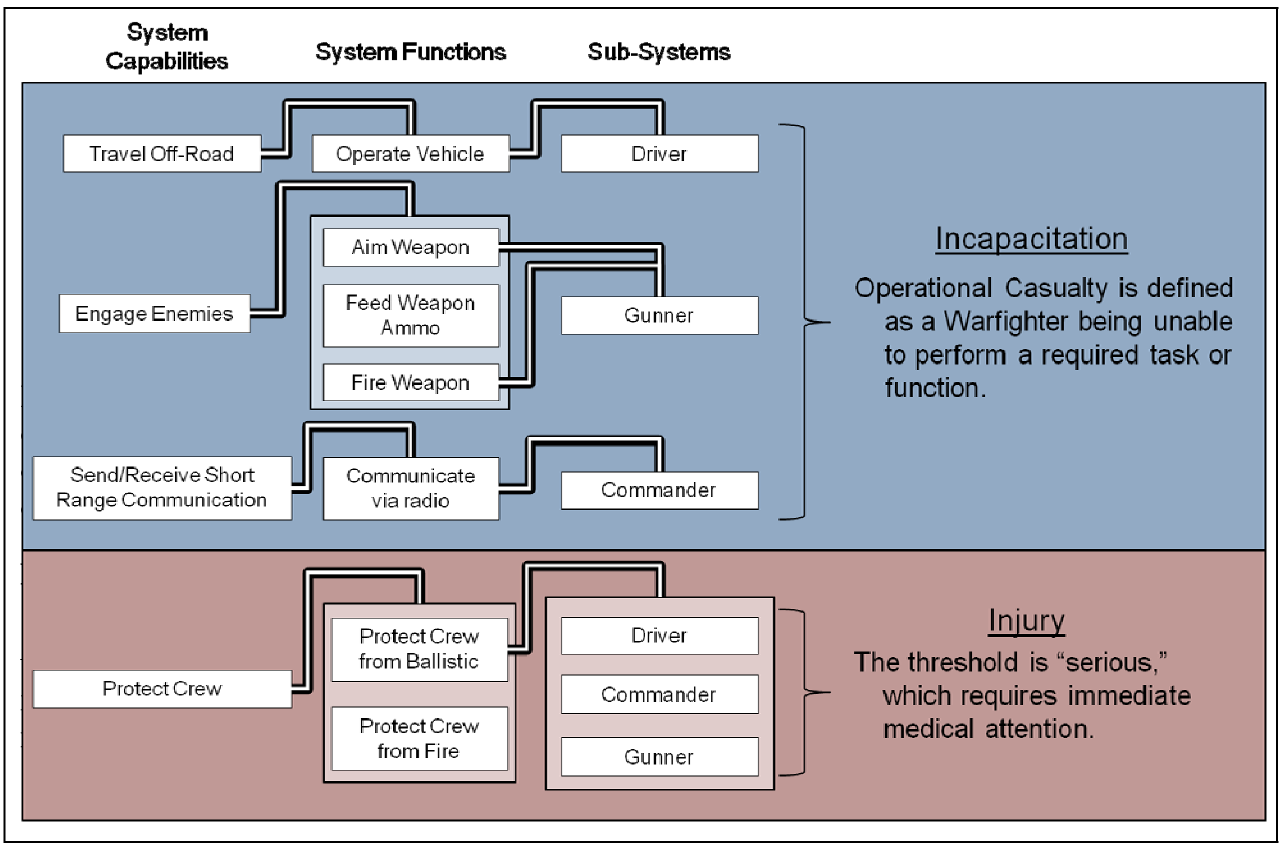


Figure 14. Incapacitation vs. injury within the FS.

Additionally, figure 14 depicts how the "protect crew" system capability would be structured for the light-duty truck.

In all SCAP analyses the injury and the incapacitation evaluation can occur simultaneously. By evaluating the two metrics as described, it is possible to determine exactly what the Warfighter is capable of accomplishing and at the same time how well the system can perform.

4.5.3 Partial Incapacitation Not Addressed With the Current Methodology

If the crew is injured or ill but still able, it is assumed they are still capable but in reality they may perform in a less than optimal state. At this time, the functional skeleton does not incorporate partial performance of the crew, so it is assumed that as long as a crew member is not incapacitated, they are considered fully functional and operationally available.

4.6 Situation Awareness

Situation awareness (SA) involves being aware of what is happening around you, and understanding how information, events, and your own actions will impact your goals and objectives, both now and in the near future. Even though SA is a common term in requirement documentation for new military systems, it is not a system capability.

Depicted in figure 15 is a possible map between SC and SA. Let's say the context is a small convey moving through a potentially hostile urban area. To understand where they are, they need to observe their location. To understand what is happening outside their area of view they need to be able to send and receive regular communication. If a threat is identified, they need to be able to protect themselves from that threat (survive). Decisions are based off of the interpretation of these and other samples of the context and system capabilities. As such, SA is defined as the qualitative aggregation of multiple exclusive SC and is not itself a SC.

4.7 Dynamic Application of the Functional Skeleton

The FS is a static framework of how the system can perform given the specific design and assembly of its components. The FS will not change during a simulation, therefore it can be dynamically applied at any given time state. The diversity of possible sources of dysfunction allows the FS to be applied in any analysis aimed at correlating component function to system capabilities. This allows an evaluator or computer simulation to compile multiple damaging events into a different level of SC after each event. It also allows for multiple sources of component dysfunction to be applied at one time. For example, if a component for movement fails due to a reliability failure, a system may slow down. If it is then attacked, the FS is reapplied at the new state to determine if the system has moved to an even lesser SC bin.

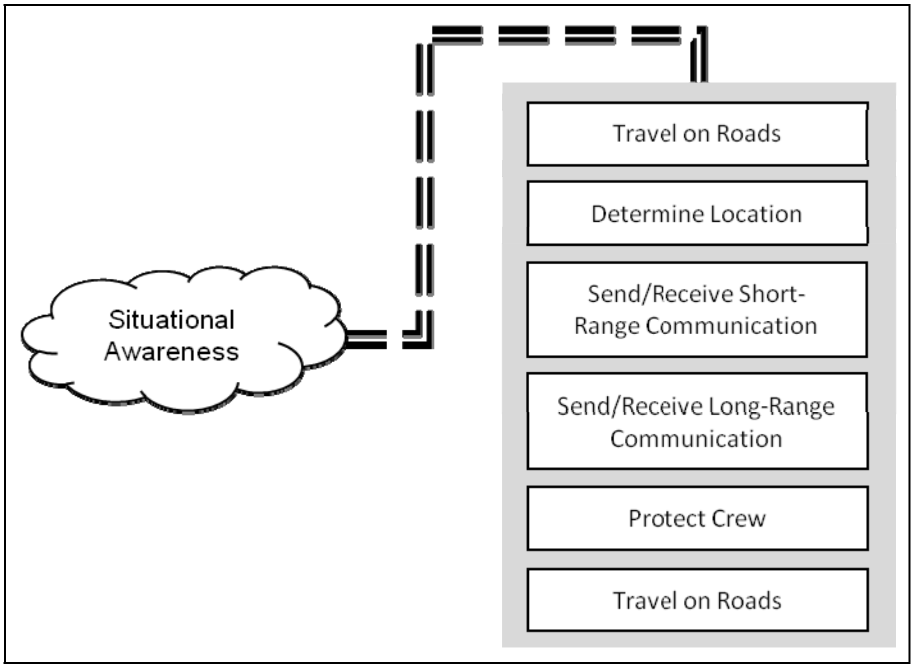


Figure 15. A possible map between situational awareness and system capabilities.

