



# **Systems Engineering for Contingency Basing**

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# 1 INTRODUCTION

Tactical Small Units (TSU) (battalion [300-1000 soldiers] and below) currently establish non-standardized base camps for contingency operations (contingency basing), potentially limiting their ability to efficiently employ Full Spectrum<sup>1</sup> operations by placing the TSU with reduced capability. The TSU may not be able to effectively support the modern Full Spectrum battlefield demands unless contingency basing capabilities specific to the TSU are combined as a single, integrated, agile, force projection platform. A contingency base should provide Soldiers with an effective, logistically supportable, affordable, and rapidly deployable environment to project force across the Full Spectrum of operations. The U.S. Army Research, Development and Engineering Command (RDECOM) and the various Program Executive Office (PEO) and Program Management (PM) stakeholders working together must develop a contingency basing capability – along with a development planning process -- that will enable an Army enterprise approach to capability delivery for the tactical edge with total system integration aligned to Army Modernization strategies and ARFORGEN (Army FORce GENeration). As such, the U.S. Army's transformation and force structure changes have resulted in a reduced capability regarding training, planning, management and expertise available to the Army units as they establish, maintain, sustain and transition a contingency base through its life cycle.<sup>2</sup>

This research focused on specific aspects of Tactical Small Unit-Contingency Basing (TSU-CB), as a force projection platform and a potential means to address the interrelated individual Soldier and TSU load (cognitive and physical) using methods and tools developed for systems engineering. The research task is to develop a set of interrelated processes, mechanisms, and tools to capture, explain, and manage the complex operational and system interaction posed by the dynamic nature of the TSU operations, along with a means to measure progress. The TSU exhibits a complex, pluralistic, set of requirements across a number of factors ill-suited to standard system engineering practices. Novel means to optimize TSU-CB need to be considered.

The primary operational outcomes being sought are:

- Reduced vulnerabilities and losses: *Human, systems, and information*
- Reduced sustainment demands: *Substantially reduce supply convoy requirements by implementing self-sustaining and “right-sized” basing capabilities with special emphasis on fuel, water and waste.*

<sup>1</sup> The Army defines Full Spectrum operations as the combination of offensive, defensive, and either stability operations overseas or civil support operations on U.S. soil (US Army Training and Doctrine Command, The Army Operating Concept 2016 – 2028, TRADOC Pamphlet 525-3-1, dated 19 August 2010.

<sup>2</sup>

[https://secureweb2.hqda.pentagon.mil/vdas\\_armyposturestatement/2011/information\\_papers/PostedDocument.asp?id=126](https://secureweb2.hqda.pentagon.mil/vdas_armyposturestatement/2011/information_papers/PostedDocument.asp?id=126)

- Cost effective choices and solutions: *Innovation that targets life cycle affordability; sustainment cost savings re-directed to resource DOTMLPF integrated solutions.*
- Effectively trained and ready Soldiers and planners with contingency basing skills effectively distributed throughout the Operating and Generating Force.
- Reduced Contingency Basing manpower burden on operational mission forces: *yielding a Force Multiplier effect.*
- Reduced time, material, equipment and personnel requirements for Base Construction/ Deconstruction: *Modular, scalable, adaptable; re-deployable “fighting bases.”* Informed by existing contingency construction planning and management systems and tools.
- Enhanced interoperability with Joint, Inter-Agency, Inter-Governmental and Multi-National (JIIM) partners. Informed by coalition partner practices.
- Reduced Environmental, Safety and Occupational Health (ESOH) Risks.

The processes and tools need to enable the measurement and assessment of improvements based on new and emerging technologies that will be integrated as capability packages into the ARFORGEN process.

Thus, this research was a collaboration among the Systems Engineering Research Center (SERC), RDECOM and its respective Research and Development Engineering Centers (RDECs), Army support functions (such as PEO Combat Support & Combat Service Support, Training and Doctrine Command, PEO Integration, and Assistant Secretary of the Army for Acquisition, Logistics and Technology, to name a few), and the Army user community. Below are seven sub tasks that were in response to the above stated eight objectives. For the first year of this research task, only three of the sub tasks were executed and will be reported up on in this Final Technical Report. All sub-tasks are summarized below, and those sub-tasks not supported are identified in italics.

1. **Focus on initial system boundaries and connections in order to facilitate early dynamic modeling.** In order to separate the critical few from the trivial many, SERC shall work with NSRDEC researchers and chief engineers to create an abstraction of the whole Contingency Basing and Soldier Load scope that can be animated at a early stage as a guide to identify the critical components and aspects that will need priority of scrutiny on order to create high-fidelity models. This will be achieved by creating high-level systemigrams and system models for Soldier load and Contingency Basing. In addition, identify means to create initial value/risk based design objectives and functions on a reduced (and thus manageable) constraint space. Consistent with this work, SERC will provide expert input to capability capture, analysis and value risk capture.
2. **Model-based systems engineering (A).** As Contingency Basing is emerging, there is a proliferation of separate, individual models: business case/cost, functional decomposition, virtual, logical, Sandia logistical support, and SysML, to name a few. It will be difficult to keep these models in synchronization -- linked -- especially during the early work on this initiative. A conceptual framework for “holistic” modeling support for complex initiatives such as Contingency Basing need to be

explored. In addition, SERC could help the Army create specifications for the interoperability of the many CB models, an area of active research. The goal is to anticipate model compatibility problems and prevent them. Furthermore, the model-based system could be used to look for patterns, such as program protection exposure, architecture for resilience, incomplete vignettes, and technology insertion candidates.

3. **Model-based systems engineering (B).** Network models will be created to identify features that belong together. Contingency basing is awash in functions, tasks, views, data, connections, causes, time orderings, priorities, and linkages. Have any been missed? One way to ascertain this is to ask a wide scope of experts who normally operate in siloed organizations about what should be connected to what else -- using social networking tools. The collective linkage network can then be interrogated to see if the already documented connections account for the clumps, cliques, and cluster suggested by an array of specialized experts. In addition, a specific perspective to prioritize functions will be provided relative to a number of dimensions, such as time-ordering, socio-political factors, regulations, doctrine, etc.
4. **Help assess and formalize Developmental Planning Process and Practices within the US Army.** *Based on the established and piloted Air Force Research Laboratory's Concept Characterization and Technical Description process (its version of early life cycle Developmental Planning, Air Force Research Laboratory Instruction 61-104, Science and Technology), SERC researchers will work with the Contingency Basing leads to tailor this early systems engineering standard to Army needs. The Air Force standard is one of the few early SE development processes that has been in place long enough for lessons learned to accumulate and to inform both the standard and its application in the science and technology area.*
5. **User CB workbench.** *In addition, the model-based system would function as a user workbench where a combatant commander could explore options for configuring contingency bases. While there would be significant computing capability "under the hood," the user would see models only in his/her terms. And as field knowledge of contingency bases grows, the workbench would grow in fidelity and decision support. SERC will help to create the specification and pilot instances of this Workbench.*
6. **Visualizing an "infinity" of data.** *All of the permutations and combinations of the input space will produce a flurry of base configurations. How will one be able to make sense of all of the combinations of inputs and then be able to react sensibly to the output? Visualization technology helps engineers see patterns in high-dimensional data. Imagine all of the possible outcomes with just the few input categories suggested by the Corps of Engineers: time, size, mission type, base systems, operations tempo, and human dimensions, resulting in a spectrum of recommendations about configuration and duration (expeditionary, temporary, and enduring). To this add the vagaries of the consumption data, such as water per day per Soldier, energy consumption per day per Soldier, etc. SERC will aid the Contingency Basing team experiment with and weigh features of visualization systems as a way to reason from the dense space of data.*

7. **Assessment and improvement of SoS engineering methods.** *Validation and verification (V&V) of Contingency Basing concepts and early formulation will be difficult because in its current form it is an applied practice, the kind that can best be validated only in the field, such as at the Systems Integration Lab at Ft. Devens. But that would be very late in the conceptual life cycle to find errors, so a form of early V&V is required. SERC researchers working with the Army would develop improved verification and validation approaches for SoS via models and formal methods. It would be desirable to verify and validate at the functional level, rather than delay every time to the final material solution. It would also be desirable to understand a model based paradigm that allows a more expedient synthesis, analysis, and evaluation of the problem and potential array of solutions, and allow trade space exploration and a better understanding of the resilience of the architecture and deployment. Accordingly, we propose an exploration of deep systems engineering practices that would formalize the characterization of testable properties as a long-term improvement for what will appear as conventional engineering in the early days of the Contingency Basing initiative.*

## 2 FOCUS ON INITIAL SYSTEM BOUNDARIES AND CONNECTIONS IN ORDER TO FACILITATE EARLY DYNAMIC MODELING

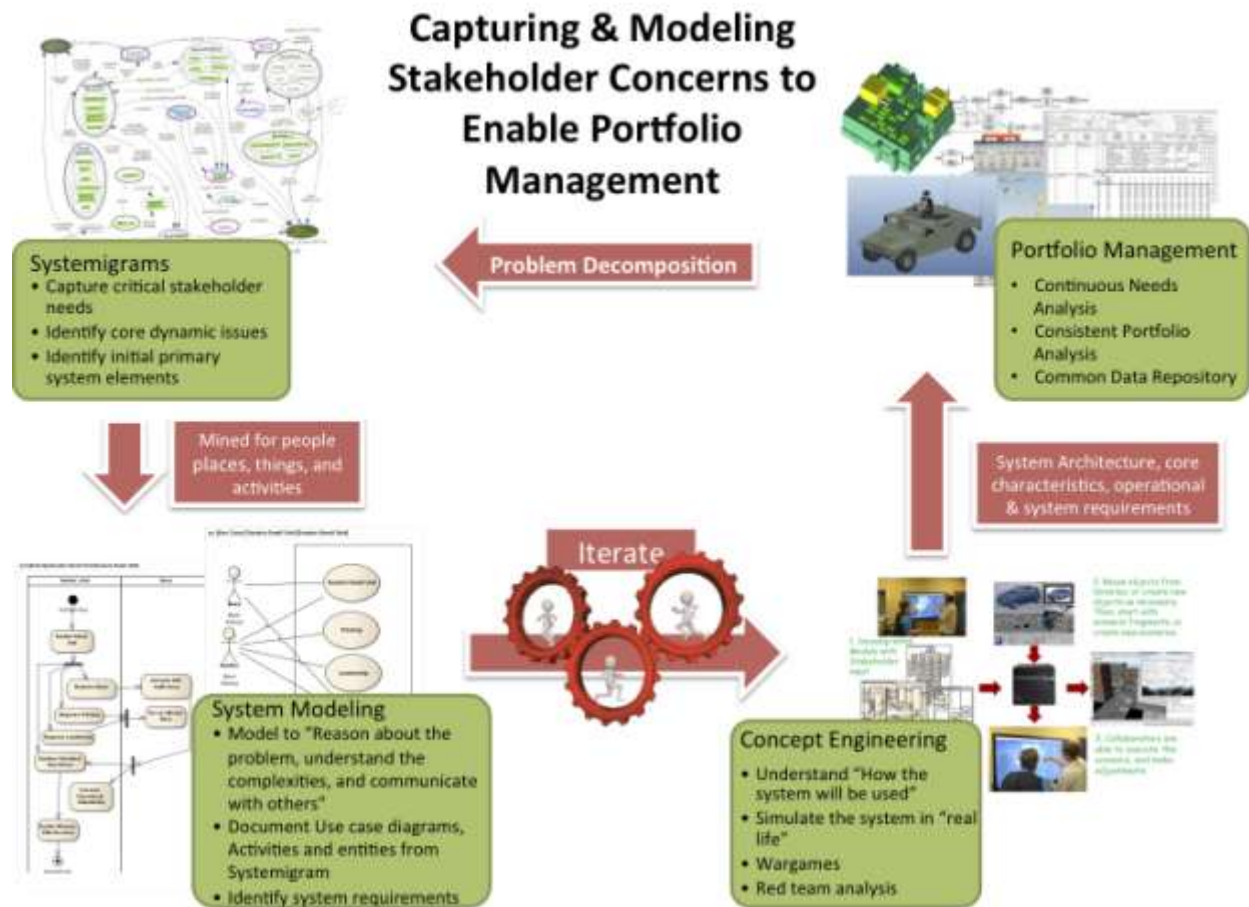
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The Department of Defense (DoD) is vigorously pursuing greater efficiency and productivity in defense spending so it can continue to provide the armed forces with superior capabilities in an environment of flat defense budgets. Toward that end, the Office of the Secretary of Defense (OSD) has issued new acquisition guidance that places increased emphasis on system engineering early in the lifecycle to balance operational performance with affordability. In response to this, some DoD efforts and academic research has matured the ideas using concept engineering for agile CONOPS (Concept of Operation) Development. Traditionally, CONOPs, functional decompositions, and other qualitative and quantitative methods, were employed to develop requirements constraints that define a typically large set of feasible system realizations. This feasible region is then explored to identify a subset of system realizations that have the most preferred operational efficacy. To this end, system objective functions are constructed and optimized over the feasible region defined within the boundaries of the requirements and constraints. However, for both contingency basing and Soldier load, when realized as systems of systems or enterprises, have a priori uncertain missions and deployment environment requirements. It is very difficult to construct a requirements constrained feasible region over which one can search for the most effective operational regimes.

Not only are the technology mappings dynamic, but also the number of requirement constraints needed to capture prior uncertainties, is unmanageably large. Modern design theory suggests systems design is better served by methodologies that focus on constructing objective functions with penalties that capture value and uncertainty, as opposed to attempting to capture the unmanageable large number of requirement-constraints. Consistent with RDECOM's vision and mission to be the Army's primary source for integrated research, development and engineering capabilities to empower, unburden, and protect the Warfighter, this research topic calls for the creation of an early collaborative and system models to express and characterize Soldier load and contingency basing at the patrol base, combat outpost, and small combat unit (company minus) level.

The long-range vision of this work is depicted in Figure 1 that will allow for capturing and modeling of stakeholder concerns to create effective systems engineering artifacts in systems modeling and CONOPS to enable portfolio management. As an initial proof of concept, this sub-task was focuses on the first two phases of this work, i.e. Systemigrams and System Modeling, as depicted in Figure 1. Thus, this research sub-task worked with U.S. Army Natick Soldier RD&E Center (NSRDEC) researchers and chief engineers to create an abstraction of the whole Contingency Basing and Soldier Load scope that can

be animated at a early stage as a guide to identify the critical components and aspects that will need priority of scrutiny in order to create high-fidelity models. This was achieved by creating high-level systemigrams and system models for Soldier Load and Contingency Basing. In addition, this research identified means to create initial value/risk based design objectives and functions on a reduced (and thus manageable) constraint space. It was then demonstrated how systemigram models can be used to capture key dimensions for input into a defined SysML tool for creating better systems engineering artifacts. The following sections will describe this effort.



**Figure 1: Capturing and Modeling Stakeholder Concerns to Enable Portfolio Management**

## SYSTEMIGRAMS

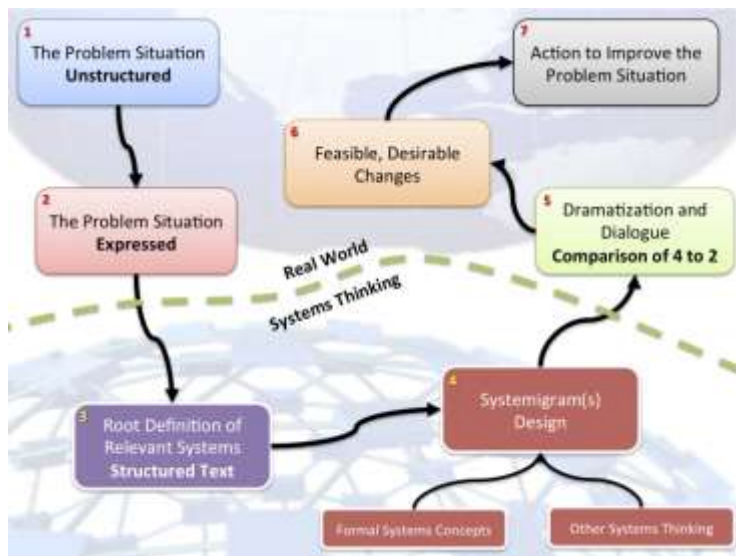
Diagrams that try to capture concepts are not new – e.g. concept diagrams, concept mapping, fishbone diagrams, Senge’s diagrams, influence diagrams, and even of course the original flow charts. The one thing about all of these though is that they capture the immediacy of prose but they then forget that and move on to the next local piece of knowledge. It is more difficult to find longer thought threads in these diagrams since they concentrate on linear thinking rather than holistic thinking. Senge’s causal loop diagrams are a possible exception to this but these are always kept deliberately small

and even when these get big it is hard for the reader to make sense of the totality of the language that the diagram conveys.

The existence of systemigrams as a value-adding proposition, one that will reveal the inner meanings of strategic intent and help build a greater shared understanding in a growing community of people, should force up the ante for defining strategic intent more completely, more thoroughly, more thoughtfully, and more purposefully. There are three distinct phases in the evolutionary process for developing systemigrams:

- concentration on graphical portrayal of structured prose;
- development of methodologies that use systemigrams for enterprise architecting purposes, e.g. extended enterprises or business process architectures;
- development of systemigram technique for drilling down from architectural vantage points into detailed consideration of solution implementation

The creation of systemigrams follow the Boardman Soft Systems Methodology (BSSM) of seven steps that can be viewed as an iterative process for defining an ill-defined problem (or system of interest) (Boardman and Sauser, 2008). BSSM is useful for understanding motivations, viewpoints, and interactions and addressing qualitative dimensions of problem situations. The seven steps of BSSM are depicted in Figure 2 followed by a description of each step as it related to this sub-task.



**Figure 2 – Boardman Soft Systems Methodology**

*Step 1 – The Problem Situation: Unstructured:* The problem situation is first expressed (textual, verbal, graphical), as it is, by the researcher (or stakeholder). As this step can be based on many presumptions, every attempt is made not to extrapolate about the nature of the situation. We made every attempt to understand the problem by

investigating the situation without bias from RDECOM. We attempted to develop a perspective of the problem with our own largely unbiased view.

*Step 2 – The Problem Situation: Expressed:* In this step, a description of the situation within which the problem occurs is formulated. Both logic and the culture of the situation are taken into account at this point. Based on our interpretations from *Step 1*, we developed an expression of the problem based on a review of relevant documentation and discussions from a body of scholars and practitioners in Contingency Basing.

*Step 3 – Structured Text:* We conceptualized the problem situation in structured text. The Structured Text identified the key elements with attention to systems thinking modeling and analysis requirements, i.e. systemigrams. Using this body of literature/knowledge gained from *Step 2*, we were able to write a document that summarized what we found, what was similar, and what was different. We made every attempt to not change the original words or thoughts of the authors, but stay true to the essence of their views on the problem. This became the source text of our systemigram.