4.8 Application to a System-of-Systems (SOS)

Because of the dynamic nature of the application of the FS, it is possible to employ this methodology to a networked and/or interacting SOS.

4.8.1 Linking Capabilities

It is possible to analyze a system-of-systems using the FS by linking the systems together at the SC level. If two systems are in an operation that is dependent on communications, then the ability to send and receive communications for both systems is linked. An example of this follows in section 5.3.

By using these links, it is possible to evaluate if a communication sent from one system is able to reach other systems. To determine if this communication is received, the information for how communications are hindered and what the probability of success will be are entered as criteria on the link between the two systems. Once the conditions that affect a communication are known, they can be compared to the conditions that exist in the analysis to determine the probability of success. Once the probability is known, a draw is taken on the probability to determine if the linked communication succeeds. Some conditions that could affect the ability to communicate are distance, electronic warfare (EW), and obstructions. As these factors change, they affect the probability that the communication is successful.

Many other system capability categories are linked in a similar manner for a SOS. Table 1 depicts several sample linked capabilities between two interacting systems. These links are not always a static link between two distinct systems, but could be a dynamic link between many systems that forms when two systems interact.

Table 1. Linked system capabilities.

Categories	First System SC	Second System SC
Firepower/survival	Fire cannon	Protect crew
Observation	Conceal IR signal	Detect IR signal
Communications	Send/receive data communications	Send/receive data communications

4.8.2 Array Capabilities

It is possible to build a set of array capabilities (AC) for a collection of systems working together for a specific purpose by utilizing linked capabilities. If multiple systems are working in concert, then the compilation of their capabilities into the AC defines for the evaluator/commander what the unit is capable of executing. As an example, consider the map in figure 16 that depicts the movement of two main battle tanks. Notice how the speeds of all the tanks will combine into the AC for the unit. If for some reason one tank loses the ability to maintain a higher-speed bin and the commander intends all the systems in the unit to stay together, then the unit will have to slow down to match the speed of the degraded tank. For the array, this results in the AC to be assessed in a lesser performing AC bin. The same kind of mapping can occur for all of the other SC categories.

This ability to build array capabilities also allows for dissimilar systems to be analyzed together in a SOS. Assume the analyst is looking at an array of vehicles that contain communications equipment, air-defense, perimeter-defense, long-range fire support, and C2 systems. By linking the capabilities of these systems together, it is possible to build a map between the individual system capabilities and the array capabilities. This allows the analyst to determine how the loss of the critical components in one system will affect the capabilities of the whole array.

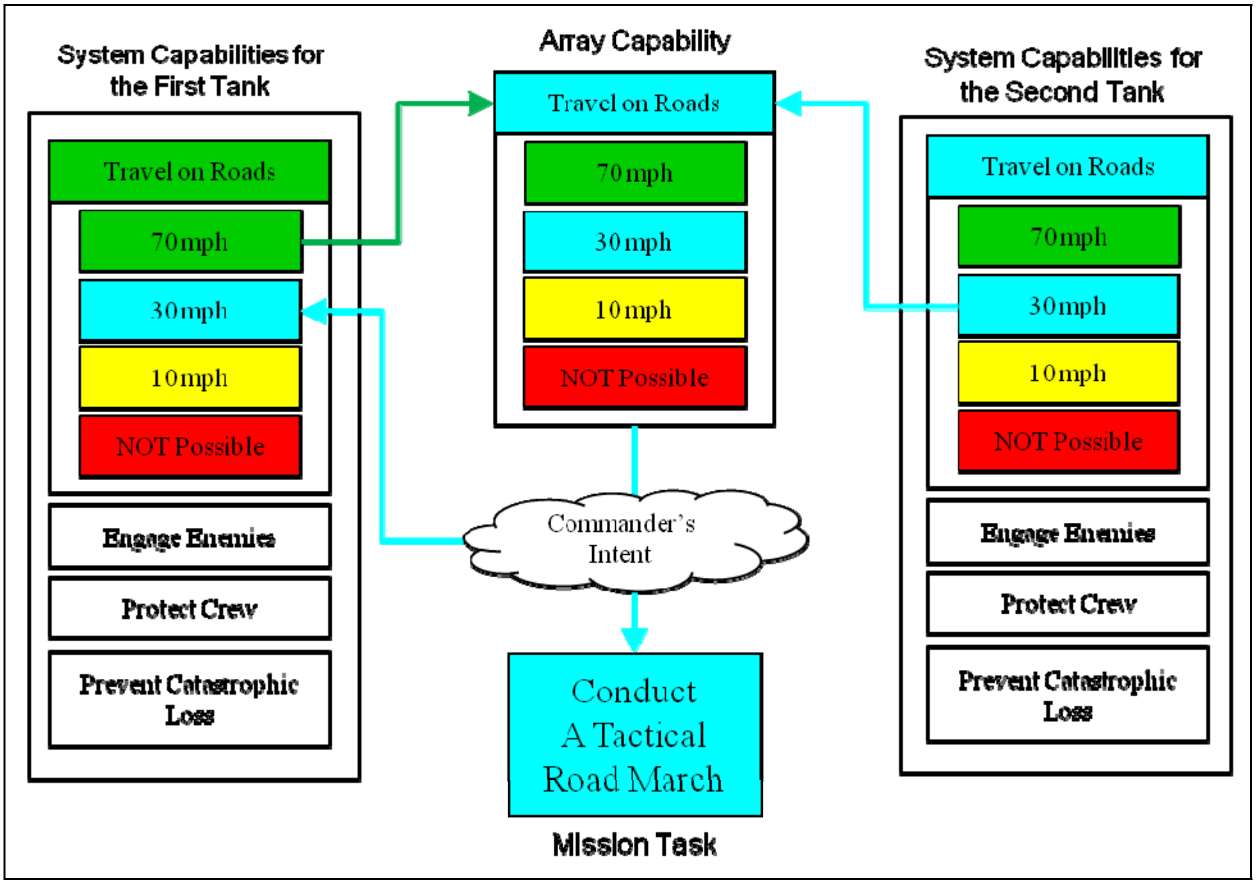


Figure 16. An array capabilities for the speed of a unit of tanks.

5. Examples of the Application of the Functional Skeleton

5.1 A Brief Overview of the Missions and Means Framework

SCAP can be used to model the relationships between two systems in a force-on-force engagement. To represent the actions and timing in this engagement, the missions and means framework (MMF) will be employed in collaboration with SCAP. MMF is a well-documented construct and is a foundation principle of Dietz et al. (*13*). The seven levels of MMF are depicted in figure 17. As MMF is well-documented, it will not be thoroughly explained in this report; however, a brief explanation follows.

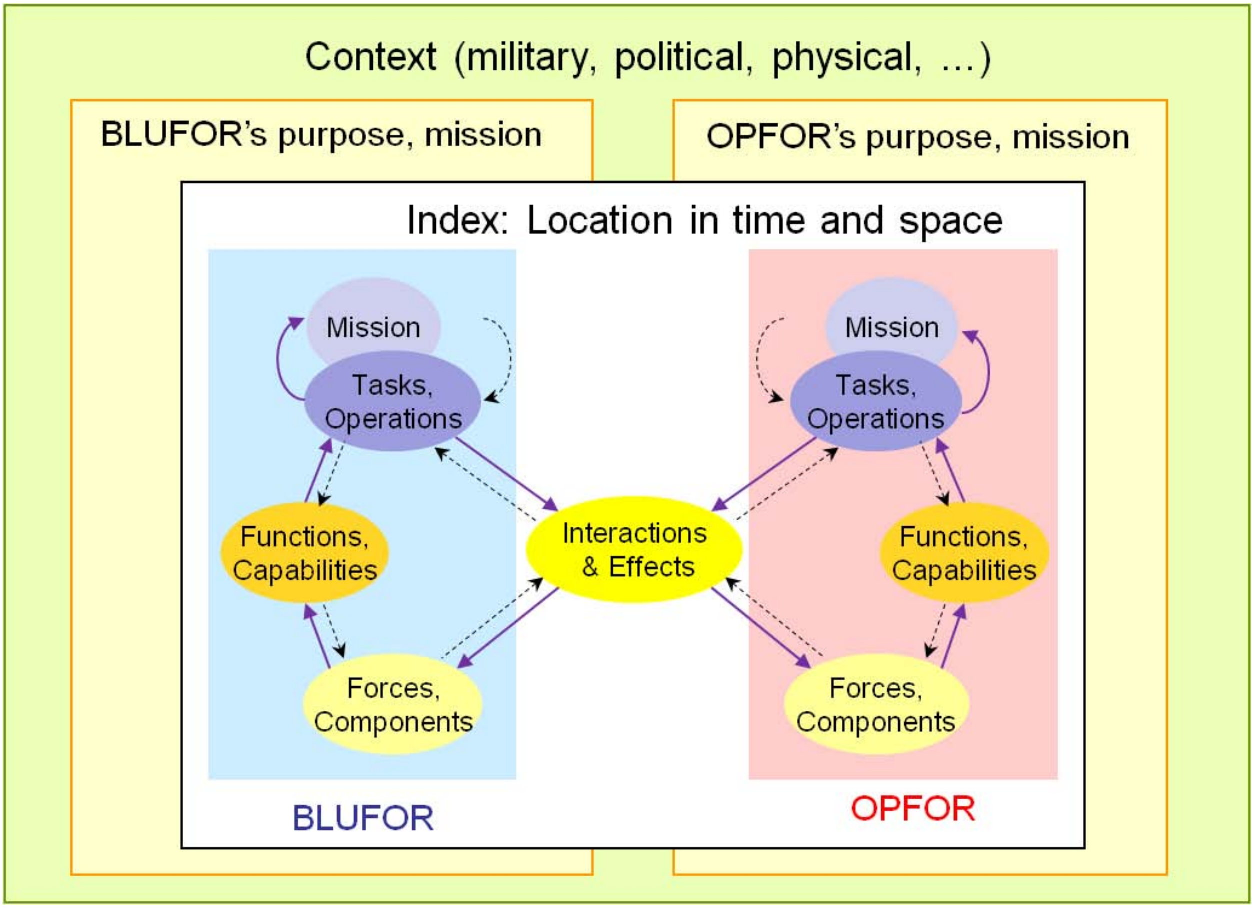


Figure 17. The missions and means framework.

MMF is depicted in the second chapter of the above-mentioned book and is a construct of three underlying paradigms. The first paradigm defines the relationships of a system's component damage state, through a system's capabilities, to the system's combat utility. The second paradigm is how systems, as they engage and interact with each other, either improve or degrade components and capabilities of another system via their respective combat utility. The third paradigm is focused on the larger scale operations. As the component damage state and the combat utility of the hardware changes through interactions, the effects will integrate into the higher-level relationships that will affect changes to the mission, purpose, and context. It can be noted that MMF is not a static process, but rather a dynamic application of ever-changing and potentially complex relationships between systems.

5.2 Example—Tanks in Combat

Assume an example of two generic tanks in combat. The initial index of this engagement is depicted in figure 18. It is assumed that the opposition force (OPFOR) tank (tank B) is sitting in defilade in a combat zone. The primary mission of tank B is to wait for a possible tank from the blue force (BLUFOR) and prevent it from entering a specific zone. Assume a BLUFOR tank (tank A) is in the area and unknowingly enters the effective combat range of tank B.

It is assumed that all components of tank B are functioning properly; therefore, it has the capability to observe tank A move into range. A decision is made by the commander of tank B to fire on tank A. At this point, the FS of tank B is referenced to see if tank B has the capability to fire on tank A. As all firepower components and sub-systems are functional; therefore, all SF are functional, tank B is capable of firing on tank A, which is depicted in figure 19. Therefore, tank B fires an anti-tank munition at tank A.

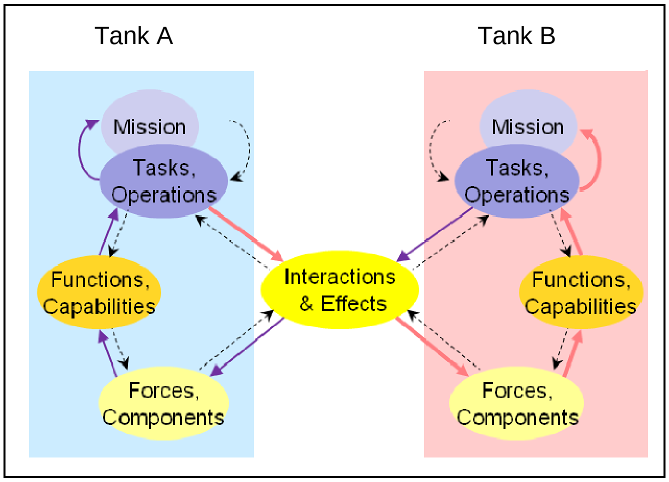


Figure 18. MMF at index 1.

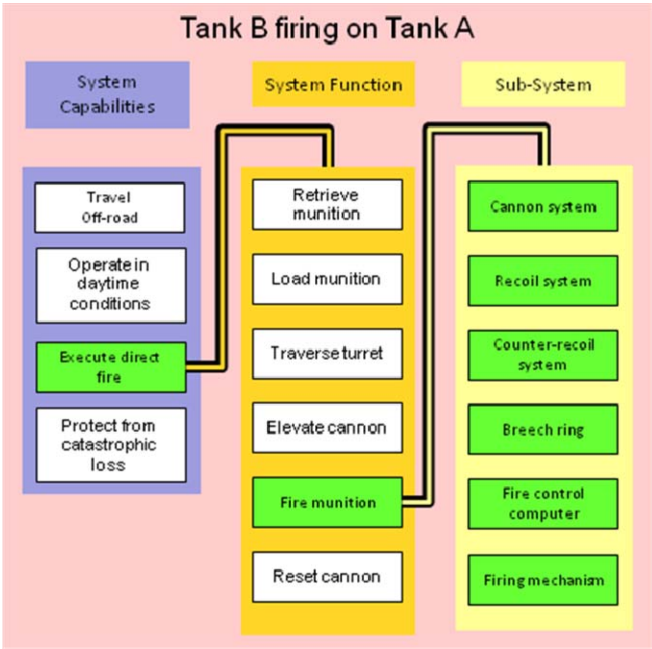


Figure 19. Tank B system capabilities at index 1.