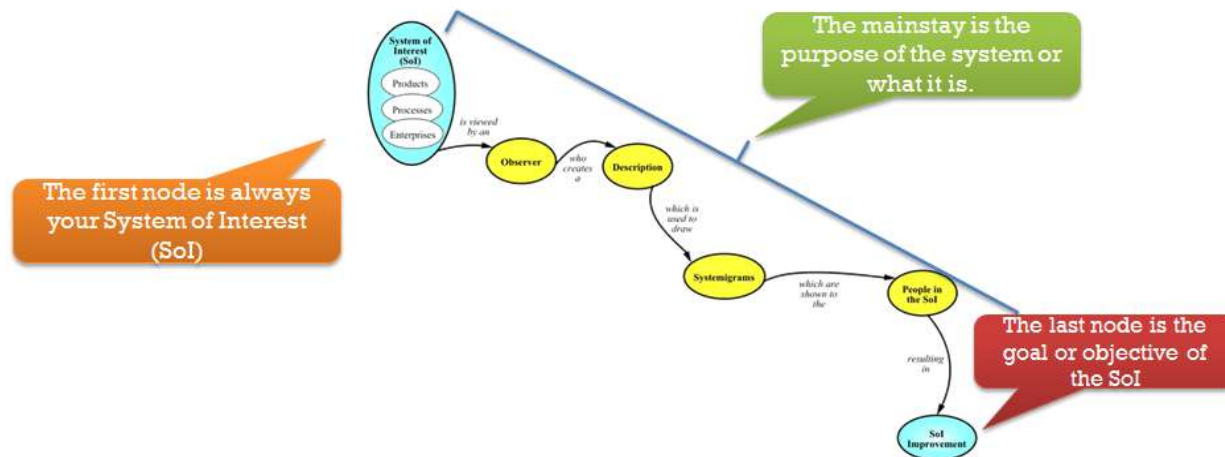
*Step 4 – Systemigram Design:* We created a systemigram model as designed from the Structured Text to capture and represent the essence of the original conceptual thinking. A systemigram is to be a network, having nodes and links, flow, inputs, and outputs, beginning and end<sup>3</sup>. This must fit on a single page. Key concepts, noun phrases specifying people, organizations, groups, artifacts and conditions will be nodes. The relationships between these nodes will be verb phrases (occasionally prepositional phrases) indicating transformation, belonging, and being. Some nodes can contain other nodes, for example to indicate break out of a document or an organizational/product/process structure. The network must be legible so that this limits the number of nodes and links. There should be no cross-over of links, improving clarity. This constraint further lends itself to systemic design. Such a network tends to be of an interconnected kind for which the ratio of nodes to links is 1.5 or thereabouts. For a systemigram of 20 nodes, the total number of possible links is 190, whereas the actual number will be about 30. This ratio is about 15%, which is held to be the optimal ratio of interfaces in a system relative to how many there could be.

The primary sentence (mainstay), which supports the purpose of the system will read from top left to bottom right. This becomes the anchor for the entire visualization. It is used to help the viewer understand the picture as a whole. The other segments of the systemigram flow out of and back into this mainstay, connecting as needed with its landmark noun phrase nodes (see Figure 3). The remaining nodes must also contain nouns or noun phrases (people, organizations, groups, artifacts, and conditions). The links should contain verb and verb phrases (transformation, belonging, and being). As

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<sup>3</sup> For a detailed description of systemigrams, see Boardman, J. and B. Sauser. (2008). *Systems Thinking: Coping with 21st Century Problems*. Boca Raton, FL: Taylor and Francis/CRC Press; or for the use of systemigrams as a graphical CONOPS, see Cloutier, et al. (2009). *Investigation of a Graphical CONOPS Development Environment for Agile Systems Engineering*. Systems Engineering Research Center Final Technical Report, Document Number SERC-2009-TR-003

the Systemigram is realized, it should capture the system transformations that have a structure and a process.



**Figure 3 - Systemigram Mainstay**

The geography of the systemigram can be exploited to say, for example the motivation for the strategic intent, its mission, and how it will be accomplished – its management. There will be relationships between the elements of each of these – the why, the what and the how; such elemental relationships are invaluable for maintaining coherence for accomplishing the strategic intent. Color can be used to draw attention, in a consistent way, to sub-families of concepts and transformations. However the finished systemigram should be aesthetically pleasing and in line with the 3 top-level requirements, which moderates its form.

*Steps 5 – Dramatization and Dialogue:* At this step the systemigram model is dramatized via storyboarding to the stakeholders. This is done so that the model and reality can be compared and contrasted. The differences become the basis for discussion: how things work, might work, and what are the implication? Thus, a completed systemigram is not the end of the story. In fact, it is the basis for telling a story. The composer of the systemigram is now in a strong position, in spite of any illiteracy of the field being defined that he/she may have, simply because it takes considerable comprehension – of the original text and of building systems – to complete the systemigram. The story can be told in a variety of ways but all have the same generic format – to create a storyboard using carefully selected scenes which are sub-nets of the systemigram.

This storyboarding helps to convey the message of the systemigram, together with the message that the author of the original text intended, to a wider audience. Each scene represents a key part of the message but by the same token it begins to tell a more detailed message which can only be amplified by having the right people listen to the systemigram story. So if there are say eight scenes then in principle eight detailed messages can be generated, all at a lower level but higher amount of detail than the systemigram. This drilling down can be continued for as long as required or until the

messages begin to fail the original top-level requirements for original text for systemigram interpretation.

This is a very important step for verifying the systemigram with respects to its ability to capture the multiple views of the stakeholders. The dramatization and dialogue was executed in a series of meetings with RDECOM stakeholders at NSRDEC. At this meetings the participants were presented with an overview and tutorial on the use of systemigrams as a systems thinking tool so as to stay true to the modeling constraints. During these meetings perspectives (even if conflicting) were captured.

*Step 6 – Feasible, Desirable Changes:* At this step the identification of feasible and desirable changes are deciphered from the previous step, understanding that they are likely to vary. Desirable asks if it is technically an improvement? Feasible asks if it fits the culture? It is common for *Step 6* to occur after *Step 5* and with the modeler deciphering all of the perspectives. For this work, we were able to make changes to the systemigram in real-time as the modeler and the stakeholders were in the room collectively utilizing the modeling tool, i.e. SystemiTool.

*Step 7 – Action to Improve the Problem Situation.* Every individual or collective input that is deemed Desirable or Feasible is incorporated into the model. Only contributions that answer “no” to one of the two questions presented in Step 6 are dismissed. Likewise, *Step 7* was executed in real-time as well.

Steps 1-7 were repeated until a successful outcome of a BSSM was achieved. Success is defined as: (i) the people concerned, i.e. stakeholders, feel that the problem has been solved; or (ii) the problem situation has been improved; or (iii) insights have been gained. What resulted from this effort was four systemigrams depicted in Figures 4-7.



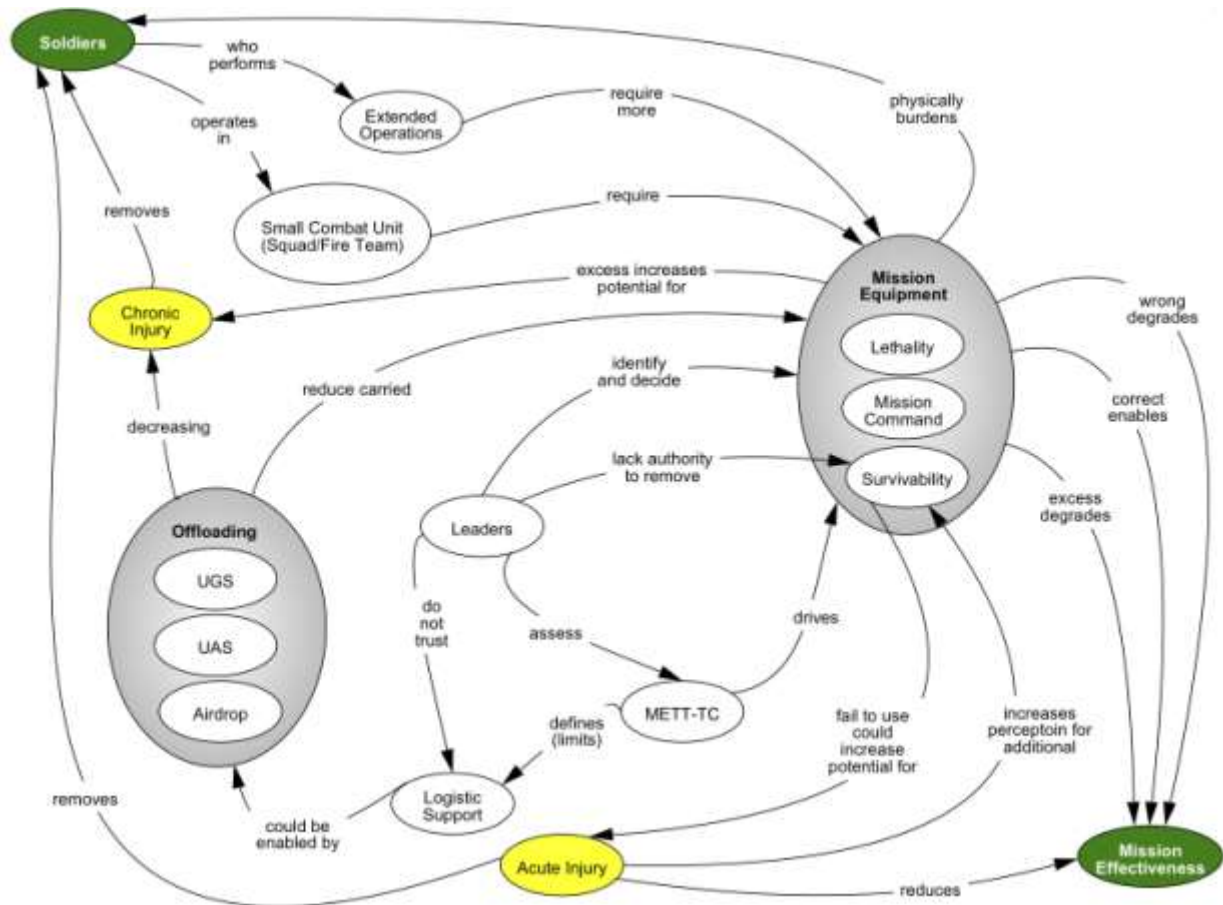


Figure 5: Soldiers Systemigram



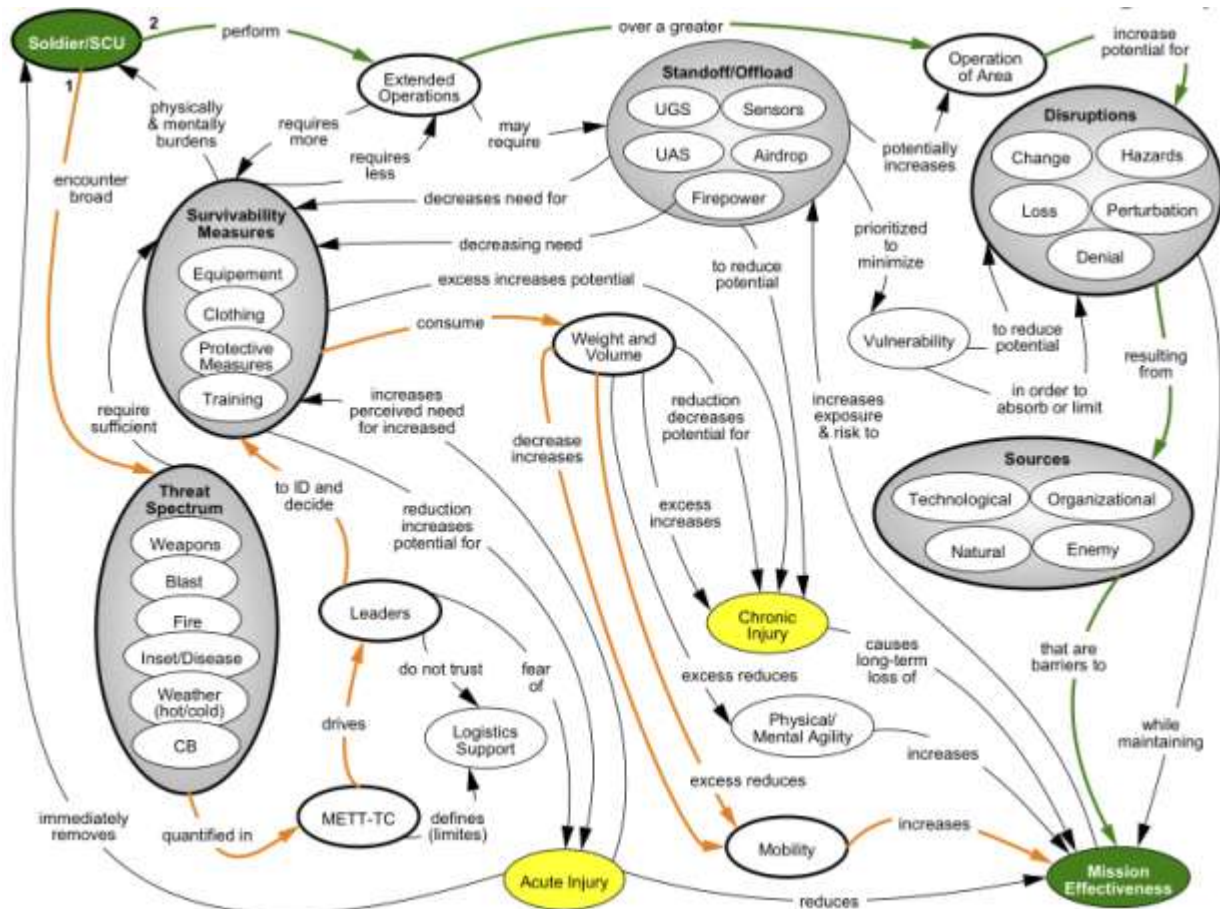


Figure 7: Soldier\_Small Combat Unit Systemigram

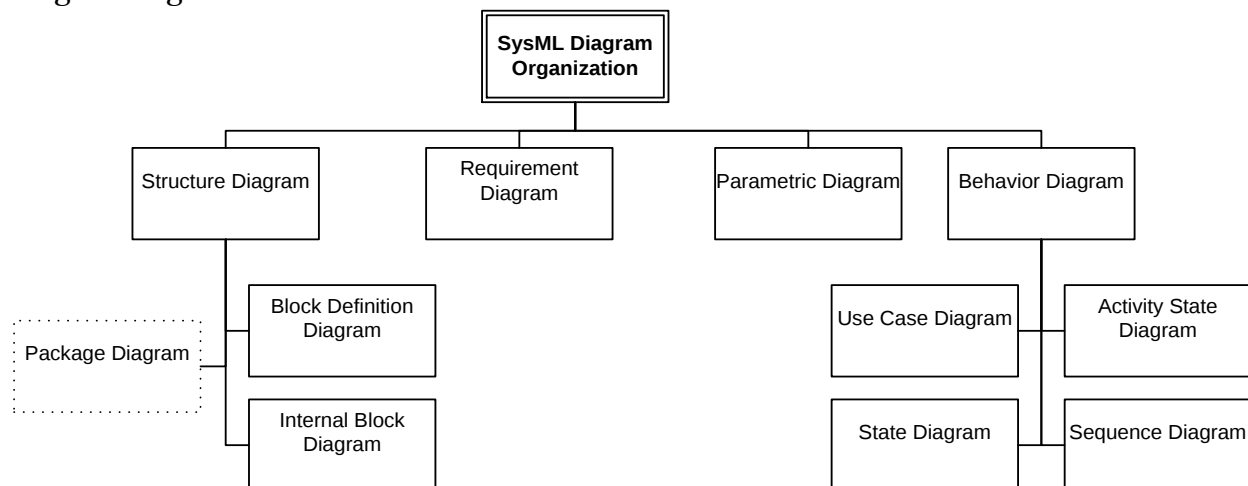
Systemigrams can be powerful storytelling aids and are useful in providing a common foundation for group discussions. Another value of systemigrams is that they do not remove the complexity from systems, but they can make complex systems understandable. See Table 1 for a review of systemigram construction guidance.

**Table 1- Systemigram Construction Guidance**

| Principle         | Systemigram Guidance                                                                                                                                                                                                                                                                                                                                                                                                     |
|-------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Correctness       | <ul style="list-style-type: none"> <li>• <i>Mainstay which supports the purpose of the system reads from top left to bottom right</i></li> <li>• <i>Ideally there should be 15-25 nodes</i></li> <li>• <i>Nodes must contain noun phrases</i></li> <li>• <i>Links should contain verb phrases (to reduce trivial links)</i></li> <li>• <i>No repetition of nodes</i></li> <li>• <i>No cross-over of links</i></li> </ul> |
| Relevant          | <ul style="list-style-type: none"> <li>• <i>Remember that the model is really “theirs”.</i></li> <li>• <i>Remember that the model is not really “theirs”</i></li> <li>• <i>Remember that the model is not reality</i></li> </ul>                                                                                                                                                                                         |
| Feasibility       | <ul style="list-style-type: none"> <li>• <i>It should compare to reality (comparing 4 to 2 in the BSSM)</i></li> </ul>                                                                                                                                                                                                                                                                                                   |
| Clarity           | <ul style="list-style-type: none"> <li>• <i>It should read well.</i></li> <li>• <i>Beautification (e.g. shading and dashing of links and nodes) should help the reader read the sentences in the diagram</i></li> <li>• <i>Exploit topology to depict why, how, what (who when and where is built into system description)</i></li> </ul>                                                                                |
| Comparability     | <ul style="list-style-type: none"> <li>• <i>It should compare to reality (comparing 4 to 2 in the BSSM)</i></li> </ul>                                                                                                                                                                                                                                                                                                   |
| Systematic Design | <ul style="list-style-type: none"> <li>• <i>Is it a system in its own right?</i></li> <li>• <i>Does every node (except for the beginning and ending nodes) have an input and an output?</i></li> <li>• <i>Can you follow any node to the end node?</i></li> </ul>                                                                                                                                                        |

## SYSTEM MODELING LANGUAGE

The systems modeling language (SysML) contains a number of diagrams that are used to capture system attributes, operations, tasks, and participants. Figure 8 represents the diagram organization.

**Figure 8 - SysML Diagram Structure**

Each diagram can be used to capture information about the system of interest, at any level or multiple levels of abstraction. Each group of diagrams is discussed next.