It is possible to show how the decision and action of tank B firing a round will affect tank A. This is done by advancing the index within MMF to the time that the round from tank B impacts tank A, known as index 2 and depicted in figure 20. By utilizing existing methodologies in vulnerability analysis, it is possible to predict the effect of the munition interacting with the components of tank A. The resultant damage state of the components, either functional or dysfunctional, can then be supplied into the FS of tank A. By tracing the effect of dysfunctional components through the fault trees, it is concluded that tank A is unable to travel further. The portion of the FS for tank A, focusing on some of the mobility components, is shown in figure 21.

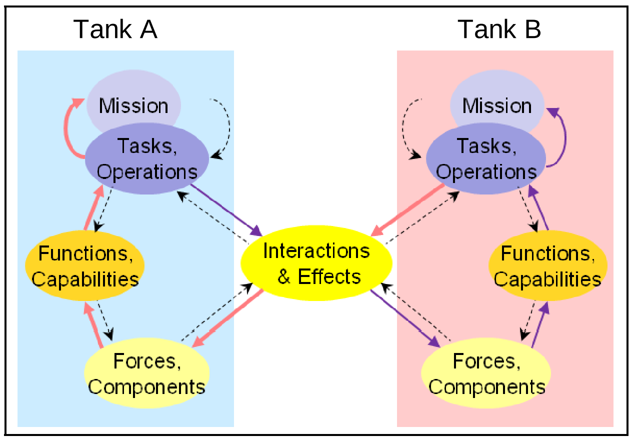


Figure 20. MMF at index 2.

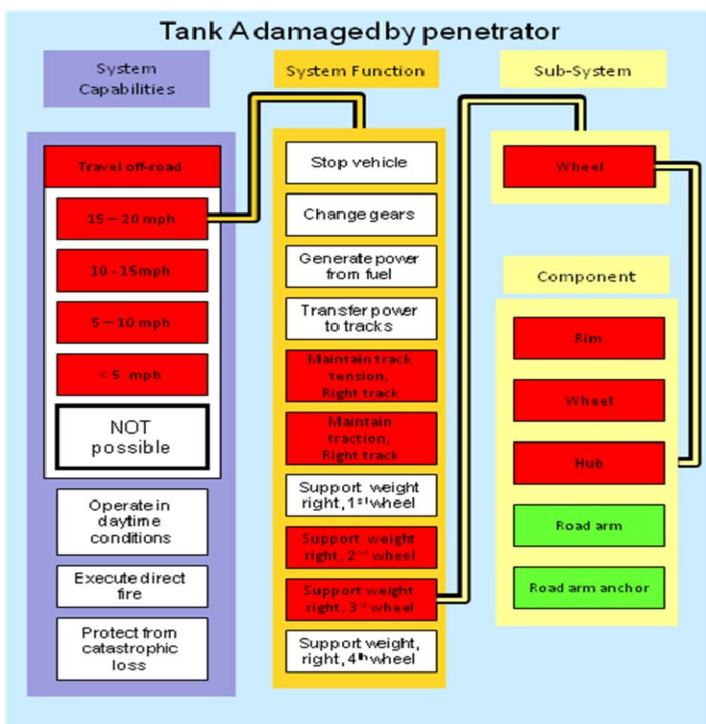


Figure 21. Tank A system capabilities at index 2.

After the damage from the first round is assessed, MMF will advance to the next time index, which is depicted in figure 22. The first interaction between the two tanks did result in a complete loss of capability for tank A to move out of combat zone, but all components for the main gun are undamaged. Therefore, using the FS for tank A as shown in figure 23, it is evident that tank A is able to fire directly on tank B in a return-fire capacity. A decision is made by the commander of tank A to return fire, and a munition is sent down-range to tank B.

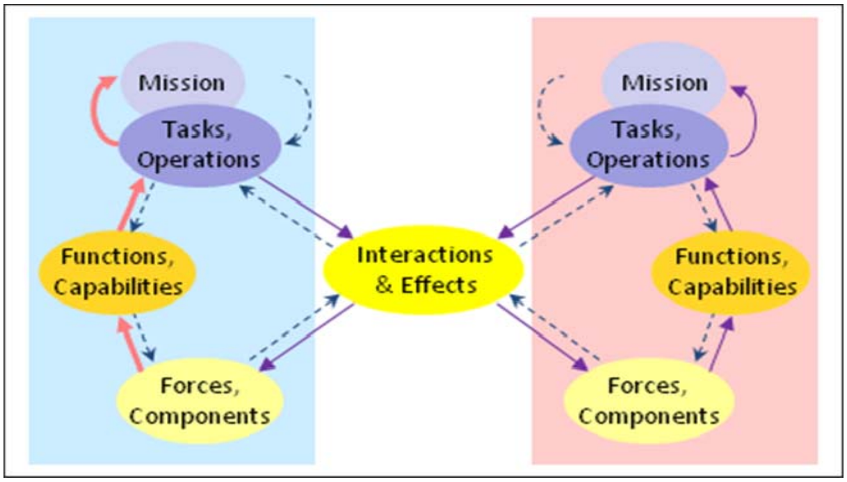


Figure 22. MMF at index 3.

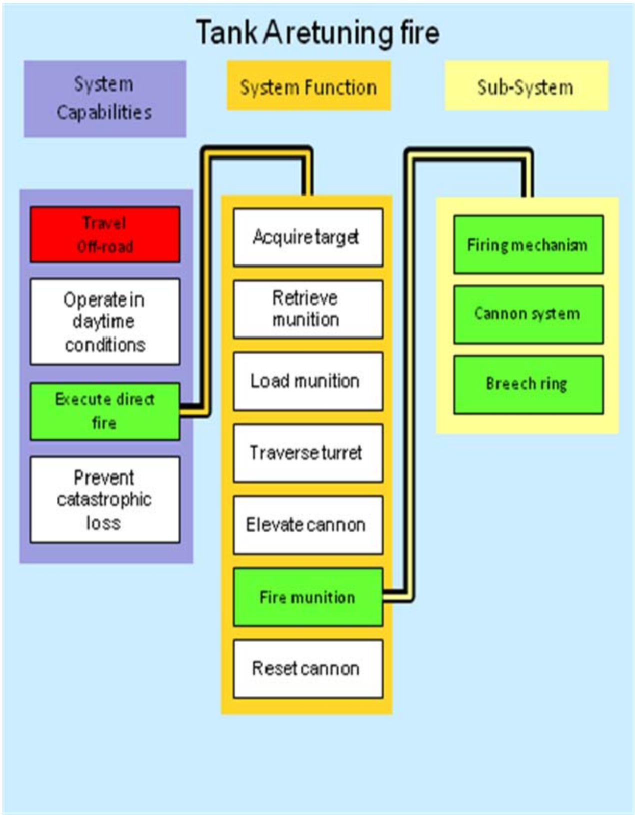


Figure 23. Tank A system capabilities at index 3.

The next time index in MMF is when the round from tank A impacts on tank B, which is depicted in figure 24. By again utilizing existing methodologies, it is possible to determine what components in tank B will be damaged and rendered dysfunctional. In this example, it is assumed that the damaged components will be some form of energetic material inside of tank B and will result in a catastrophic detonation, which is depicted in figure 25.

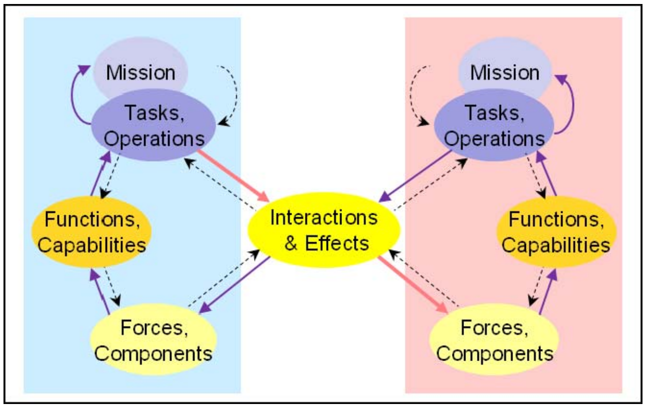


Figure 24. MMF at index 4.

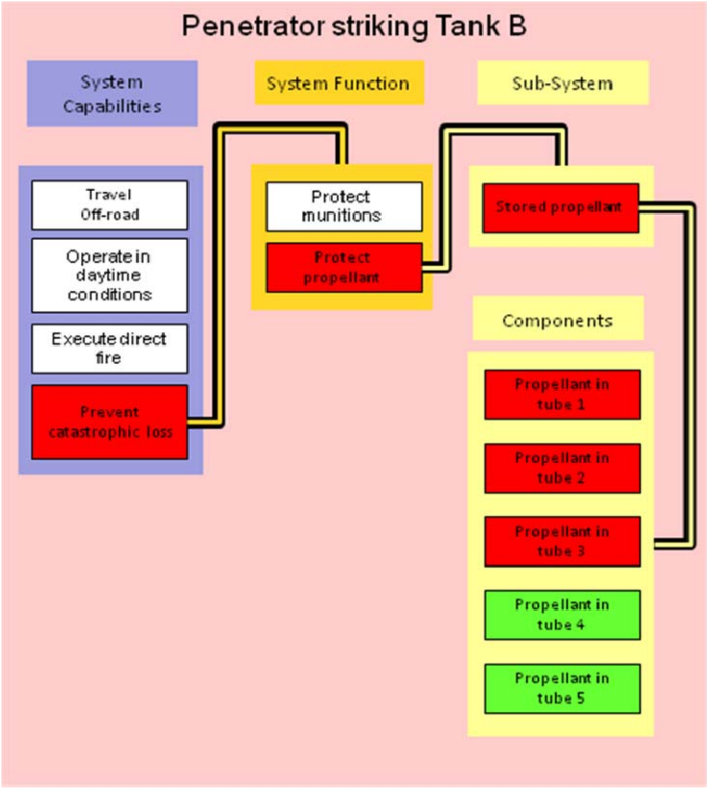


Figure 25. Tank B system capabilities at index 4.

The final time index in this engagement is the resultant state of tank B after the interaction of the munition from tank A interacts with the components of tank B. Because a catastrophic detonation has occurred in tank B, it is assumed all components of tank B are destroyed and, therefore, dysfunctional. Utilizing the FS, one can see that tank B has no remaining SC. By referencing these lost SC into MMF, it is shown that tank B has no remaining combat utility. As tank B is unable to perform any further activities in MMF, it has failed in its missions and is no longer able to affect the outcome of the conflict.

5.3 Example—UAV as a Forward Observer

An example of how SC can be linked will now be explored for an unmanned aerial vehicle (UAV) serving as a forward observer for a self-propelled howitzer in an indirect fire support mission. This example was inspired by an example in Deitz et al. (*13*) where a UAV is serving as a forward observer for a ground combat vehicle when explaining possible ways to depict vulnerability analysis of an SoS.

Assume a UAV is on a persistent surveillance mission in an isolated combat zone. No BLUFOR units are in the vicinity of the UAV's observed zone. As the UAV patrols, the IR sensor on the UAV moves closer to an object on the ground that is emitting an IR signature. We will assume that all components on the UAV are functional (as shown in figure 26), therefore, the IR-sensor system is functional and will use a probability of detection for all signals it encounters. Assume the IR-sensor system is at a known distance from the potential target and the IR signal is strong due to inadequate thermal shielding of the object on the ground. Using the discussion from section 4.4.3.2, we will see that conditions on the UAV (range, signal strength) shows that it is capable of detecting the IR-signature with a success rate of about 60%.

A random draw occurs to see if the UAV detects the target using a Bernoulli trial with a probability of success of 60%. In this case, it is assumed that the Bernoulli trial produces a successful result, and therefore the PSF of "detect signature" is successful and the UAV detects a target of opportunity.

As the UAV has successfully detected a target of opportunity, a communication is to be sent to a fire support battalion. Assuming the components for the antennae sub-system are functional and all other critical communications sub-systems are also functional; therefore, the UAV has the capability to send a long-range communication.