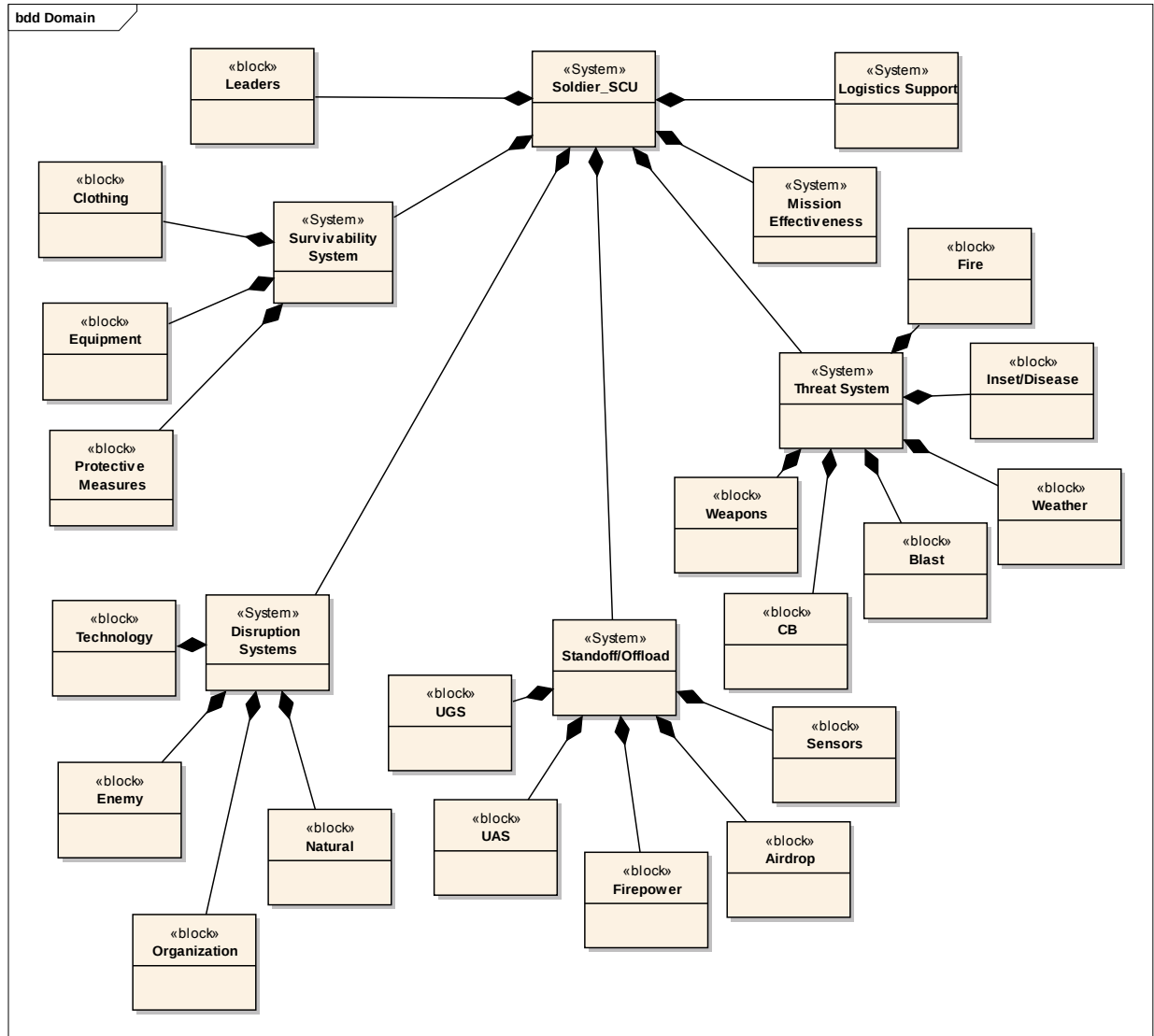
1. **Structure (System) diagram** represented as block definition diagrams and internal block diagrams identifies the physical and logical layout for a system.
  - **Block definition diagram** describes the system hierarchy and system/system element classifications. Blocks are generally nouns.
  - **Internal block diagram** describes the internal structure of a system in terms of how its parts are inter-connected using ports and connectors. Blocks are generally nouns.
  - **Package diagram** is used to organize the model into packages that contain other model elements.
2. **Requirements diagrams** capture requirements hierarchies and the derivation, satisfaction, and verification relationships. Requirement diagram captures the interrelationship of requirements.
3. **Parametric diagram** represents constraints on system parameter values, such as performance, reliability, and mass properties to support engineering analysis.
4. **Behavior diagrams** include the following:
  - **Use-case diagrams** provide a high-level description of the system functionality in terms of how external systems use the system under consideration to achieve their goals. The “use cases” generally represent things to be done, and the actors represent nouns in the form of either stakeholders or other systems.
  - **Activity diagrams** represent the flow of data (artifacts, which are nouns) and control between activities.
  - **Sequence diagrams** represent the exchange of information between collaborating parts of a system (which are nouns).
  - **State diagrams** describe the states of a system or its parts (nouns), and the transitions between the states in response to triggering events, along with the actions that occur upon transition, entry, exit of while in the state.

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## MODELING THE SYSTEM USING SYSTEMIGRAMS AND SysML

We model to reason about the problem, to understand the complexities, and to communicate with others (R. Cloutier). This research was to explore the use of systemigrams and SysML to accomplish those three modeling goals. From this point forward, we will look at the process of initiating a SysML diagram from a systemigram. The Soldier/SCU systemigram was constructed as the result of a joint workshop between Drs. Sauser and Cloutier of Stevens Institute and subject matter experts at the Soldier Center in Natick, MA. From that workshop, the top level Systemigram was constructed, and decomposed into several lower level Systemigrams.





**Figure 10 - Identified Nouns from Soldier/SCU Systemigram**

Next, we identify the use cases from the Systemigram

1. For each adjective that is not directly linked to another adjective create a Use Case Diagram (Figures 11-15)
2. In each Use Case Diagram use the adjective to create a Use Case.
3. Each Noun (System) that is linked, in the Systemigram, to the adjective is connected in the Use Case Diagram.
4. Include Adjectives that are connected to other adjectives, in the Systemigram, as Use Case's within the other adjectives Use Case Diagram (see Chronic Injury – Figure 12, and Mobility – Figure 14, below for example).

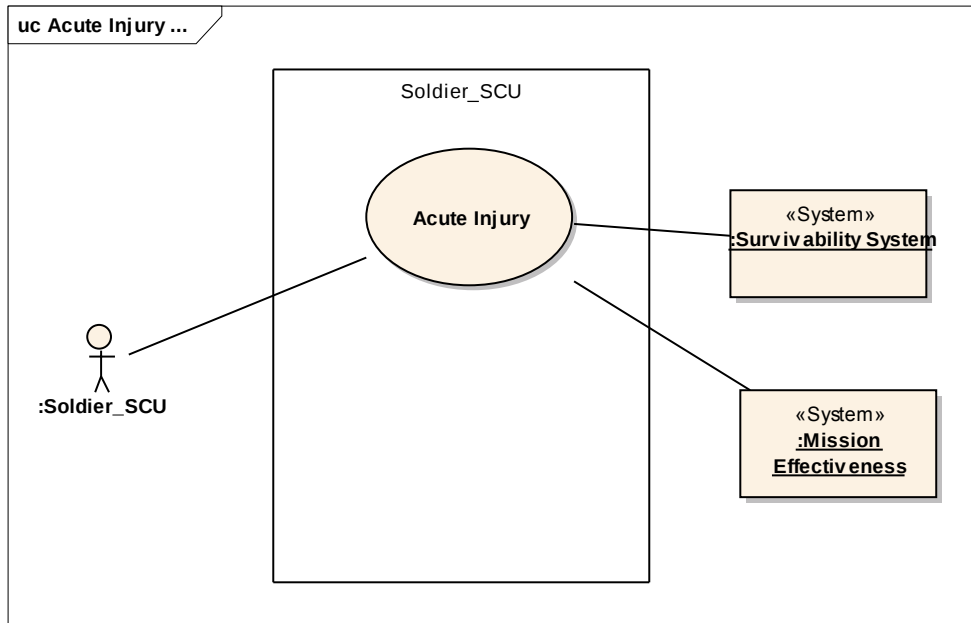


Figure 11 - Acute Injury Use Case

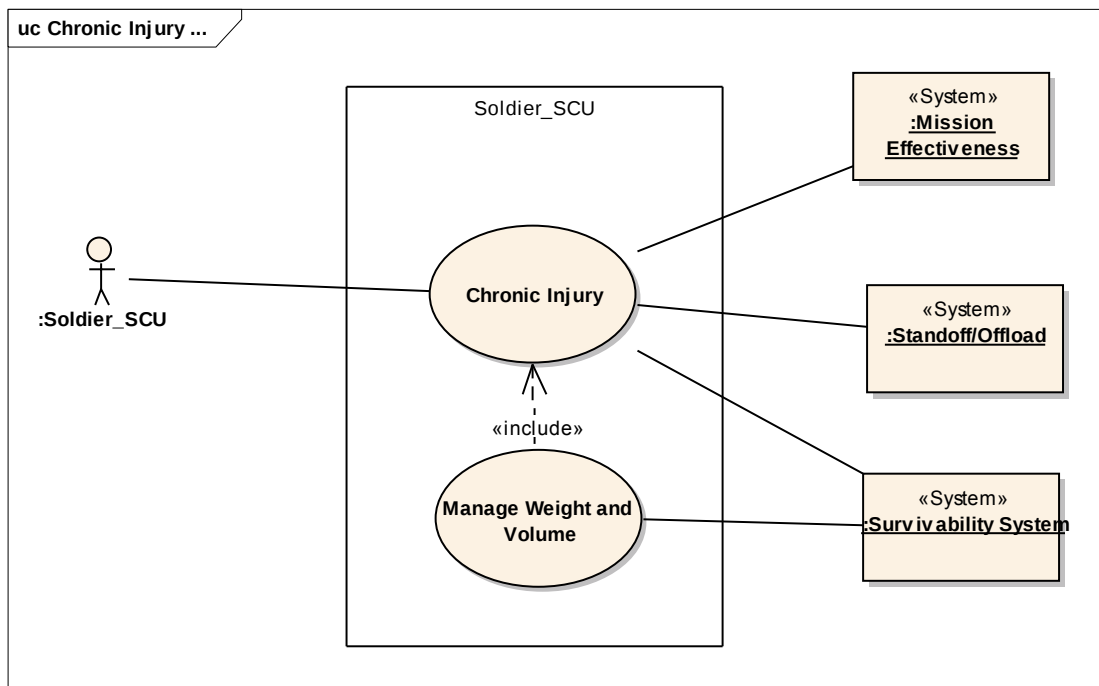


Figure 12 - Chronic Injury Use Case

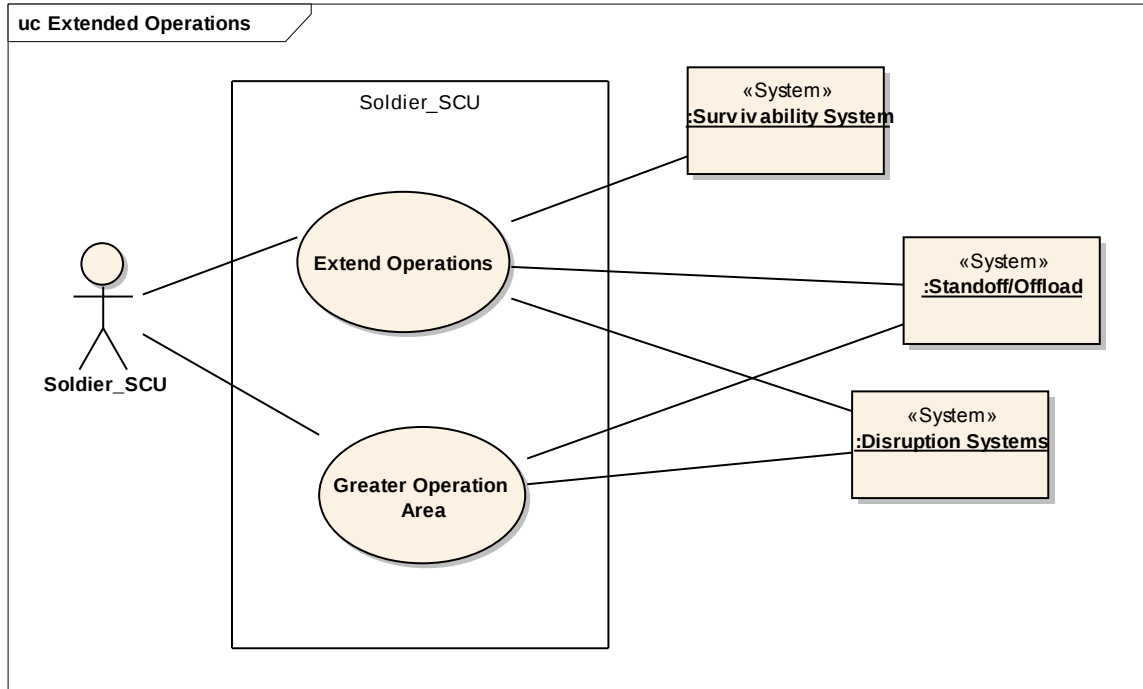


Figure 13 - Extended Operations Use Case

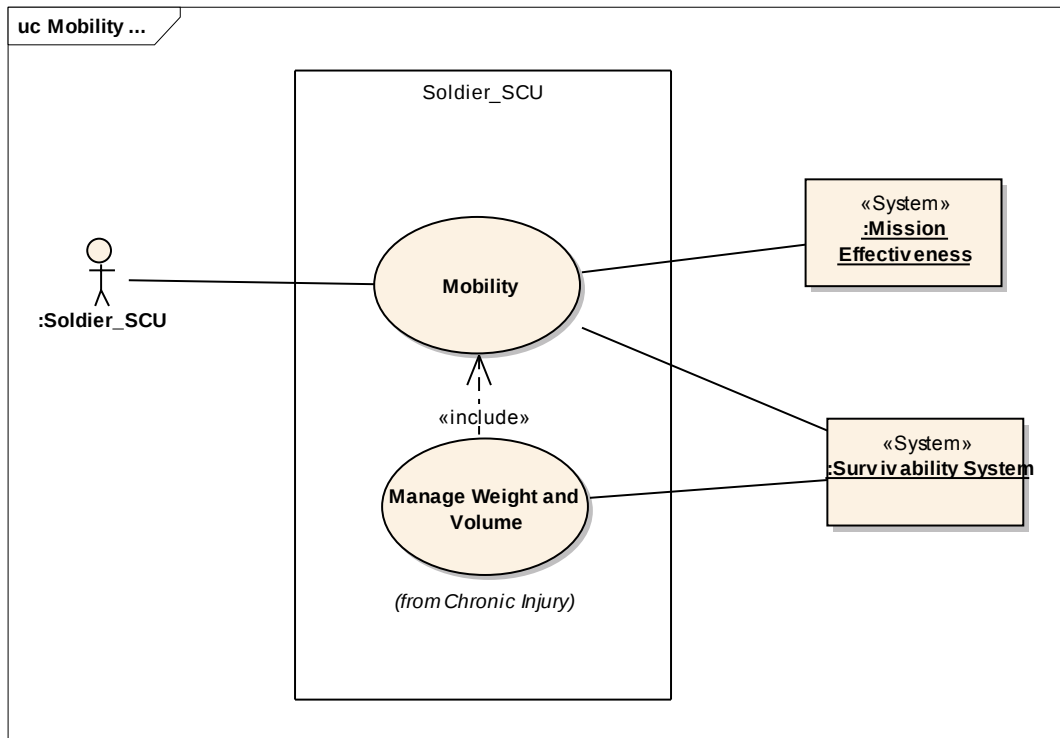
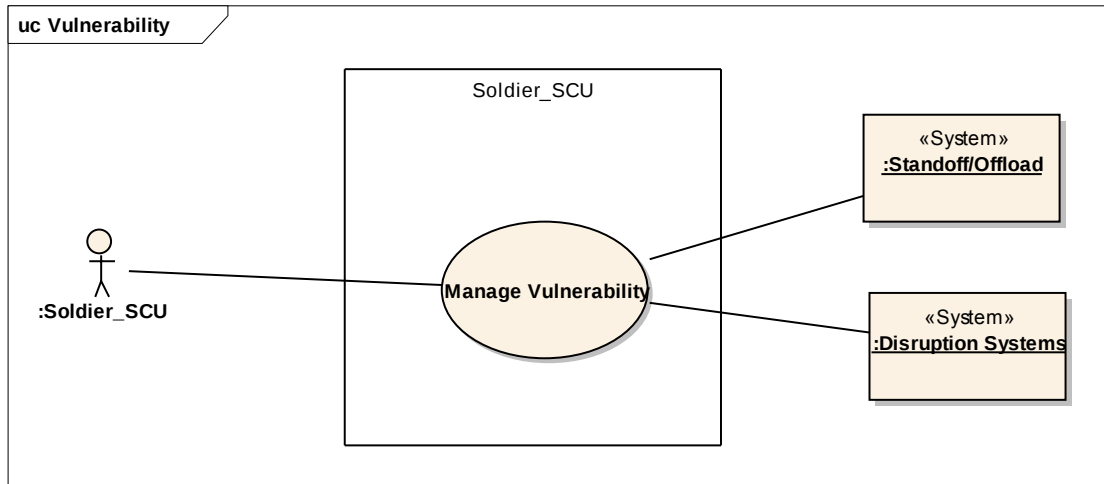


Figure 14 - Mobility Use Case

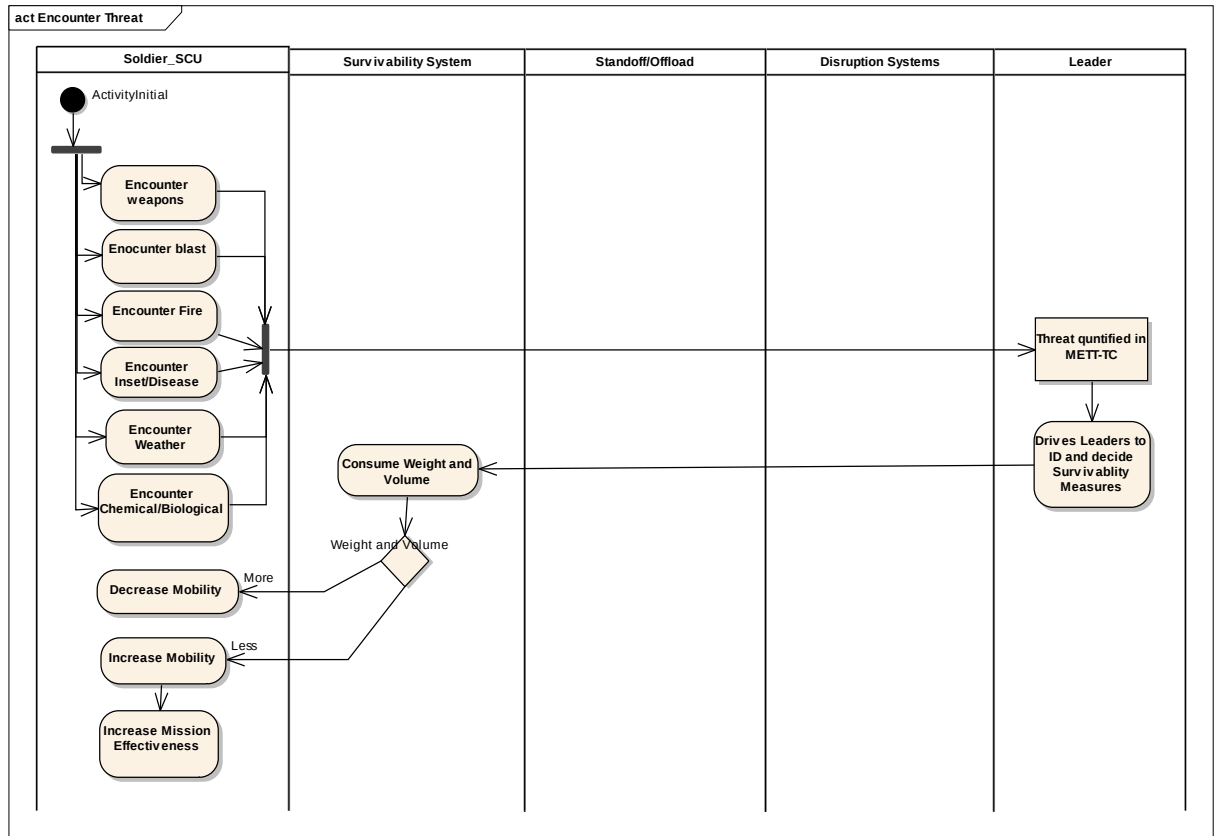


**Figure 15 - Vulnerability Use Case**

## UNDERSTANDING THE FLOW OF ACTIVITIES

The Systemigram indirectly represents flow of events. These can be captured in SysML Activity diagrams

1. Starting at the upper left corner of the Systemigram follow the flow of the main stories (in this example it would be the gold and green paths). Develop an activity diagram detailing the flow (Figures 16-17).



**Figure 16 Activity Diagram of Gold Path in Systemigram**

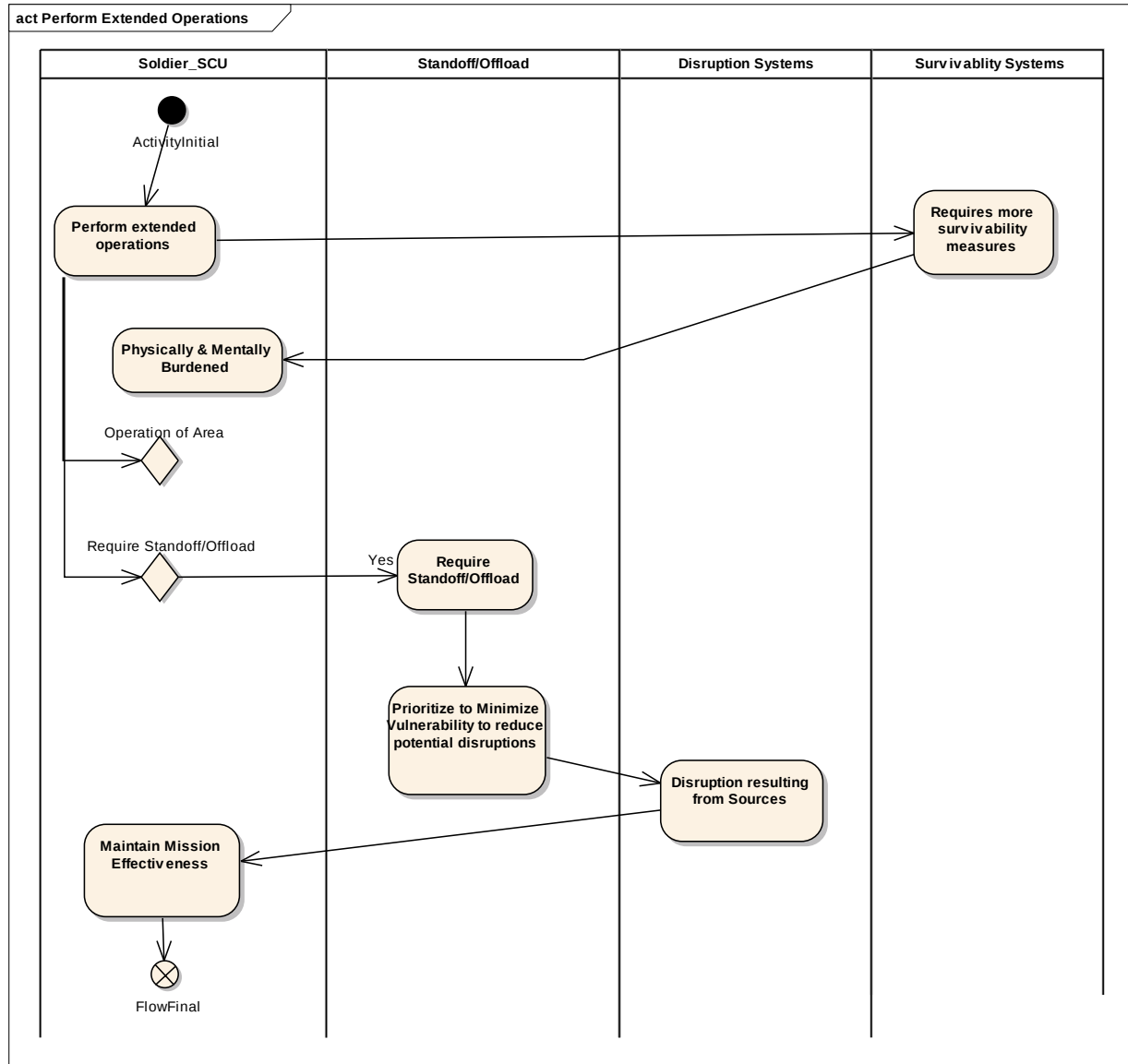


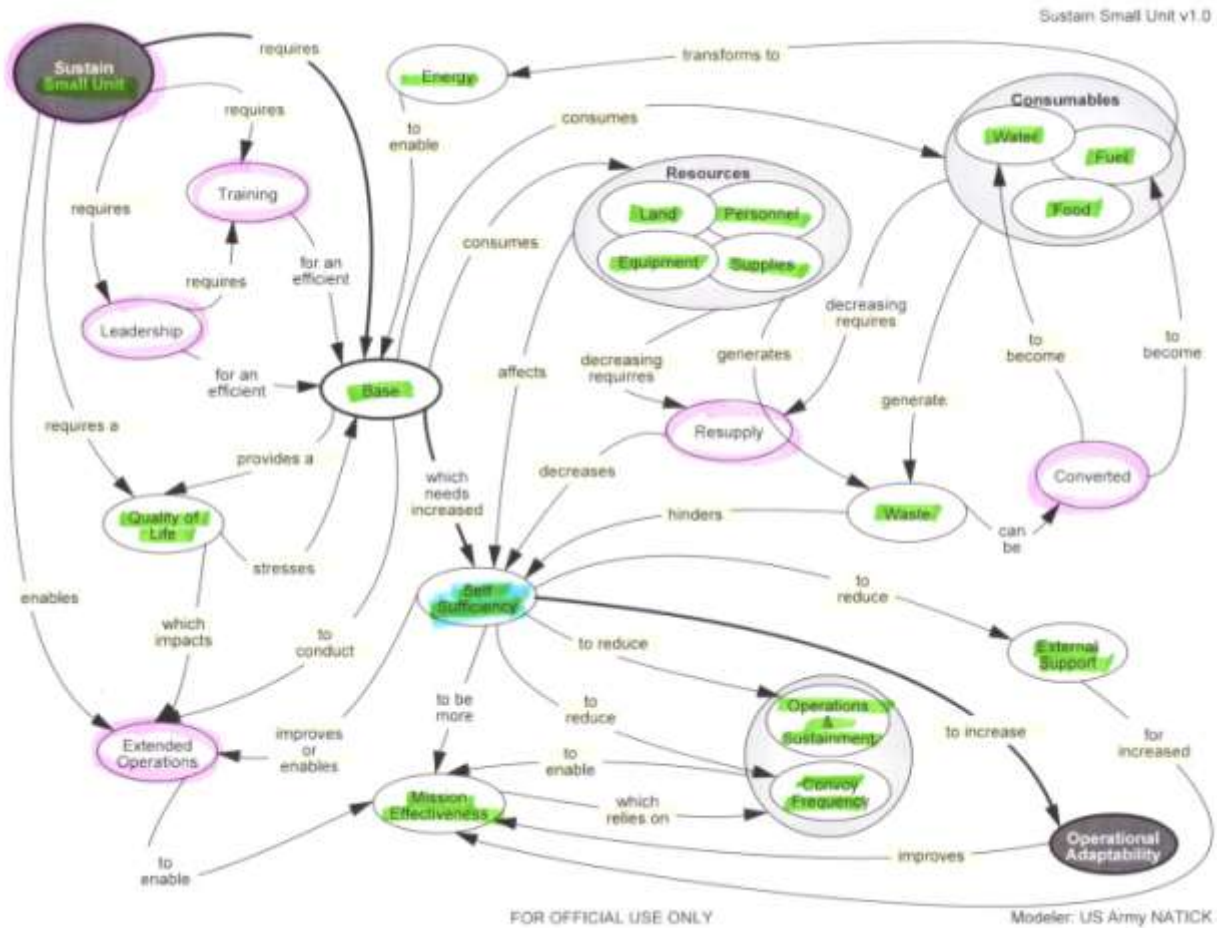
Figure 17 Activity Diagram for Green Path in Systemigram

## DECOMPOSING THE PROBLEM

Mentioned earlier, the Soldier/SCU Systemigram represented the high level system. However, it could be decomposed into lower level Systemigrams to foster more understanding. Those were: 1) Sustain Small Unit Systemigram, 2) Gunners Systemigram, and 3) Soldier Systemigram. The process was replicated for each of those Systemigrams, as discussed below.

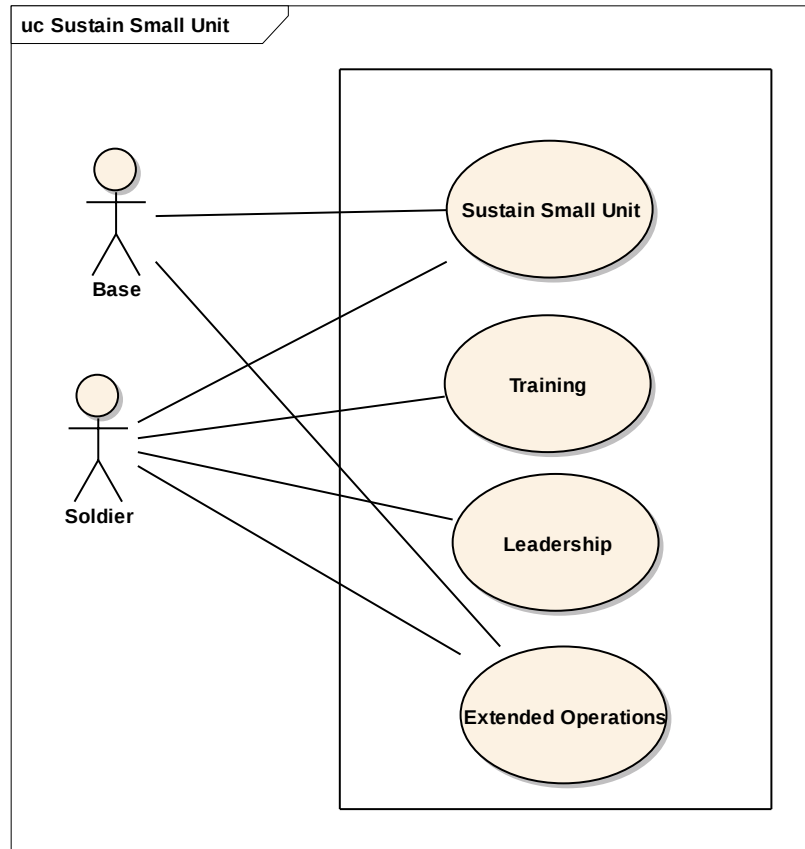
## SUSTAIN SMALL UNIT SYSTEMIGRAM

1. Highlight the nouns, verbs, and adjectives in the, Sustain Small Unit Systemigram (Figure 18).

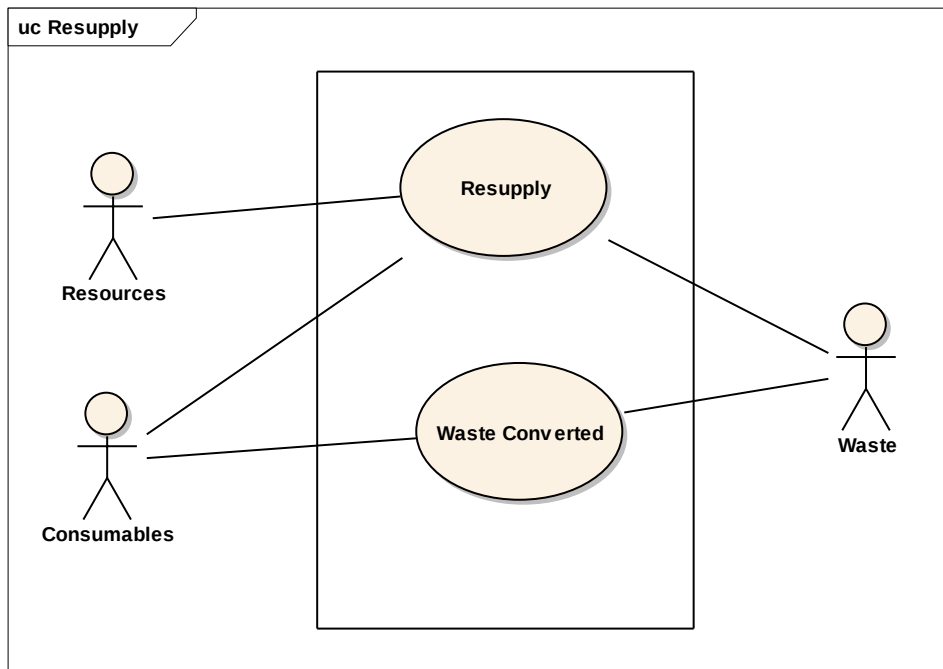


**Figure 18 - Sustain Small Unit Systemigram**

2. For each adjective that is not directly linked to another adjective create the necessary Use Case Diagrams (Figures 19 and 20).
3. In each Use Case Diagram use the adjective to create a Use Case.