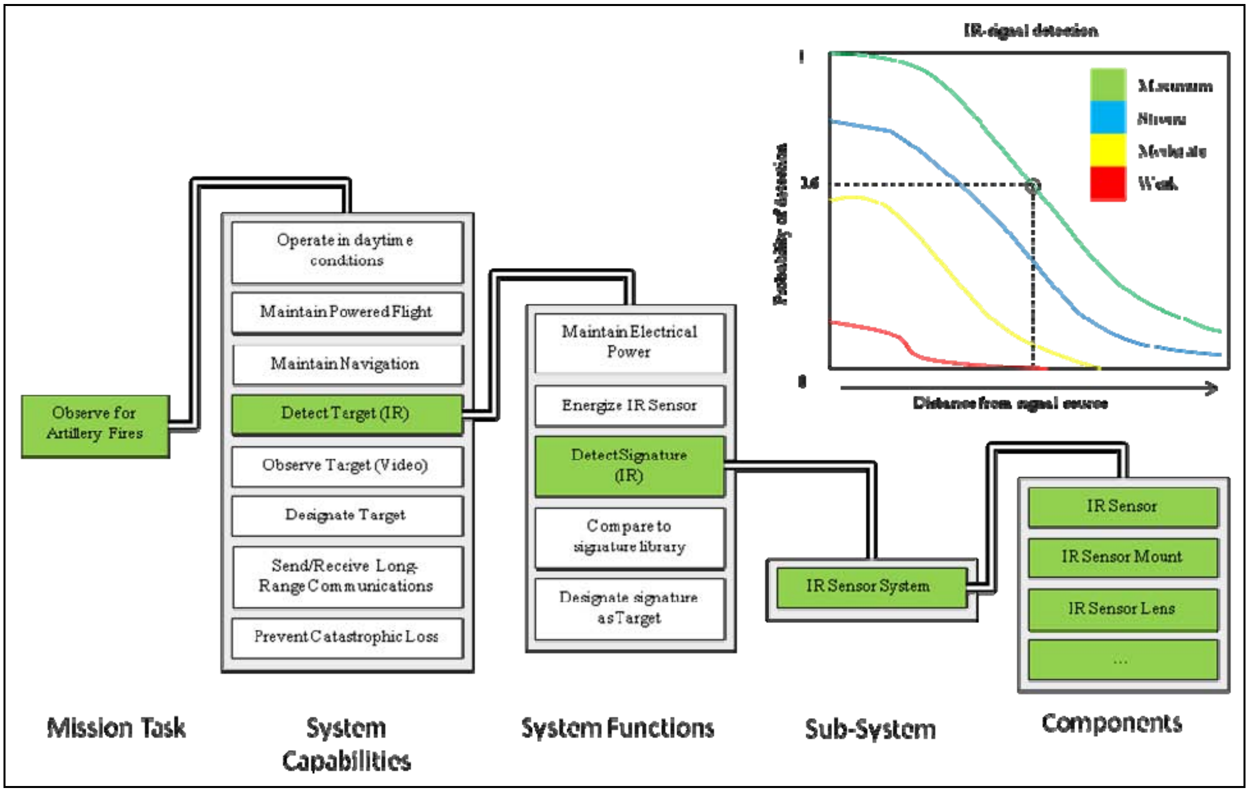


Figure 26. A sample of the UAV functional skeleton.

Changing our attention to the emplaced fire-support battalion, it is assumed that all components critical to communication are functional. Therefore, the SPH of interest is capable of receiving the communication from the UAV. Recalling the sample definition from earlier, we can see in figure 27 that the self-propelled Howitzer (SPH) is capable of firing on the target in an indirect fire mission.

As discussed in this example, and depicted in figure 28, the FS for systems within an SoS are linked by mutual SC. Due to this linkage, it is possible to directly correlate the component state of one system to the capability of a networked system and also to determine the overall effect on a mission vignette. This has not been possible with traditional vulnerability/lethality (V/L) methodologies.

If a critical communications component of either system was dysfunctional, then it would be possible to determine the overall combat utility of the SoS due to the lost communication. In this example, the fire mission would not occur and a mission to suppress hostile activity in a remote region would be unsuccessful, even though one system would be fully functional.

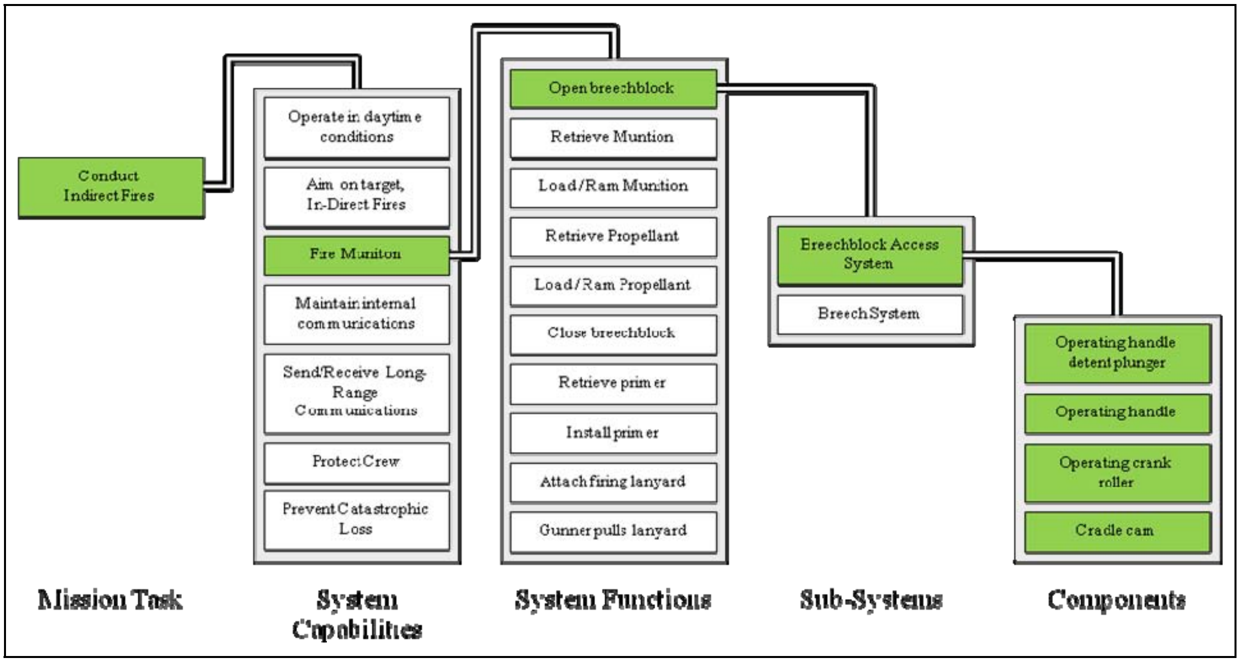


Figure 27. A sample of the SPH functional skeleton.

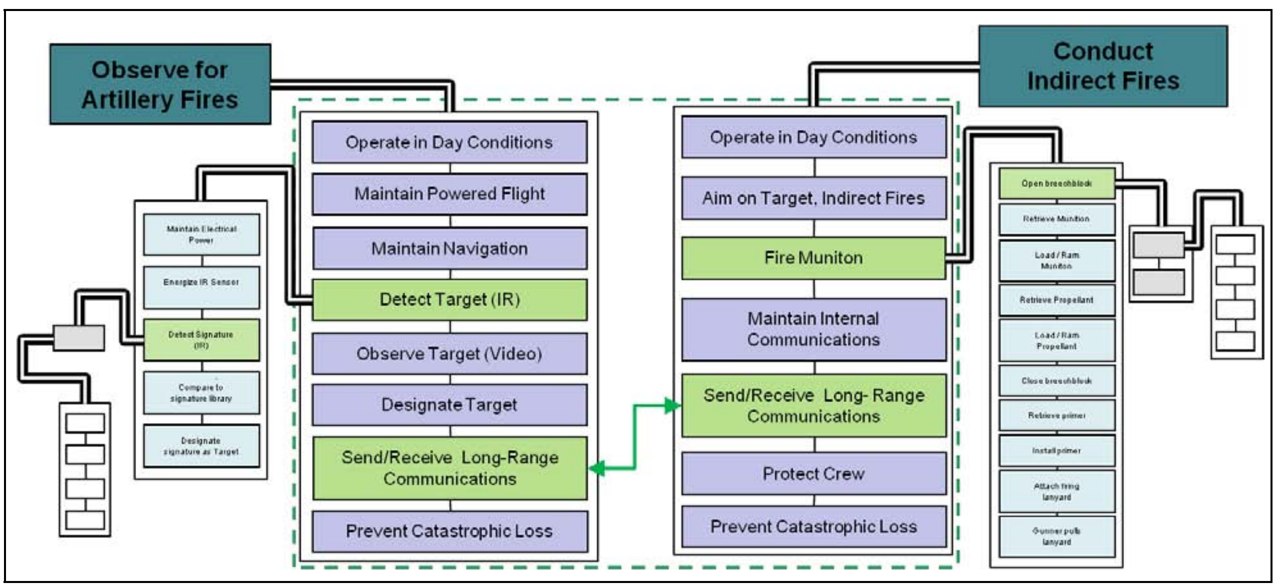


Figure 28. A sample of the linked capabilities.