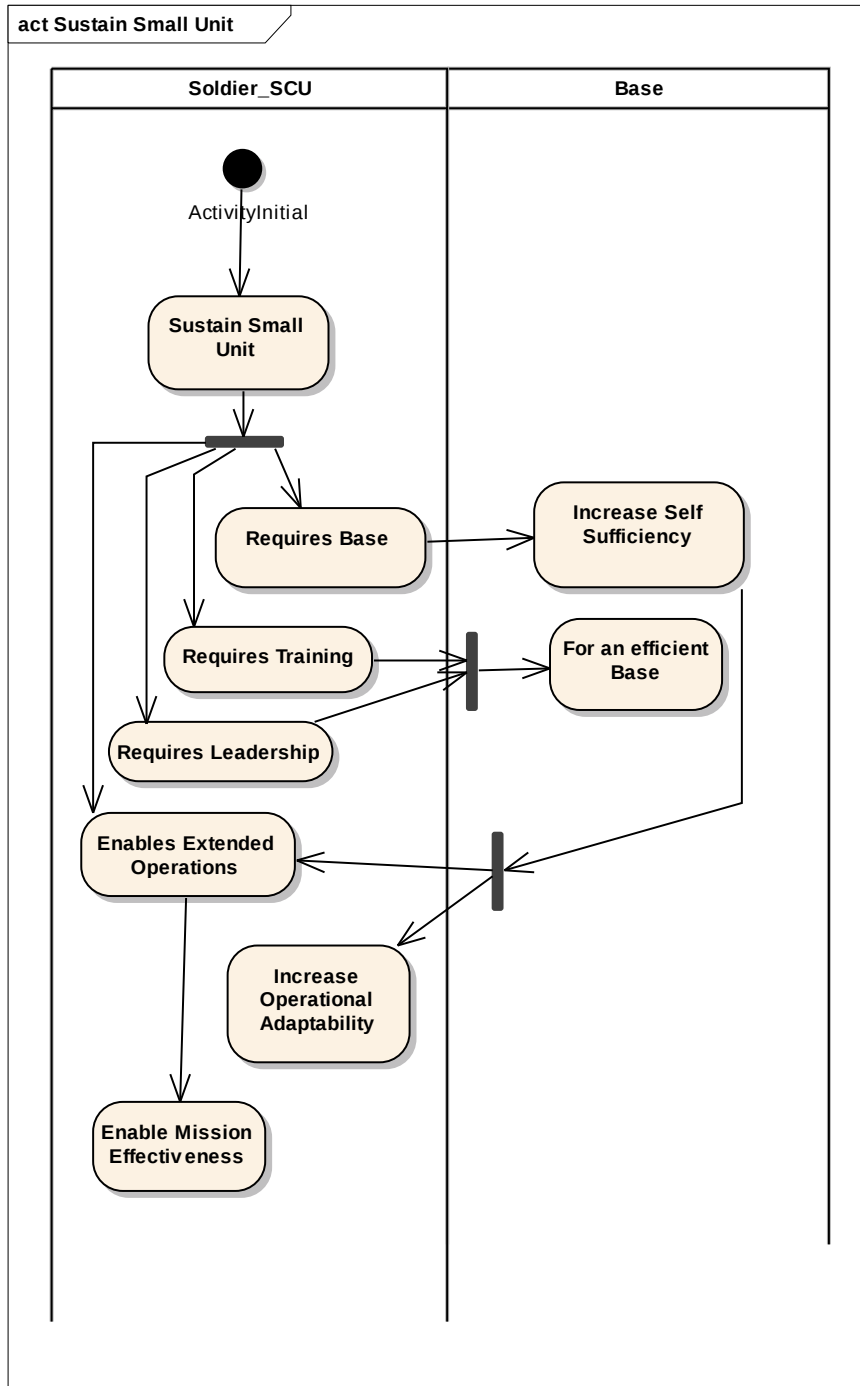


**Figure 19 Sustain Small Unit Use Case**

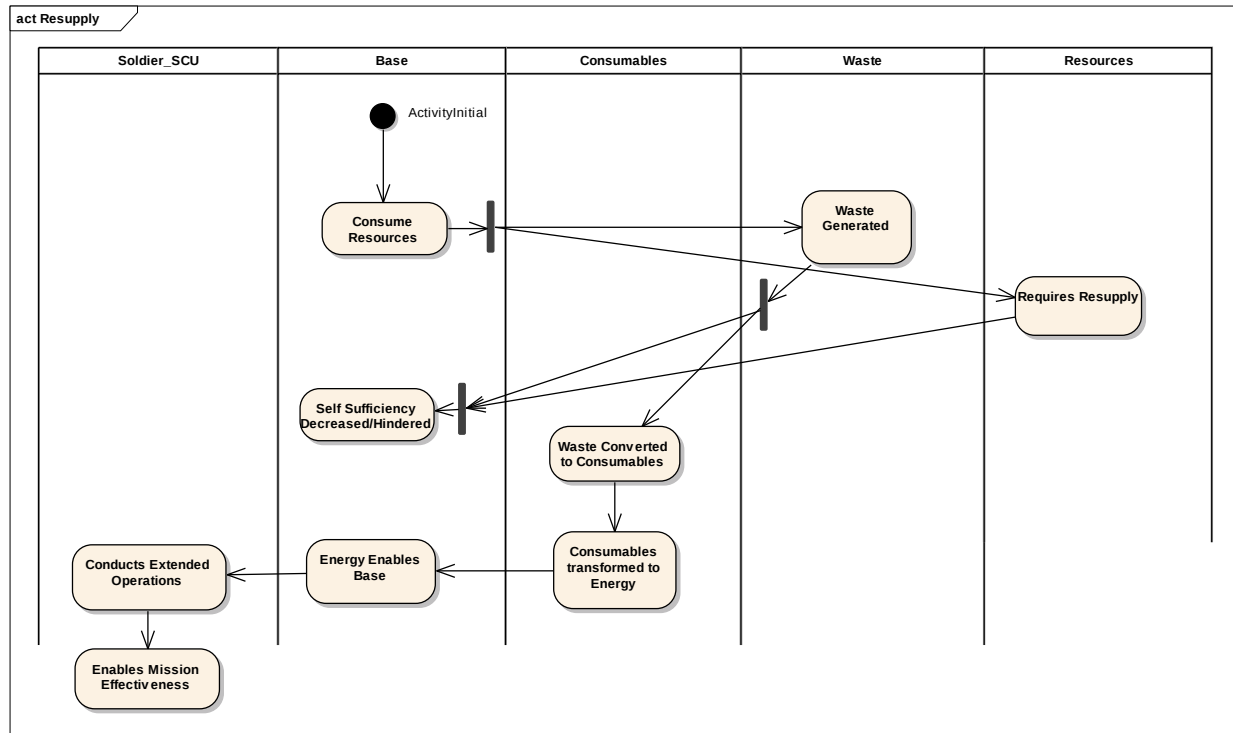


**Figure 20 Resupply Use Case**

4. For each Use Case create an Activity diagram using the links described in the systemigram (Figures 21 and 22).



**Figure 21 Sustain Small Unit Activity Diagram**



**Figure 22 Resupply Activity Diagram**

## GUNNERS SYSTEMIGRAM

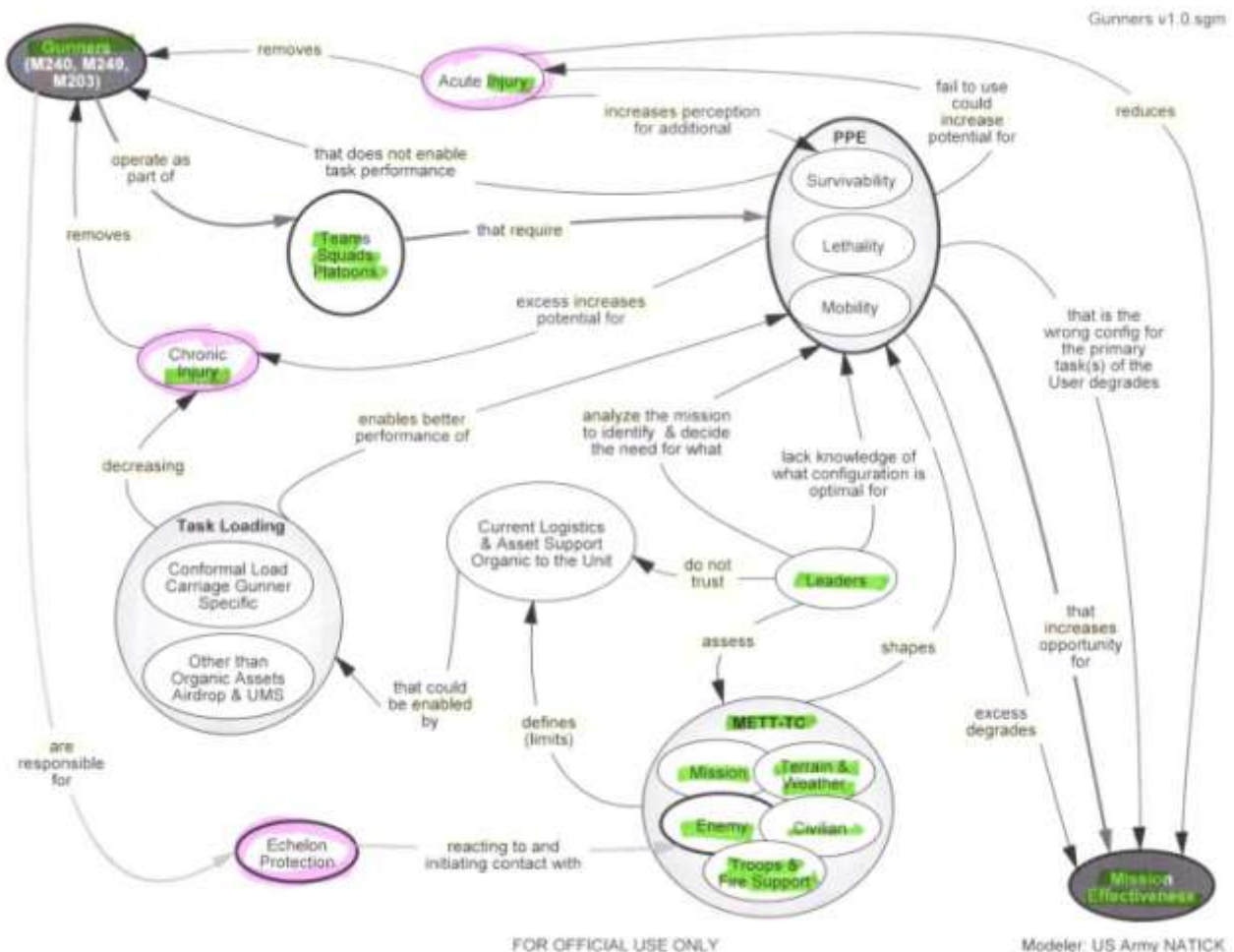
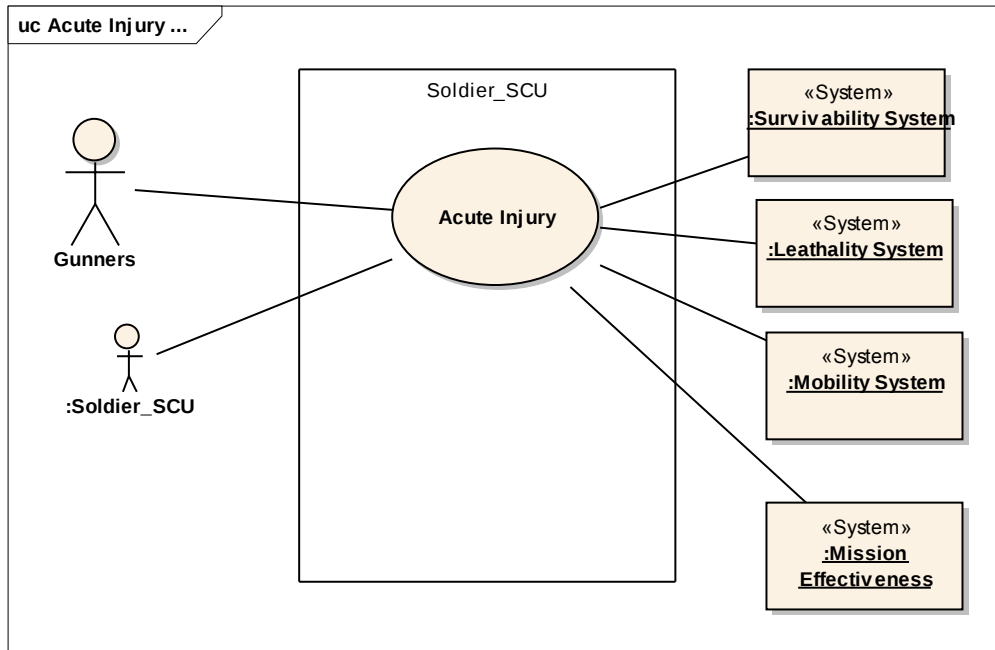


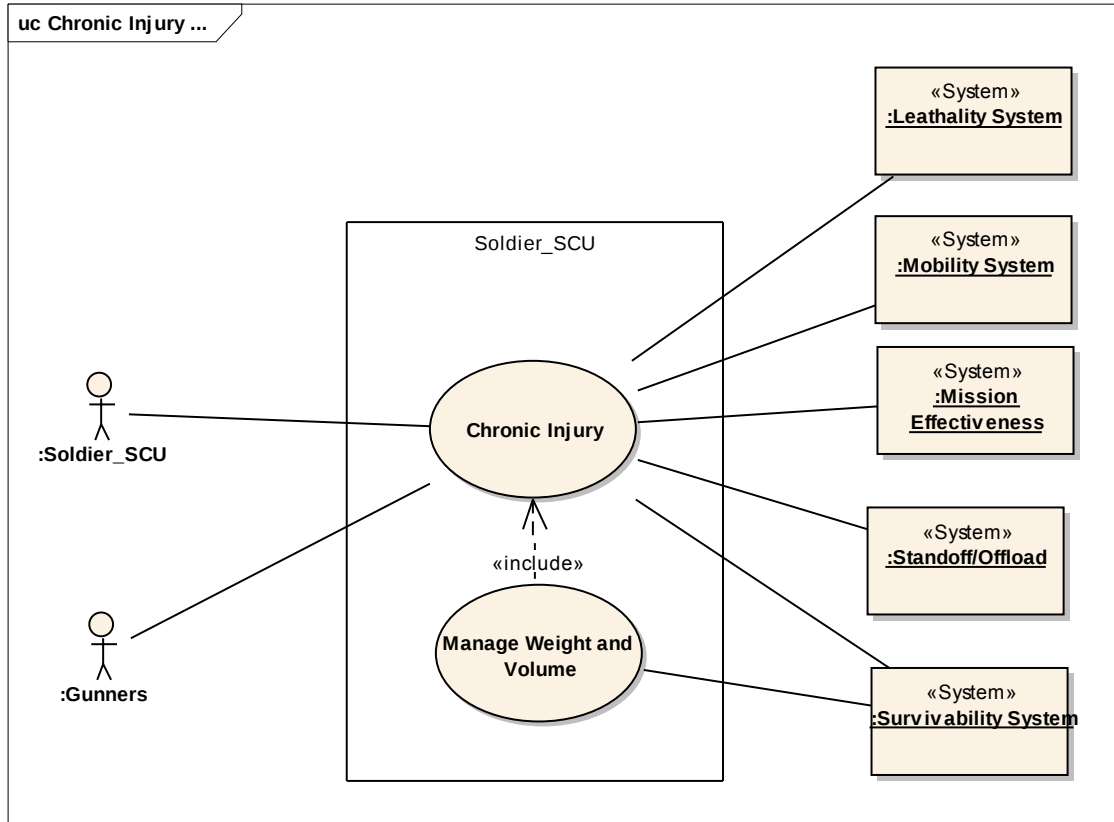
Figure 23 Gunner Systemigram

1. Highlight the nouns, verbs, and adjectives in the, Gunnery, Systemigram (Figure 23).
2. Two of the highlighted use cases, Acute Injury and Chronic Injury, in pink are recognized as already being developed for the Soldier SCU Systemigram. Since the two use cases are already developed the nouns linked to each use case are compared to those already connected in the model. It is recognized that Lethality System, Mobility System, and Gunnery should be added to the Acute Injury Use Case (see Figure 24).



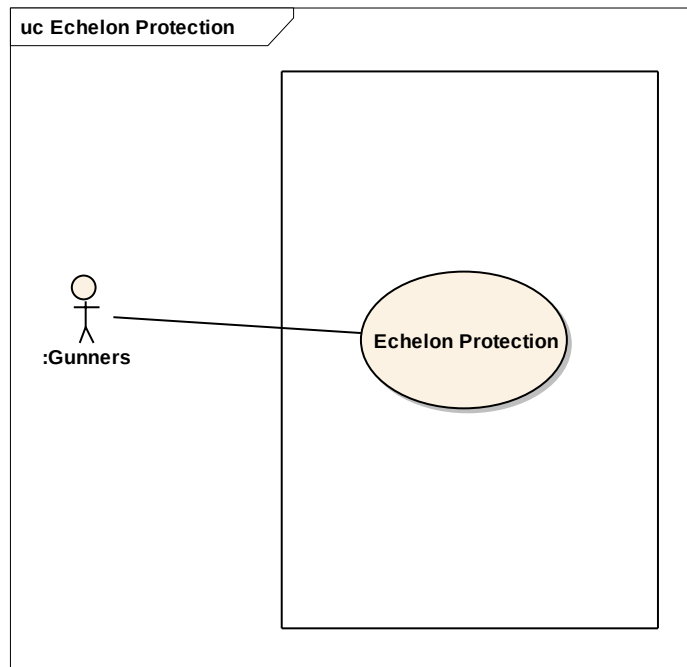
**Figure 24 Updated Acute Injury Use Case Diagram for Gunner Systemigram**

3. During the modification of the Use Case diagram it is discovered that Leathality System and Mobility System need to be added to the Soldier\_SCU Domain diagram. The two systems are added to the domain diagram.
4. The question of where Gunners should be represented on the domain and actor diagrams is not resolved since they are not represented together in any Systemigram.
5. Next the Chronic Injury use case is updated to include the Leathality and Mobility Systems (see Figure 25).



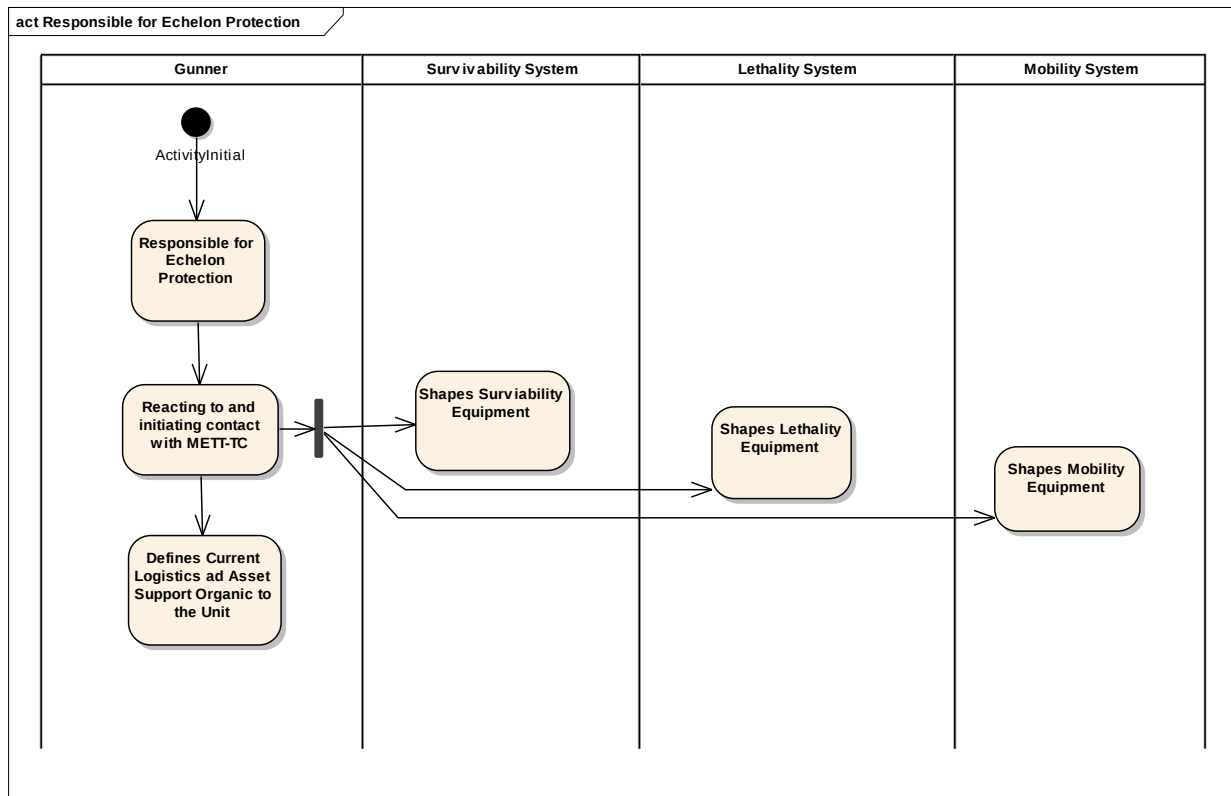
**Figure 25 Updated Chronic Injury Use Case for Gunner Systemigram**

6. A new use case was created for Echelon Protection (see Figure 26).

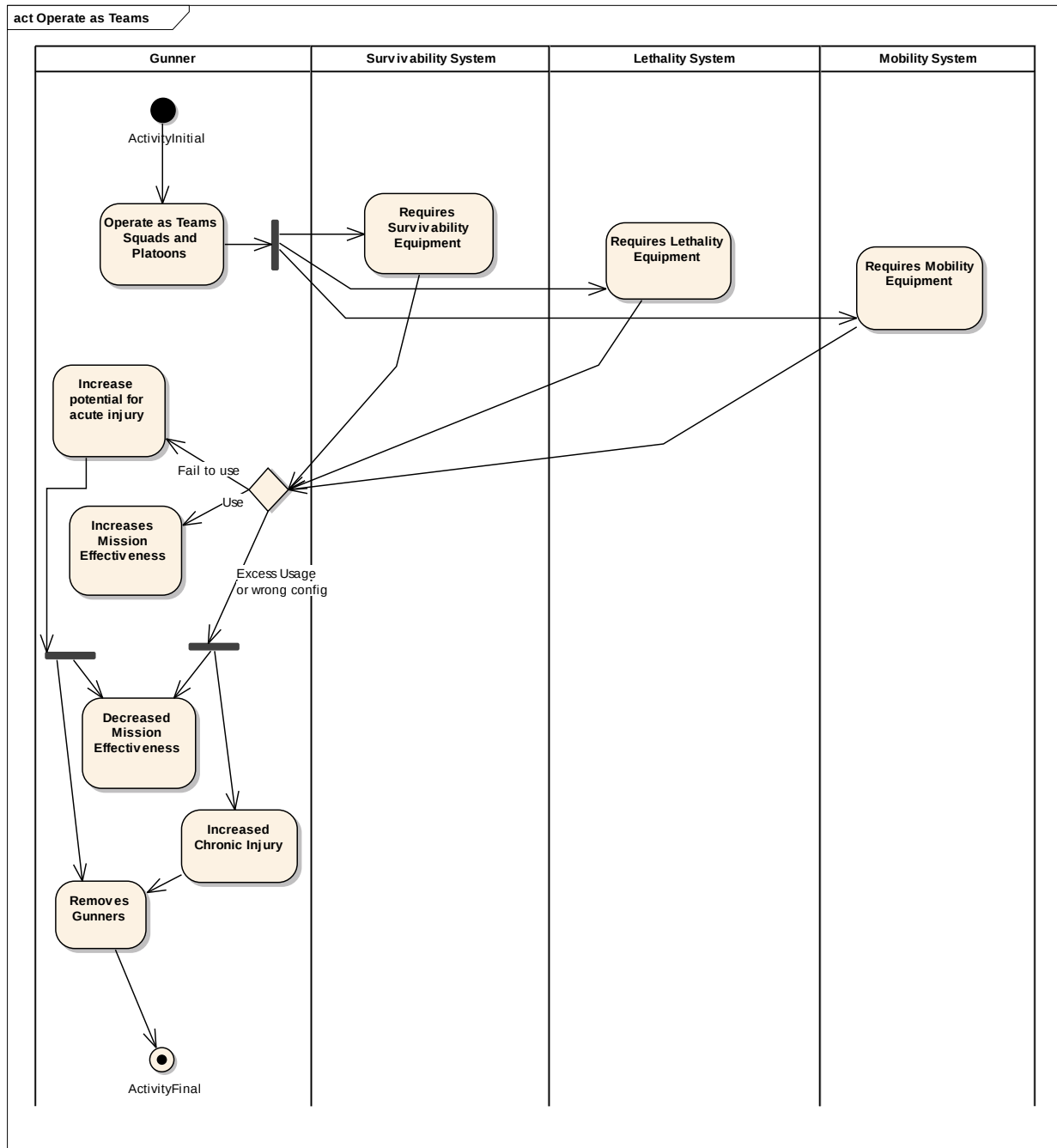


**Figure 26 Echelon Protection Use Case**

7. Starting at the upper left of the Gunner Systemigram the Operate as part of the Teams Squads Platoons activity diagram is identified by the outgoing link (main path) from Gunners.
8. The Teams Squads Platoons activity diagram was created (see Figure 27) by following the main path in the Systemigram plus adding in additional links that flowed from objects in the main path of the Systemigram.

**Figure 27 Operate as part of Teams Squads Platoons Activity Diagram**

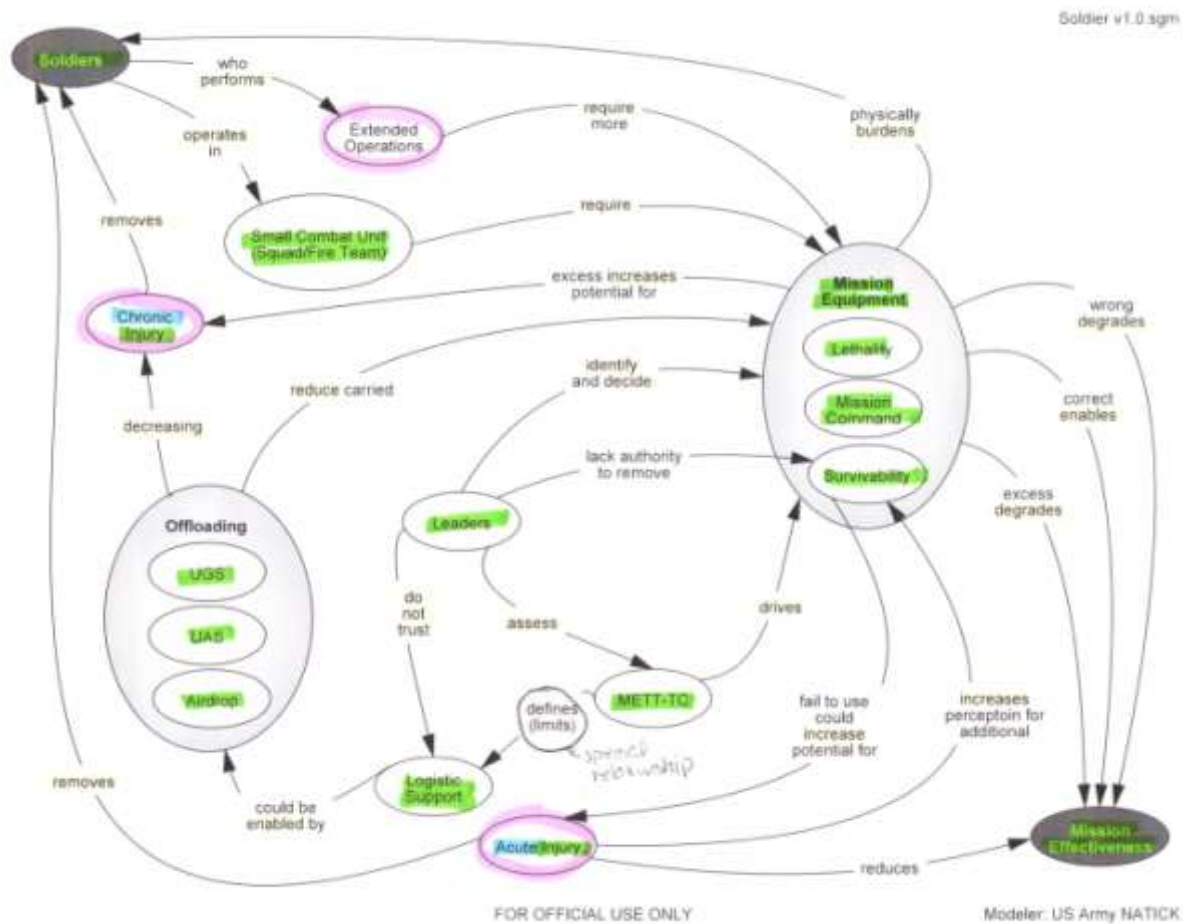
9. The next path that is analyzed from the Systemigram is Responsible for Echelon Protection (Figure 28). This path is turned into an activity diagram using the flow and links shown in the Systemigram.



**Figure 28 Responsible for Echelon Protection Activity Diagram**

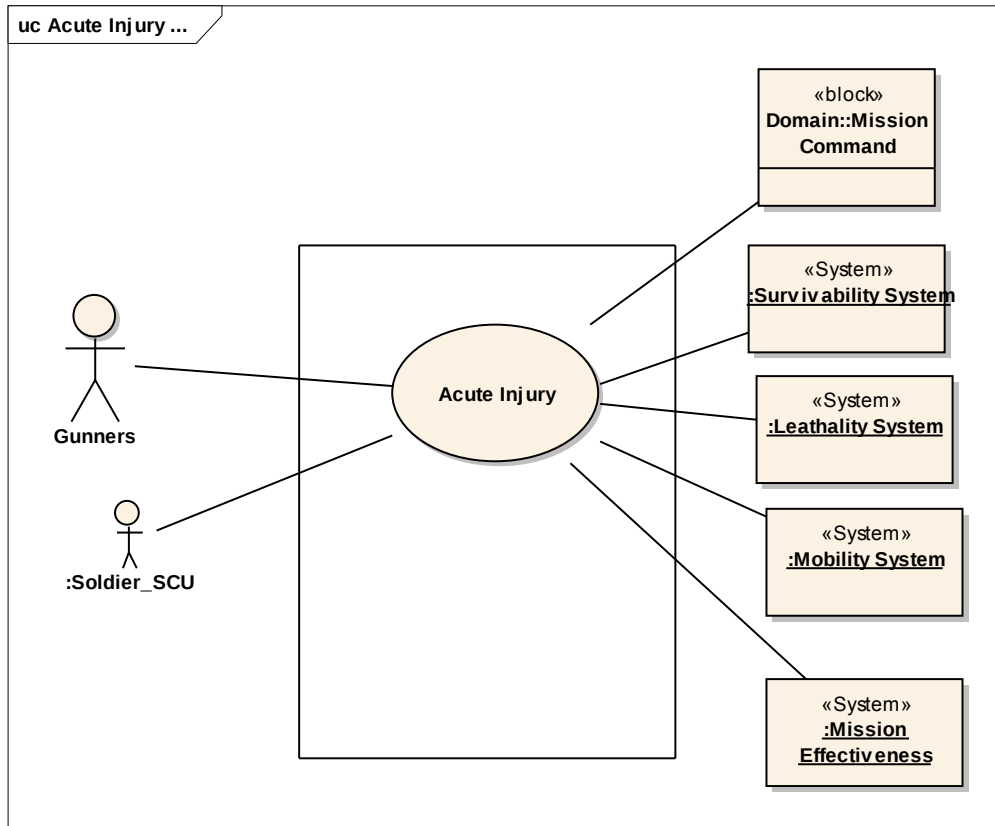
## SOLDIER SYSTEMIGRAM

1. Highlight the nouns, verbs, and adjectives in the, Soldiers, Systemigram (see Figure 29).

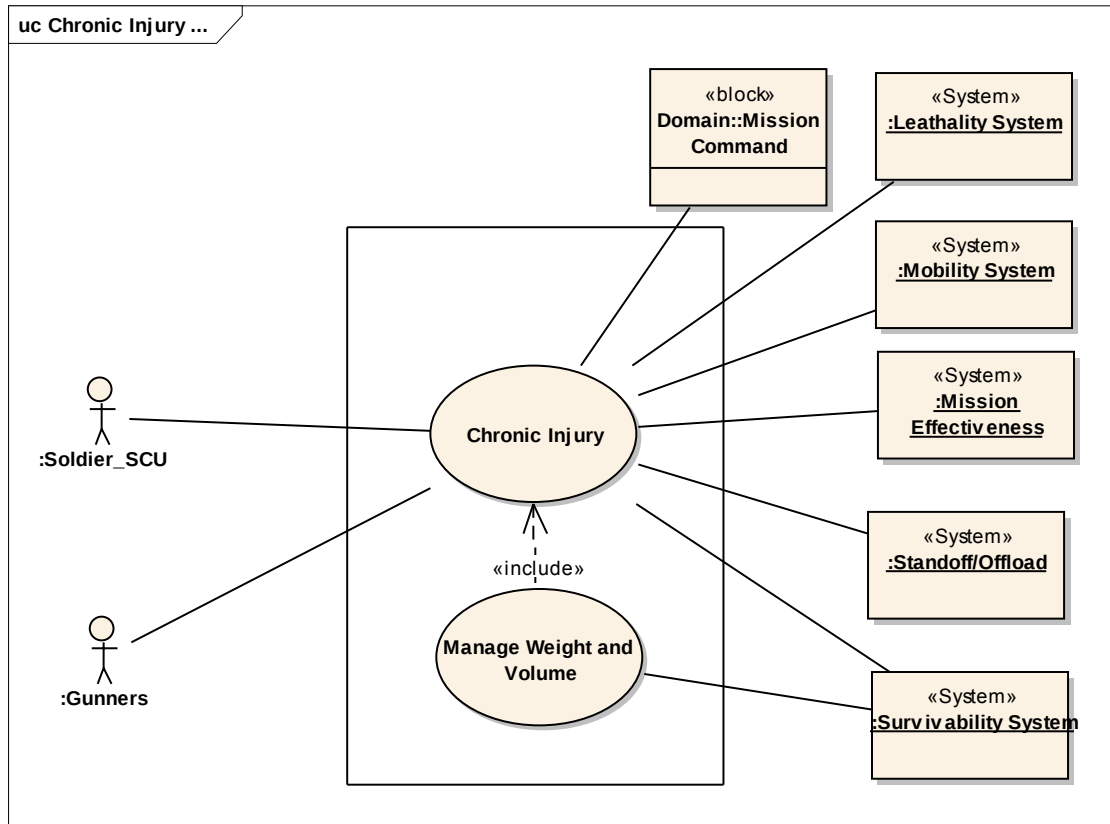


**Figure 29 Soldier Systemigram**

2. Two of the highlighted use cases, Acute Injury and Chronic Injury, in pink are recognized as already being developed for the Soldier\_SCU Systemigram. Since the two use cases are already developed the nouns linked to each use case are compared to those already connected in the model. It is recognized that Mission Command should be added to the Acute Injury Use Case (Figure 30) and Chronic Injury Use Case (Figure 31).

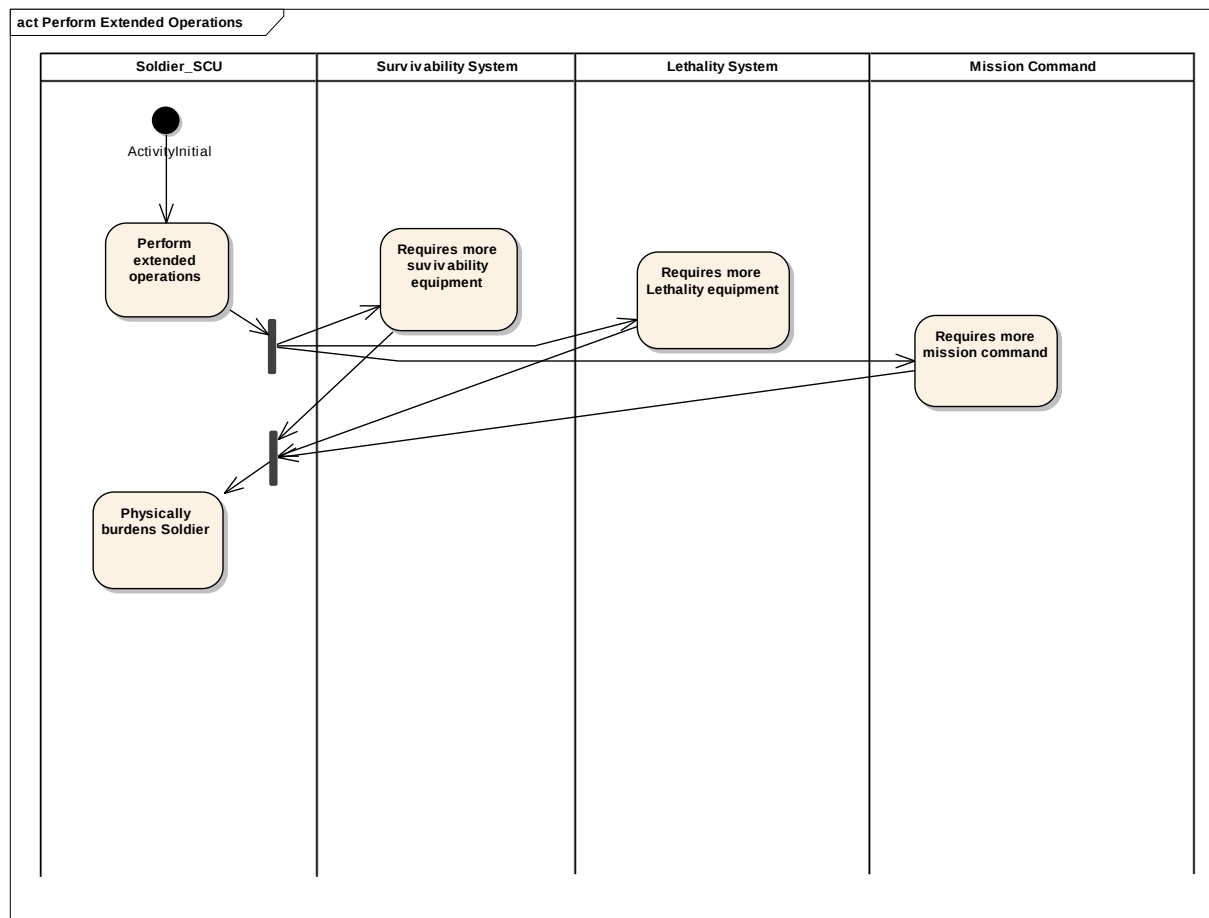


**Figure 30 Updated Acute Injury Use Case for Soldier Systemigram**



**Figure 31 Updated Chronic Injury Use Case for Soldier Systemigram**

3. It is noticed while updating the use case diagrams that Mission Command needs to be added to the Domain diagram. The domain diagram is updated to include Mission Command.
4. Starting at the upper left of the Soldier Systemigram the Performs Extended Operations activity diagram is identified by the outgoing link from Soldiers.
5. The Performs Extended Operations Activity Diagram was created (see Figure 32) by following the path in the Systemigram.



**Figure 32 Performs Extended Operations Activity Diagram**

## TRANSFORMATION CHALLENGES

During this research, the team found there were certain relationships/links on the Systemigram that do not translate well. For instance, “resulting from” and “quantified in” links are difficult to model. Other challenges to consider when translating a Systemigram to SysML include:

- (1) The relationship within the overall domain can be hard to translate. For example in the set of Systemigrams used for this exercise we have a gunner and a soldier but nowhere in any of the diagrams is that relationship described. So in the final domain diagram “Leader” is not connected because from the Systemigram it is unknown if a “Leader” is a soldier or the exact relationship is.
- (2) At the current time nodes such as “Leaders” in the “Gunners” Systemigram that appear in the middle of Systemigram but have no input links (only outputs) are not translated into SysML diagrams

The lesson learned here is that when decomposing Systemigrams, it is important to not reuse nodes at the different levels of Systemigrams unless they are exact nodes.

## 3 MODEL BASED SYSTEMS ENGINEERING

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### INTRODUCTION

This collaborative work was conducted by researchers at the University of Virginia and the Fraunhofer Center for Experimental Software Engineering. Input, feedback, and resources describing Army contingency bases (CBs) were provided by experts from PEOs within the Office of the US Assistant Secretary of the Army for Acquisition, Logistics, and Technology (ASA(ALT)) and the Army Corps of Engineers. This work is a companion to the ASA(ALT) Contingency Basing Initiative – an ongoing effort to establish a contingency basing Program of Record.

---

### PROBLEM STATEMENT

This part of this project addressed two research and development problems in the systems engineering of Army Contingency Basis (CB).

First, CB planning efforts are producing a diversity of partial, often not well validated, not well reconciled, and non-interoperable CB models. This state of affairs complicates the tasks of designing, provisioning, operating, and evolving CBs by deny designers the tools needed to adequately analyze, update, and employ valid, comprehensive models. Models developed to date include models of cost, functional decomposition, structure and behavior using SysML, dynamic logistics (Sandia), and now Systemigram models, as introduced above. These models are in turn represented concretely within a variety of modeling tools and formalisms without the benefits of consistency maintenance through tool interoperability.

Second, the complexity of CB modeling, design, and operation is greatly complicated by the extensive, often poorly understood coupling of diverse concerns, particularly when such concerns are handled by separate, "siloe" organizations within the US Army. The problem is that when decisions that are coupled in actuality are optimized in isolation, the outcomes at the system level are often far from optimal. A minimal approach to this problem requires far better mapping (representation) of concerns and coupling among concerns (e.g., power, water, and so forth), so that system-level consequences of local decisions, actions and conditions can be reasoned about effectively. A more far-reaching approach involves the restructuring of dependencies through improved modularization of CB designs and operations. Even when dependencies are understood, overly tight and extensive coupling creates significant problems, particularly by limiting the capacity for and increasing the cost of and time required for CB adaptation and evolution.

---

## PROJECT GOALS

We formulated goals for the pair of model-based systems engineering tasks, taken as a cohesive project. First, we sought to develop a conceptual framework implemented in an early prototype modeling tool through which we could start to reconcile and represent and reconcile important concepts found in the diverse current models, and in terms of which we could explicitly represent coupling relationships among them in a computable, analyzable form. These concerns include definitions of key measures of CB performance (outcome parameters), external conditions (environment parameters), and parameters over which CB designers and operators have control.

Central to this effort was explicit attention to the issue of coupling both within and among *environment*, *design/decision*, and *outcome* parameters, even if only in informal (as opposed to precise mathematical) terms. For example, in early stages of modeling, we aim for it to be possible to model coupling of decisions about locale, water supply, power, and resupply demand without the usability burden of mathematical precision.

The explicit, even if informal, representation of coupling relationships among explicit, even if informally described system parameters is at central to our work. It is necessary for human reasoning about the effects of decisions, for automated analysis of coupling and modularity properties, and to support decision-making about any restructuring of CB designs, operational activities, and supporting organizations and their interactions.

In addition to providing a capability for modeling coupling of technical parameters, as described above, we also aimed for a framework in terms of which we could model the organizational structures that support CBs. Our premise, based on our task definitions, was that separate organizational units often handle separate CB parameter decisions, and that these decisions are often not sufficiently well coordinated, leading to outcomes that are significantly suboptimal in important dimensions. Our modeling approach thus explicitly represents organizational roles and the mapping of these roles to technical (environment, decision, and outcome) parameters. The coupling among the technical parameters can then be used to reason about required interactions for coordination among the supporting organizational units. Our goal was to enable reasoning about required interactions, comparisons between required and actual interactions, and thus about the possible need for interventions and courses of action relevant to achieving adequate coordination of decision making in the design, operation, and evolution of CBs.

Next, we aimed to provide a prototype of "social" modeling tool: one that distributed modelers engaged in developing such models could use collaboratively in the process of determining what are pertinent system parameters, relationships, roles, assignments of responsibility, and consequences of given structures and assumptions. We thus sought to produce a prototype, web- and cloud-computing-based modeling environment for these purposes. To this end we adapted and significant developed technology that we produced in our labs by earlier research.

Finally, we aimed to validate our modeling approach and the tool support developed for it through empirical study and early experimental applications in the CB domain.

---

## APPROACH

Our approach was in two parts. The University of Virginia took primary responsibility for developing the conceptual underpinnings and technological for modeling in the style presented above. The Fraunhofer Institute team took the lead on empirical investigation and evaluation. With the technology developing at the same time as the empirical work was conducted, Fraunhofer sought to develop CB models grounded in the best data that was available to our team, including interviews with CB subject matter experts, with an emphasis on identifying technical and organizational parameters and their coupling and mapping relationships, but without an attempt to map results strictly into the University of Virginia framework. The University of Virginia sought to evolve the conceptual model and prototype tooling to the point we could begin to evaluate its use for CB modeling, to identify any shortcomings, and to drive an incremental and evolutionary modeling and software development process based on mutual interaction. The teams interacted on a regular basis and these interactions informed the activities of each group throughout the period of our project. We also had numerous on-site meetings with the subject matter experts at our sponsoring site, as well as regular telecons with other organizations that were participating in the Army CB effort. The remainder of this section described the methods and outcomes of this joint research and development activity.

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## EMPIRICAL EXPLORATION AND BUILDING OF CONTINGENCY BASE MODELS

Our empirical work aimed first to map key CB issues through interviews with subject matter experts, available documentation, and other means, and then to map the results broadly into the modeling framework discussed herein. In this section, we describe our process for extracting models of contingency base environment, decision, and outcome parameters, as well as organizational-to-technical parameter mappings.

---

## MODELING GOALS

The impetus for this work was an initiative on the part of our sponsors to improve the effectiveness and efficiency of decision making in planning and operation of US Army CBs. Decision processes include many tacit relationships and multiple stakeholders whose relationships are not always clearly defined. For CBs, these decision processes are primarily captured in Army guidance documents (standards, handbooks, regulations) and in expert knowledge. We sought to build CB models in a scientifically rigorous way.