6. Mathematical Representation the Functional Skeleton

6.1 Representing a Single System by Vectors

Now that several examples have been shown on how the functional skeleton can be used in a SoS using a storyboard approach, the mathematical treatment of the methodology within a SoS is discussed.

Recalling the discussion in section 3 about how elements in a fault tree are represented, as well as the discussions of the various levels of the FS in sections 4.4.1 through 4.4.4, each element within the FS is therefore represented as an element with the following nomenclature:

$C_i \equiv$ a specific component

$SF_i \equiv$ a specific system function

$SC_i \equiv$ a specific system capability

When the criticality analysis is complete, all components that are required for the system to function as the Warfighter intends will be known. Assume that the total count of critical components is assigned the variable of "*n*".

$n \equiv$ total count of critical components

Each critical component will be assigned an element identifier, as depicted in the following table:

C_1 = left-front tire
C_2 = left-front wheel
C_3 = engine block
C_4 = transmission block
C_5 = fuel pump
…
C_n = *the last critical component*

It is now possible to take the collection of component elements and compile them into a vector as depicted in equation 5. Recalling the earlier discussion of dysfunction, each component C_i will be represented as either a "0" or a "1" depending on its current functional state.

$$\vec{\mathbf{C}} \equiv \begin{Bmatrix} \text{left front tire} \\ \text{left front wheel} \\ \text{engine block} \\ \text{transmission block} \\ \text{fuel pump} \\ \ldots \\ \textit{last critical comp} \end{Bmatrix} \equiv \begin{Bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \\ \ldots \\ C_n \end{Bmatrix} = \begin{Bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ \ldots \\ 1 \end{Bmatrix}. \tag{5}$$

As $\vec{\mathbf{C}}$ is a vector, it is equivalent to a one-dimensional matrix with dimensions $n \times 1$. A similar construct exists for all system functions and system capability bins within the functional skeleton.

$$\overrightarrow{\mathbf{SF}} \equiv \begin{Bmatrix} \text{Support weight at left-front wheel} \\ \text{Generate power from fuel} \\ \text{Transfer power to left-front wheel} \\ \text{Maintain lubrication} \\ \text{Maintain directional control} \\ \ldots \\ \textit{last critical system function} \end{Bmatrix} \equiv \begin{Bmatrix} SF_1 \\ SF_2 \\ SF_3 \\ SF_4 \\ SF_5 \\ \ldots \\ SF_n \end{Bmatrix} = \begin{Bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ \ldots \\ 1 \end{Bmatrix}. \tag{6}$$

$$\overrightarrow{\mathbf{SC}} \equiv \begin{Bmatrix} \text{Travel on roads 50mph} \\ \text{Send/Receive short-range communictaions} \\ \text{Operate in night conditions} \\ \text{Protect crew from "}xx\text{"} \\ \text{Haul load} \\ \ldots \\ \textit{last critical system capability} \end{Bmatrix} \equiv \begin{Bmatrix} SC_1 \\ SC_2 \\ SC_3 \\ SC_4 \\ SC_5 \\ \ldots \\ SC_n \end{Bmatrix} = \begin{Bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ \ldots \\ 1 \end{Bmatrix}. \tag{7}$$

Every system within a SoS simulation will be represented by a vector set which includes the $\vec{\mathbf{C}}$, $\overrightarrow{\mathbf{SF}}$, and $\overrightarrow{\mathbf{SC}}$ vectors for that system. The decisions within the SoS will be based on the availability depicted within the $\overrightarrow{\mathbf{SF}}$ and $\overrightarrow{\mathbf{SC}}$ vectors, and the component availability will be represented within the $\vec{\mathbf{C}}$ vector. When a battlefield threat or other interaction occurs on the components in the $\vec{\mathbf{C}}$ vector and changes their values, then the FS can be used as a transfer function that adjusts the values in the $\overrightarrow{\mathbf{SF}}$ and $\overrightarrow{\mathbf{SC}}$ vectors. This allows for the systems to be dynamically interrogated and greatly simplifies the constructs required to represent the systems within a simulation.

How will the transfer functions be compiled for the construction of the $\overrightarrow{\mathbf{SF}}$ and $\overrightarrow{\mathbf{SC}}$ vectors? Simply stated, they are the relationships that are defined in the functional skeleton and are depicted mathematically as described in section 3. For a generic system with a known $\vec{\mathbf{C}}$ vector, the $\overrightarrow{\mathbf{SF}}$ and $\overrightarrow{\mathbf{SC}}$ vectors are compiled as depicted in equations 8 and 9. As the component state in the vector $\vec{\mathbf{C}}$ changes, the equations embedded as the transfer functions within the $\overrightarrow{\mathbf{SF}}$ and $\overrightarrow{\mathbf{SC}}$ vectors will adjust the corresponding values to either a “1” or a “0”.

$$\overrightarrow{\mathbf{SF}} \equiv \left\{ \begin{matrix} \text{Support weight at left-front wheel} \\ \text{Generate power from fuel} \\ \text{Transfer power to left-front wheel} \\ \text{Maintain lubrication} \\ \text{Maintain directional control} \\ \ldots \\ \textit{last critical system function} \end{matrix} \right\} \equiv \left\{ \begin{matrix} SF_1 \\ SF_2 \\ SF_3 \\ SF_4 \\ SF_5 \\ \ldots \\ SF_n \end{matrix} \right\} \equiv \left\{ \begin{matrix} C_1 \cdot C_2 \\ C_2 \cdot C_5 \\ C_3 \\ \ldots \\ \ldots \\ \ldots \\ C_n \end{matrix} \right\} = \left\{ \begin{matrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ \ldots \\ 1 \end{matrix} \right\}. \tag{8}$$

$$\overrightarrow{\mathbf{SC}} \equiv \left\{ \begin{matrix} \text{Travel on roads 50mph} \\ \text{Send/Receive short-range communictaions} \\ \text{Operate in night conditions} \\ \text{Protect crew from "}\textit{xx}\text{"} \\ \text{Haul load} \\ \ldots \\ \textit{last critical system capability} \end{matrix} \right\} \equiv \left\{ \begin{matrix} SC_1 \\ SC_2 \\ SC_3 \\ SC_4 \\ SC_5 \\ \ldots \\ SC_n \end{matrix} \right\} \equiv \left\{ \begin{matrix} SF_1 \cdot SF_2 \cdot SF_3 \cdot \ldots \\ \ldots \\ \ldots \\ \ldots \\ \ldots \\ \ldots \\ \ldots \end{matrix} \right\} = \left\{ \begin{matrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ \ldots \\ 1 \end{matrix} \right\}. \tag{9}$$

6.2 Vector Representation of an Array of Systems

Recalling the discussion of linking capabilities in section 4.8.1 as well as the UAV/SPH example in section 5.3, it is possible to explain how the mathematical representation of single systems can be expanded into the mathematical representations of array capabilities, which were presented in section 4.8.2.

If we represent the UAV and the SPH by their respective $\overrightarrow{\mathbf{SC}}$ vectors, as shown in equations 10 and 11, then it is possible to create the array capabilities from the independent systems by having the $\overrightarrow{\mathbf{SC}}$ vectors linked as shown in equation 12. In this equation, λ is defined as all of the conditions that exist between the UAV and the SPH. As λ changes, so will the array capabilities.

$$\overrightarrow{\mathbf{SC}_{UAV}} \equiv \left\{ \begin{array}{c} \text{Operate in daytime conditions} \\ \text{Maintain powered flight} \\ \text{Maintain navigation} \\ \text{Detect target (IR)} \\ \text{Observe target (video)} \\ \text{Designate target} \\ \text{Send/Receive long-range communications} \\ \text{Prevent catastrophic loss} \end{array} \right\} \equiv \begin{Bmatrix} SC_{\text{UAV 1}} \\ SC_{\text{UAV 2}} \\ SC_{\text{UAV 3}} \\ SC_{\text{UAV 4}} \\ SC_{\text{UAV 5}} \\ SC_{\text{UAV 6}} \\ SC_{\text{UAV 7}} \\ SC_{\text{UAV 8}} \end{Bmatrix} = \begin{Bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{Bmatrix}. \qquad (10)$$

$$\overrightarrow{\mathbf{SC}_{\text{SPH}}} \equiv \left\{ \begin{array}{c} \text{Operate in daytime conditions} \\ \text{Aim on target, indirect fires} \\ \text{Fire munition} \\ \text{Maintain internal communictions} \\ \text{Send/Receive long-range communications} \\ \text{Send/Receive short-range communications} \\ \text{Protect crew} \\ \text{Prevent catastrophic loss} \end{array} \right\} \equiv \begin{Bmatrix} SC_{\text{SPH 1}} \\ SC_{\text{SPH 2}} \\ SC_{\text{SPH 3}} \\ SC_{\text{SPH 4}} \\ SC_{\text{SPH 5}} \\ SC_{\text{SPH 6}} \\ SC_{\text{SPH 7}} \\ SC_{\text{SPH 8}} \end{Bmatrix} = \begin{Bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{Bmatrix}. \qquad (11)$$

$$\overrightarrow{\mathbf{SC}_{\text{Array}}} \equiv f\left(\overrightarrow{\mathbf{SC}_{\text{UAV}}}, \lambda, \overrightarrow{\mathbf{SC}_{\text{SPH}}}\right). \qquad (12)$$

7. Construction of the Functional Skeleton

The FS is a framework that contains information about the design of system. So how does an analyst construct the FS?

The answer is rather straightforward: it depends on what information you know about the system. If the design of the system is known, then the analyst will start the construction from the components and move up to the capabilities. If the required tasks, capabilities, and/or performance requirements are known, then the analyst will decompose from the SC to the SF and then identify what sub-systems, and possibly the components, are required to produce these capabilities. It is also possible to employ both approaches in a hybrid manner: if the design is known and the required capabilities are defined, then the map can be compiled from both ends to determine if the design of the system matches the requirements for the system.

For the SC bins, it is best to first create the top-performance bin within each SC. Once the top bin is known, then it is usually far easier to copy the bin into a lesser bin and remove the SF that are required for the higher bin and not required for the lesser bin. There may be times when a specific SF will be added to a lesser bin that is required to maintain the degraded state, but is not required to perform in a higher bin. One example of this would be the application of a secondary braking system only if the primary has failed.

In all SC, it is necessary to add a bin at the bottom of the series that is the “not possible” bin. Most of the time, these bins will contain no SF and are the default result assessed if all other SC bins are lost. These “not possible” bins are required for two reasons: the first is that if all capabilities are lost, then the only possible performance is a “not possible.” The second reason is a mathematical requirement: if the frequencies of all bins are added up, including the “not possible” bin, then the result should equal 100%. This allows an analyst to determine the critical hardware that causes a total system failure and also determine the frequency of these occurrences for a given condition.

8. Next Steps

A series of next steps are already planned since SCAP is continuing to evolve.

8.1 Methodology

Two main shortcomings have yet to be addressed at the time of this report’s composition. The first is the ability to handle time-dependant degradation of SC’s. For this concept to be accurately represented, the variable representing time after a component becomes dysfunctional needs to be incorporated into the results of when a related SC will become dysfunctional. At this time, an untested abstract has been proposed and will be pursued to check for its validity.

The second construct that needs to be explored is how to represent crew that will adjust their positions and roles when a fellow crew member becomes injured or incapacitated. As was seen in section 4.5, crews are an important component for the system capabilities. In combat, a critical system capability that is lost due to a Warfighter incapacitation will be restored by an operationally capable Warfighter, assuming the required switch is possible. Again, an untested abstract has been proposed and will be pursued to test its validity.

8.2 Applications

At the time of this writing, several applications for SCAP have already been identified. The two primary customers of SCAP and the ES are the U.S. Army Test and Evaluation Command’s (ATEC) mission-based test and evaluation (MBT&E) and ARL/SLAD’s system of systems survivability simulation (S4). Both are looking to incorporate the FS, albeit in different manners.

Also in ARL, the Human Research and Engineering Directorate (HRED) is currently explorating a potential application of SCAP for human-factor studies. Finally, it appears that SCAP will be able to merge with reliability analysis, and is currently in a very early stage of investigation.

8.3 Documentation

Because SCAP methodology and applications are continuing to evolve, it is anticipated a number of follow-on documents will be presented that will go “in-depth” on various topics. Also anticipated is a follow-on document that will supersede this report when the issues identified in section 8.1 are resolved and various trials are completed.

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List of Symbols, Abbreviations, and Acronyms

AC	array capability
ARL	U.S. Army Research Laboratory
ATEC	U.S. Army Test and Evaluation Command
AUTL	Army Universal Task List
BLUFOR	blue force
C	component
C2	command and control
CA	criticality analysis
CBRNE	chemical, biological, radiological, nuclear, and electromagnetic
DOD	U.S. Department of Defense
EW	electronic warfare
FM	field manual
FOV	family of vehicles
FS	functional skeleton
GPS	global positioning system
HRED	Human Research and Engineering Directorate
IR	infra-red
LFT&E	live fire test and evaluation
LOF	loss of function
M2	machine gun, Browning 0.50 caliber
MBT&E	mission-based test and evaluation
MMF	missions and means framework
MT	mission task
OPFOR	opposition force

PSF	probabilistic system functions
S4	systems of systems survivability simulation
SA	situational awareness
SC	system capability
SCAP	system capabilities analytic process
SF	system function
SLAD	Survivability/Lethality Analysis Directorate
SOS	system of systems
SPH	self-propelled Howitzer
SS	sub-system
T&E	test and evaluation
UAV	unmanned aerial vehicle
V/L	vulnerability/lethality

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