**Goal 1:** To define a *rigorous analytical method for extracting models* of decision making processes from qualitative sources;

**Goal 2:** To create *useful models of Contingency Basing* decision processes that capture the variables, relations, and stakeholders involved in the decision.

To have confidence in our CB modeling activity (the results of Goal 2), our analytical method (Goal 1) addresses five model-building challenges identified in our proposal:

**Challenge 1:** Define scope - An analysis of this type requires a **common unit of analysis** so that key concepts can be identified and analyzed across different documents, even if referred to under different terminology. Our units of analysis are *the resources that are consumed or generated by a Contingency Base*. We adopted the set of 8 resources identified in the functional decomposition model created by other members of ASA(ALT)'s CB project.

Reconciling the ontologies that are implicit in the multiple models and documents we encountered is a key challenge for a CB modeling, analysis, and design improvement initiative. Our results suggest that the general form, and perhaps web-based aspects of our framework and tooling, have significant potential to assist in this fundamental aspect of model integration and analysis. Eventually a formal approach to ontology, even if only for the most essential concepts, seems to be an activity worth considering.

**Challenge 2:** Cohesion – The models developed must be internally consistent so that they can be more easily understood and useful. Our analysis is **iterative**, beginning with a semi-unstructured series of questions to extract model components, followed by analysis of component relationships, leading to more structured questions as important concepts begin to emerge.

**Challenge 3:** Consistent vocabulary – Experts from different functional areas may use different terms. The concepts elicited must be mapped to one another consistently despite differences in the technical vocabularies to **develop a consistent vocabulary that brings key concepts together**.

**Challenge 4:** Traceability – The **source of each individual finding must be identified** so that we have traceability back to the original source to elicit more details if needed, as well as a mechanism for resolving potential discrepancies among sources. (If two different sources present incompatible information about decision making, it may be that each is accurate but only if different domains / contexts.)

**Challenge 5:** Verified – Results of such an analysis should be repeatable – not simply the result of one person's opinion or (potentially biased) understanding of the problem domain. Our analysis was conducted by three researchers independently and the findings triangulated and discussed to obtain confidence in the results.

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## MODELING APPROACH – ITERATIVE DOCUMENT ANALYSIS AND CODING

Our model-building approach relied on a rigorous qualitative analysis technique known as **coding**. Coding is a well-accepted technique that extracts concepts from qualitative data by attaching “codes, or labels, to pieces of text that are relevant to a particular theme or idea of interest” [Seamano7]. Coding outputs a set of concepts that can be

arranged hierarchically (at different levels of abstraction) and form the basis of the basic ontology necessary to develop a mapping between various domains and terminology. For example, in prior work, we used similar techniques to create a hierarchical model of information sources (e.g. documentation, local experts, etc.) and the ways these resources are used in software maintenance in the aerospace domain [Seaman02, Lutters07]. Coding analysis is appropriate for qualitative sources of information that are in a narrative of semi-structured form, such as the guidance documents and regulations we used as sources of data. We now describe the source materials used in our coding analysis and provide a detailed description of the analysis steps.

## Source materials

To identify and model the variables and stakeholders involved in the decision process of contingency base planning, we proposed to build our models based on both Army CB documentation (standards/guides) and on interviews with Army CB experts. These resources would provide the best sources of information that cover a broad swath of CB decisions, rather than focus on specific aspects of CB operations (e.g. power generation and optimization). Unfortunately due to availability constraints of the experts, we were not able to conduct these interviews.

We applied coding to the following documents to obtain an overview on the decision hierarchy and potential stakeholders involved in the decision process of contingency base planning:

- ATTP 3-37.10/MCRP 3-17.7N – Base Camps: “a compilation of tactics, techniques, and procedures (TTP) found in doctrine, lessons learned, and other reference material that, for the first time, provides an integrated systematic approach to base camps. It codifies the recent efforts of the Base Camp Integrated Capabilities Development Team as part of the Army capabilities-based assessment process and serves commanders and their staffs as a comprehensive ‘how-to’ guide for performing all aspects of the base camp life cycle during deployments.”
- Army Corps of Engineers Base Camp Development EP 1105-3-1 – Base Camp Development in the Theater of Operations: focuses primarily on the engineer-specific areas of base camp planning, such as selecting a location, and documentation needed for a base camp in any geographic area.
- Joint Forward Operations Base (JFOB) Force Protection Handbook: designed as a quick reference guide for a systematic approach to planning, developing, and improving JFOB defensive capabilities to counter threats to JFOBs in Iraq and describes best practices based upon lessons learned in Iraq.
- US Army R 415-1 – Construction and Base Camp Development in the USCENTCOM Area of Responsibility (“The Sandbook”): describes basic standards for the construction of base camps. The document is aimed at engineering units at forces and contract authorities. The Sandbook is mostly a subset of the information in the JFOB Handbook.

- Contingency Basing Functional Decomposition: an analysis of the functional capabilities required of a VFOB (Very Large Forward Operating Base) prepared by members of the ASA(ALT) Contingency Base project.

## Modeling process

Our modeling process is summarized in the steps below.

1. Identify unit for analysis
2. Independent document analysis
  - a. Identify variables, relations, and stakeholders
  - b. Merge similar terms
  - c. Organize variables into groups (e.g. facilities, mission parameters, activities, facilities, decision nodes)
3. Compare findings from individuals
4. Collate model components from multiple sources
5. Identify dependencies and model relationships
6. Build visual models

**Step 1: Identify unit for analysis** – The scope of the decisions made in CB planning and operations was too large to model given our available resources. Thus, we focused on specific resource areas as identified in the Army’s CB Functional Decomposition (FD). The FD identified eight resource areas: power, fuel, base footprint, building footprint, waste, water, food, and network. We focused on the decision hierarchies two resources, water and fuel, as well as the decisions involving the operation of a medical facility. We chose these resources based on the diverse concerns and dependencies in water and fuel management as communicated to us in meeting with the Army CB project team and because these resources frequently appeared in the source materials as examples. Water and fuel supply and management are central to planning and running a base, and water in particular is well documented. Medical facilities are sufficiently complex to show the use of those two resources and the complexity of the decision process while giving some pointers to other resources used or produced that need to be accounted for when planning.

**Step 2: Independent document analysis** – Each document from Section o was assigned to two Fraunhofer researchers to perform coding analysis on independently. We searched and read these documents for keywords related to fuel (e.g. fuel, coal, gas, petrol, generator), water, and medical facilities. We extracted and coded text according to the following parts of the decision space model:

- Variables (Parameters)– white water, gray water, black water, billeting, dining, laundry, maintenance, construction, waste water transportation, potable water distribution, weather, temperature, threat level, etc.
- Relations – e.g., self-reliant water production REDUCES supply line strain; personal water container type IMPACTS waste management cost.
- Stakeholders – e.g. Base Camp Commander, logistics staff officer, safety officer.

After applying the codes, similar terms were merged, for example “drinking water” and “potable water” are very similar, as are “jet fuel” and “JP8”. After merging similar terms, the variables were organized into groups. For example, white water, gray water, and black water were grouped under “Water type”, while billeting, dining, and laundry were grouped under “facilities”. These groups allowed for a more easy conceptual understanding of the elements of a CB.

**Step 3: Compare findings from individuals** – In this step, the group met to compare the results of the coding analysis. Agreement was generally high, though the reviewers for a given document may not overlap completely. The codes were merged to form a complete set – in no case did the reviewers disagree about the coding of a particular section after the group discussion. The combined set of codes for each source document was used as the basis for the model building.

**Step 4: Collate model components from multiple sources** – The variables, relations, and stakeholders from each document were combined to paint a more complete picture of the fuel, water, and medical facility management on a CB. During this step, it became obvious that no one source material provided all of the information needed to understand the complete picture of the decisions involving water, fuel, or medical facilities. This is, perhaps, not surprising, but is indicative of the challenges facing CB planners: all of the considerations that go into a decision are seemingly not laid out in one cohesive source reference.

**Step 5: Identify dependencies and model relationships** - Our coding activities yielded a set of key concepts related to each resource which is important for contingency base planning and the relationships among these areas. We extracted decision hierarchies, potential stakeholders involved in those decisions or sub decisions, as well as dependencies or relationships that may impact the actual decisions or have to be considered when making these decisions. In the models, these constraints or relationships appear as parameters. We distinguish between the following parameters:

- Environment parameters, i.e., parameters that describe the situation and can't be changed, such as threat level, geographic location, or minimum amount of drinking water required per person per day
- Decision parameters, i.e., parameters that can be changed or modified, in order to obtain different results, such as the number of water deliveries scheduled per week, number of people planned on base, the number and types of facilities to be built, if water is to be provided by a well or sent in by truck, and
- Performance parameters, i.e., quality parameters that are impacted by the decision parameters, such as tank size needed on base, amount of fuel consumed by the facilities, amount of food needed

**Step 6: Build visual models** – We visually modeled the fuel, water, and medical facility decision spaces to support more useful analysis. The textual responses from each expert were transformed into a graphical representation. The use of diagrams has shown to be extremely useful not only in capturing processes and flows, but also when

reviewing the resulting models with experts [Cordingly89]. A major part of decision making in general involves analyzing the available alternatives described in terms of cost (or constraints on making a decision) and benefit. Detailed cost/benefit or constraint analysis requires expert opinion. To show the key elements of the decision process in our models, we therefore decided to represent decisions and sub decision nodes, along with costs/benefits/constraints associated, and stakeholders who may be able to provide this analysis. The visualization step provided a helpful means of representing the information gained, both for our own analysis and as a useful artifact that can be applied during later interactions with experts to better elicit their knowledge and feedback.

### **Relationship to other models being worked**

We designed our modeling and visualization approach to complement and eventually to integrate, not to duplicate, other ongoing work in the Army's Contingency Basing initiative. Other models being worked include:

1. A low-level, executable model of resource consumption and production by Sandia National Labs. This model can be executed to identify the effects of various resource allocations.
2. A model of the number of resources necessary to establish CBs of different sizes developed by the Army Corps of Engineers. The model helps to understand the resource cost-drivers in CB operation.
3. A functional decomposition that maps contingency base requirements (e.g. project the force, collect intelligence histories) to inputs, outputs, and loads. This model is used as one of our source documents.

In contrast, each of our models shows a more high-level view of the decisions to be taken for planning of that resource or facility. The models would enable a decision maker to have a unified view of decisions that are spread out over different parts in different guidebooks. We based our models on the guidebooks, because they are already distilled versions of the key decisions to make and dependencies to take into account and are vetted and approved by stakeholders and can thus be seen as common understanding. These guidebooks can be assumed to be the core information available to any base commander or decision maker to start out with when planning a base.

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## **CONTINGENCY BASE MODELS**

Based on the information available in the guidebooks, we captured information related to the two resources water and fuel, and a medical facility to see how the use of these ties in with decision modeling of an actual facility. Our "empirically based" models (meant to feed into our novel modeling formalism) show the decisions to be taken in the course of the planning process along with interfaces and dependencies or follow-up decisions, as extracted in the guidebooks.

## Water Modeling

The documents distinguish between *white water* – fresh, potable water, *grey water* – water that is typically relatively easy to treat, such as laundry or showers, and *black water* – any water containing human waste. Accordingly, we developed a model each for white water, grey water, and black water, following the steps described in o.

The main problem – how to provide potable water of sufficient amount, quality, and price – can be broken down into several sub decisions, such as a decision on what source(s) to use, how the water will be transported, or how to ensure water quality.

Figure 33 shows the decision hierarchy of how to provide whitewater of sufficient quality and at the required amount at given cost in contingency base planning and how this decision is broken down in sub decisions – modeling the decision process of a contingency base planner. One of the contributions of this "empirical" modeling to the development of our conceptual modeling formalism was to emphasize the need for hierarchically structured sets of system parameters. This in turn led to a key insight for future development of our conceptual modeling approach and supporting tool: that we can leverage the theory of *types* (from the disciplines of programming languages and software engineering) to inform the design of our modeling framework and tools. This insight is very clearly reflected in carefully documented plans for a "version two" of our initial prototype tool.

Our empirically derived models in this area are based on different documents. Therefore, we found it important that information in the model can also be traced back to the original sources and viewpoints. Thus, any information taken from the Army's Base Camp 101 was drawn in blue, information taken from the Army Corps of Engineers Handbook is drawn in red, and information taken from the JFOB Handbook is drawn in green. The need for traceability of abstractly modeled decision (and other) parameters to original source materials is a second insight leading to a requirement to be handled in the ongoing evolution of our conceptual modeling approach and toolset.

In the diagram, dotted lines show decisions that might not always have to be taken. For instance, the decision on the water source would in most cases only require one of its sub decisions, water supplied by well, or water by contractors or water by purification unit.

Note, that we added a decision node that was not mentioned in any of the documents to the diagram – *decide on distribution of water across facilities*. We decided that an important aspect of overall base planning is to decide how water distribution across different facilities will be negotiated in case it is a scarce or limited resource. When a planner walks through one of these decision hierarchies, each of these decisions and sub decisions is impacted by parameters that may need to be considered when making the decision. For instance, the decision to use a well as a water source requires a local aquifer. Some decisions may impact further decisions. For instance, if a purification unit is to be used, additional power sources will be required as a consequence. In our diagrams, these parameters and relationships between the parameters and the decision nodes show as trapezoids (parameters and relationships are summarized into one shape

to increase legibility) and color-coded according to the source document the information was extracted from (blue for Army's Base Camp 101, red for Army Corps of Engineers Handbook, and green for the JFOB Handbook).

In addition, every single one of these decisions and sub decisions is impacted by mission parameters (omitted from the diagrams for better legibility).

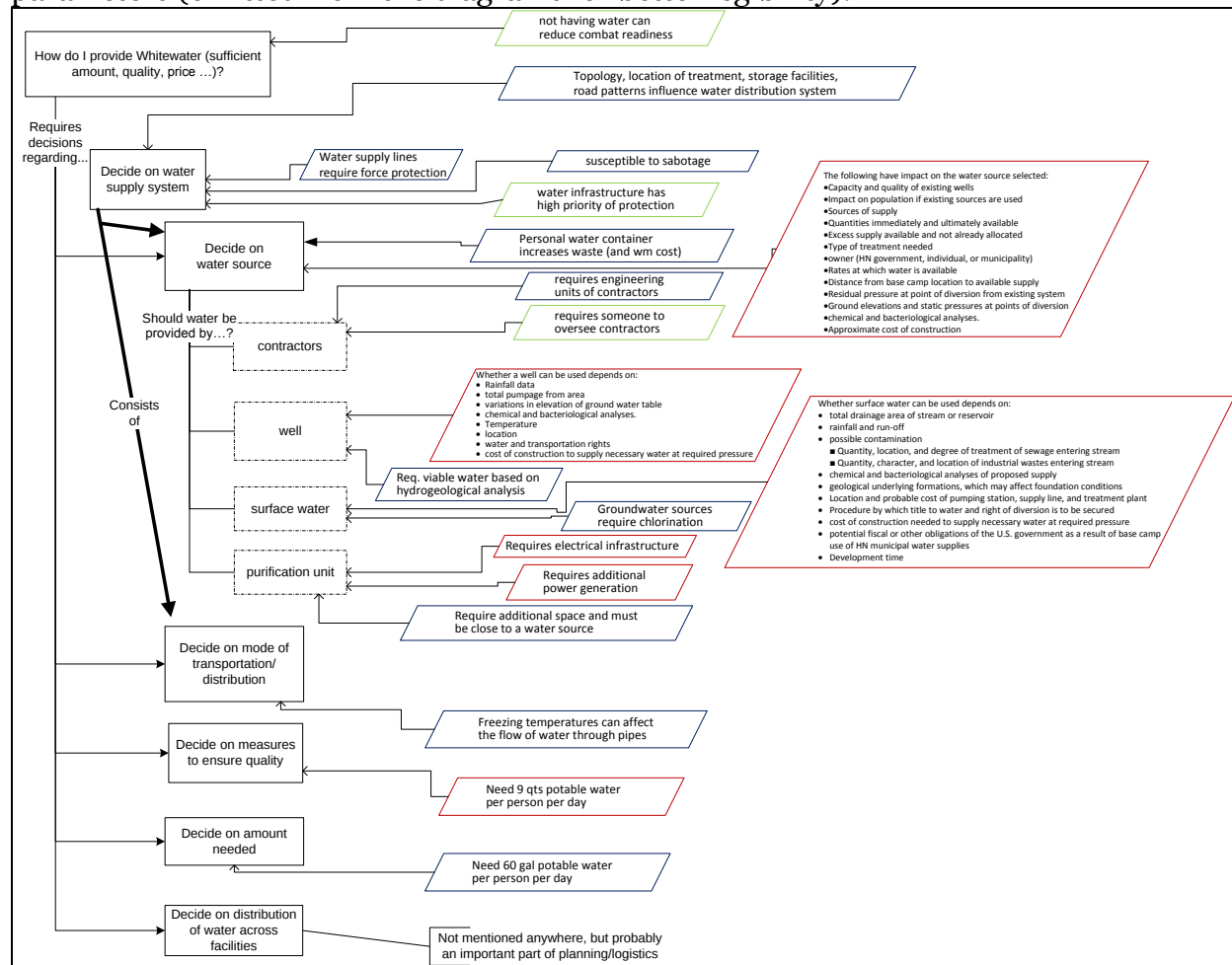


Figure 33: Whitewater decision hierarchy with constraints

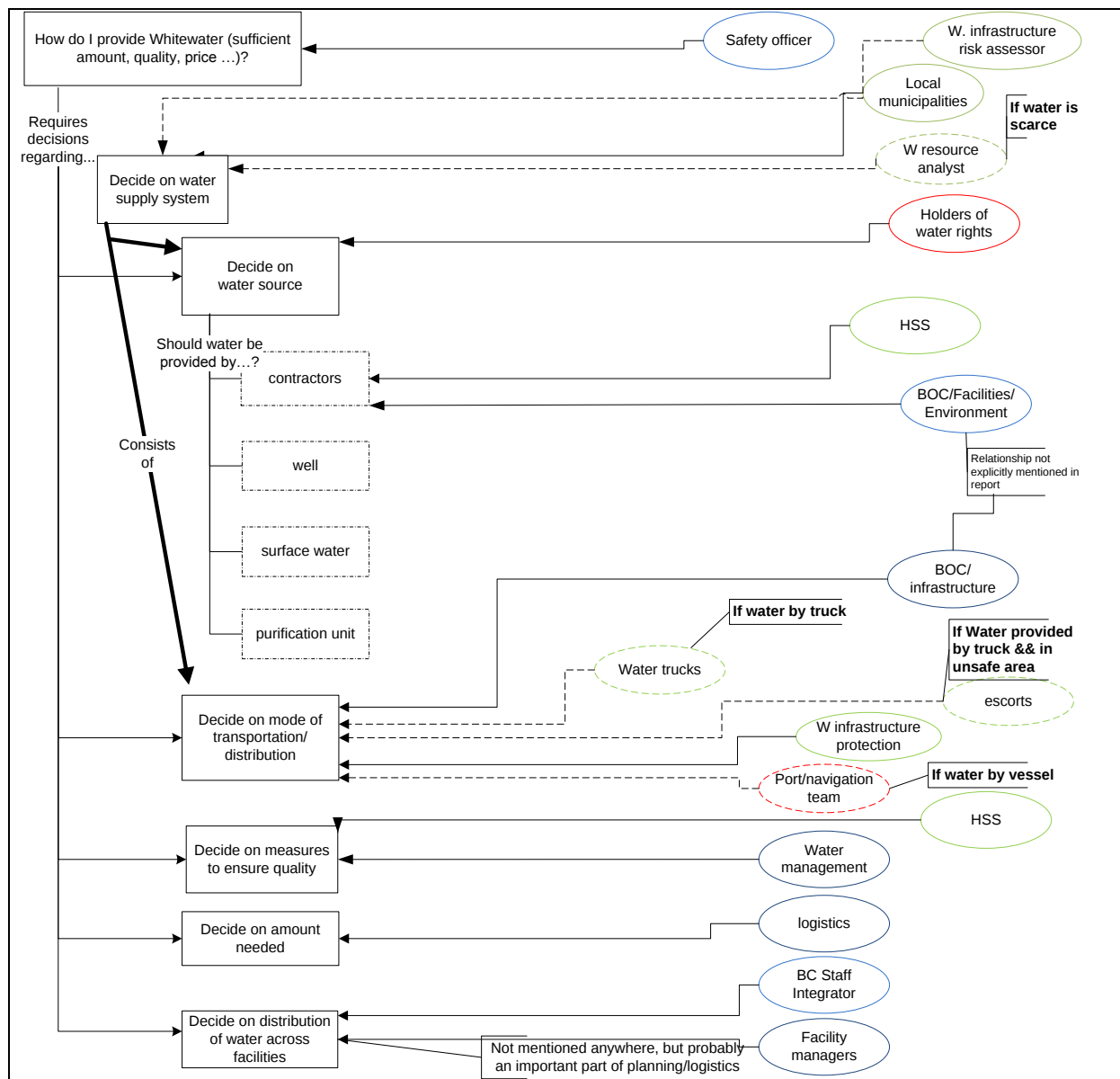
Note that we found inconsistent information when comparing the amount of water required per person and per day in two different documents. Whereas the Army Base Camp 101 document, which is based upon experience in desert environment, mentions 60 gal – 240 quarts – of potable water per person and day, the Army Corps of Development mentions a required 9 quarts of water per day. Driving toward a canonical representation of information in terms of environment, decision, and outcome variables, organizational units, mapping of responsibilities, and coordination requirements at the organizational level induced by coupling of technical parameters is showing itself to be a useful, systematic, and fundamental, method for integrating existing models and related documents.

Apart from the inconsistency mentioned, information drawn from different documents differs in level of detail. For instance, the Army Corps of Engineers Handbook provides a lot more detail the type of water analysis to be performed. However, the handbook lacks guidelines on how the detailed analysis of water is used, and how it impacts further decisions, e.g, what to do if a data point is above the threshold.

Making an informed decision often requires a planner to take into account expert knowledge. Therefore, many other stakeholders are involved in the decision process. A major goal of our work relates to the social network required to ‘traverse’ the decision hierarchy.

Figure 34 shows the (same) decision hierarchy of whitewater supply with its associated stakeholders involved in each level of decisions. The diagram uses ovals to show stakeholders; blue ovals for stakeholders as identified from the Army’s Base Camp 101, red ovals for stakeholders taken from the Army Corps of Engineers Handbook, and green ovals for stakeholders taken from the JFOB Handbook.

Some stakeholders only come into play under certain circumstances, for instance, a water resource analyst is only needed in situations where water is a scarce resource. In the model, these stakeholders are drawn with dotted lines, along with a note under what circumstances these stakeholders are involved.



**Figure 34: Whitewater decision hierarchy with stakeholders involved**

The stakeholders are taken from the documents, thus they don't always correspond to roles (i.e., a set of responsibilities or skills necessary to perform a task), but sometimes positions or divisions.

Although supplying of water has several options for water sources – contractors, well, surface, purification unit – actual stakeholders couldn't be extracted from the documentation. However, a decision maker who has to find feasible water sources might need to know who can provide their expertise in selecting a water source or ruling out a water source.

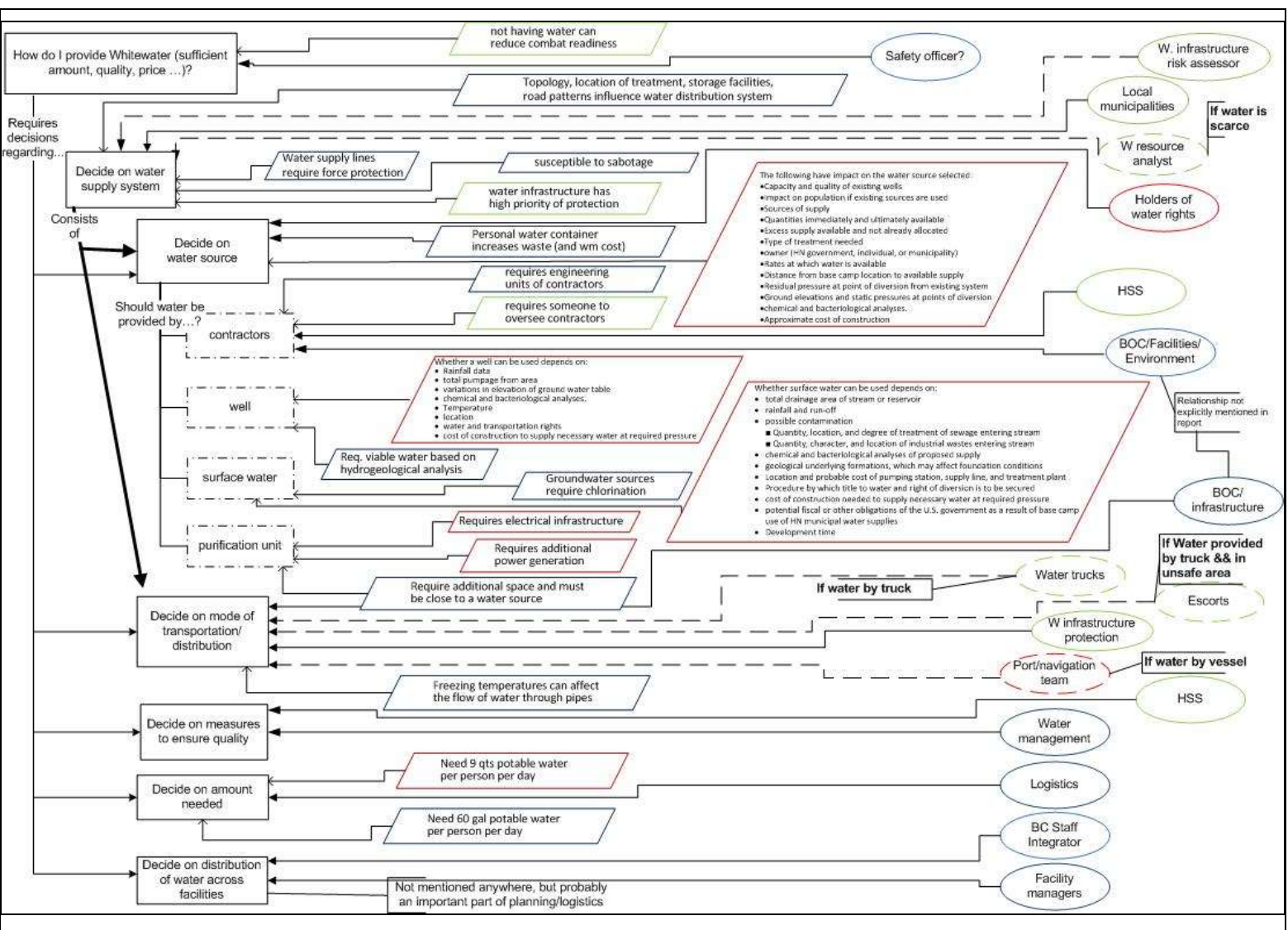
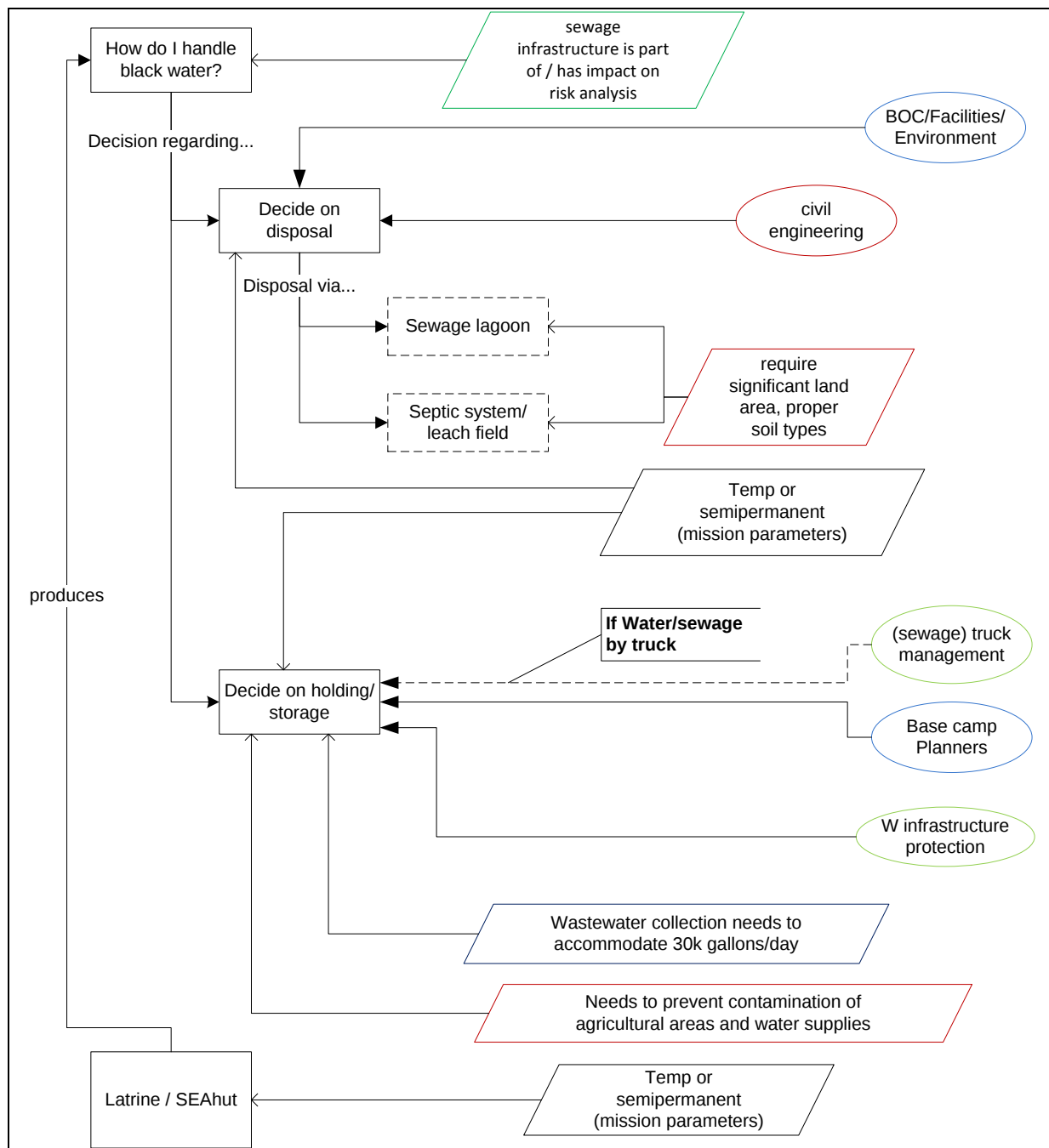


Figure 35: Whitewater decision hierarchy with stakeholders and parameters

Figure 35 shows the whitewater decision tree with the parameters and stakeholders involved – a combined view of Figure 33 and Figure 34.

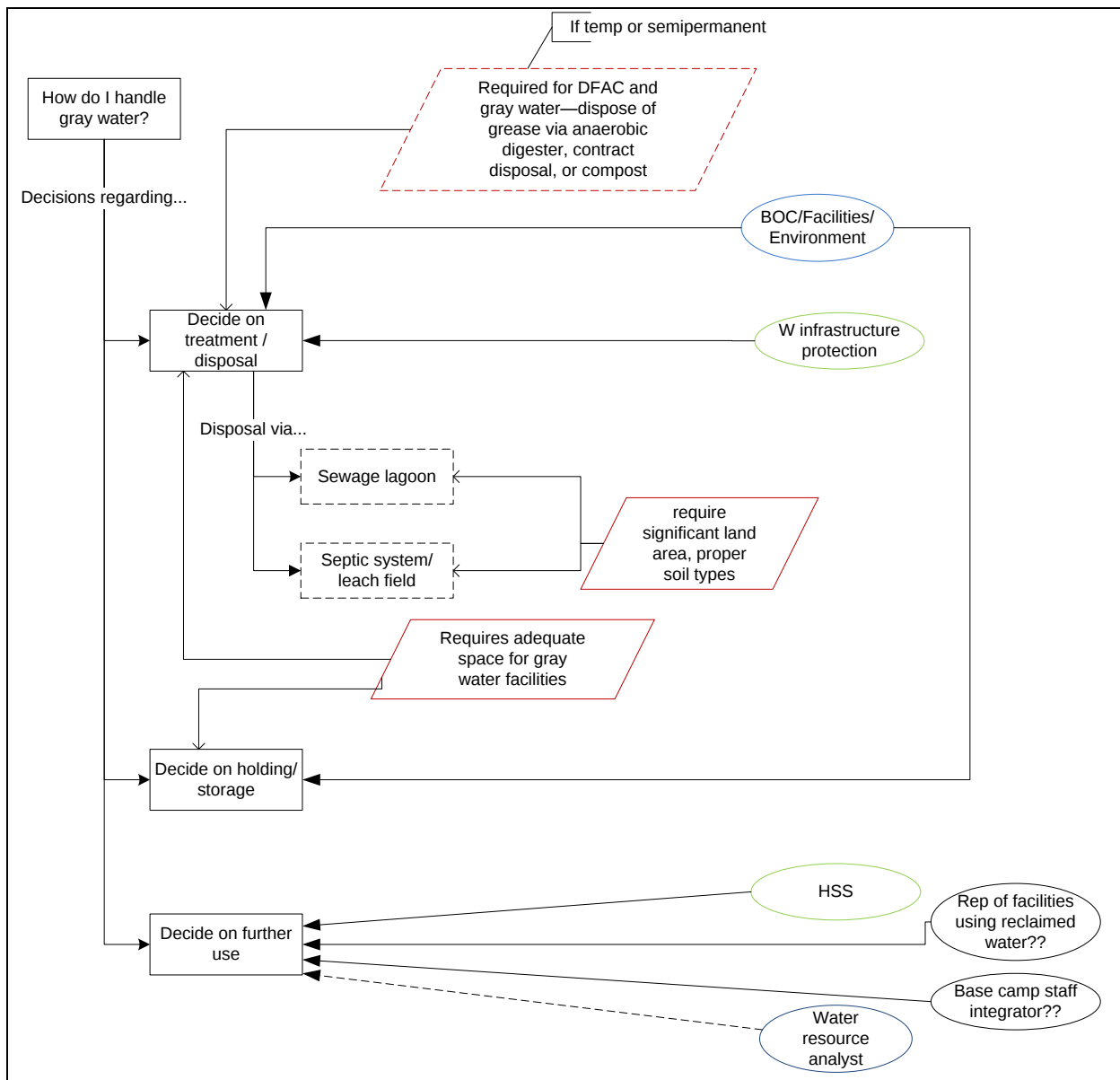
The diagram shows the complex relationships; many stakeholders are involved in the decision hierarchies and in the different aspects of providing water, and for each decision many parameters have to be taken into account. It seems that it is almost impossible for a single individual to make an informed decision, given all the additional parameters that need to be taken into account.

Some parameters are tied to more complex decisions. For instance, the decision if water comes from a well, surface water or other sources has a lot of detailed decision parameters associated with it that impact the decision (e.g., ‘whether a well can be used depends on....’ – ‘whether surface water can be used ...’). For these decisions, expert or stakeholder involvement would be expected at two levels – running the analyses and providing the data to the decision maker, and then interpreting the data to help the decision maker determine which water sources are feasible. However, the guidebooks do not mention any additional stakeholders or experts who could support the decision maker. For instance, one would expect a water analyst to be involved in such a complex and important decision.



**Figure 36: Blackwater decision hierarchy**

Figure 36 shows the decision hierarchy for black water, together with stakeholders involved in the decisions. The decision hierarchies include questions on treatment, and holding/storage. The main parameters influencing how black water is treated and stored are the mission parameters. Sewage handling has an impact on risk analysis, however, we did not find explicit stakeholders attached to any of the decisions. Black water has additional ties to white water, as contamination of agricultural areas and water supplies need to be prevented.



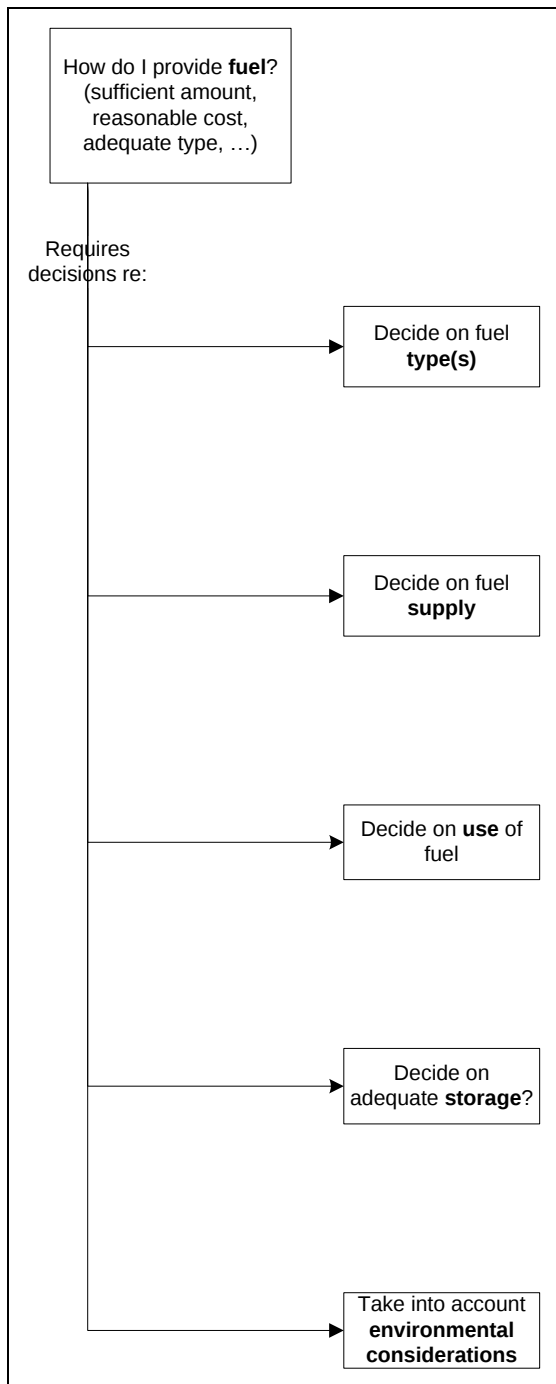
**Figure 37: Graywater decision hierarchy**

Figure 37 shows the decision hierarchy for gray water, together with stakeholders involved in the decisions. The decision hierarchies includes questions on treatment, holding/storage, and on further use of gray water. The decision points for gray water are very similar to the ones for black water. Possible further use of gray water is mentioned, however, parameters influencing that decision aren't explicitly mentioned in any of the reports.

Black and gray water are a lot less documented than white, the distinction between black or gray water is not always clear in reports. Altogether, the decision hierarchy of gray water is not much different from the black water decision hierarchy.

Black and gray water may be treated the same way, although reports claim that recycling gray water might be more energy-efficient or that recycling gray could reduce logistics requirement by using gray water for wash racks or toilets. These would indicate an additional relationship with energy or logistics/white water use.

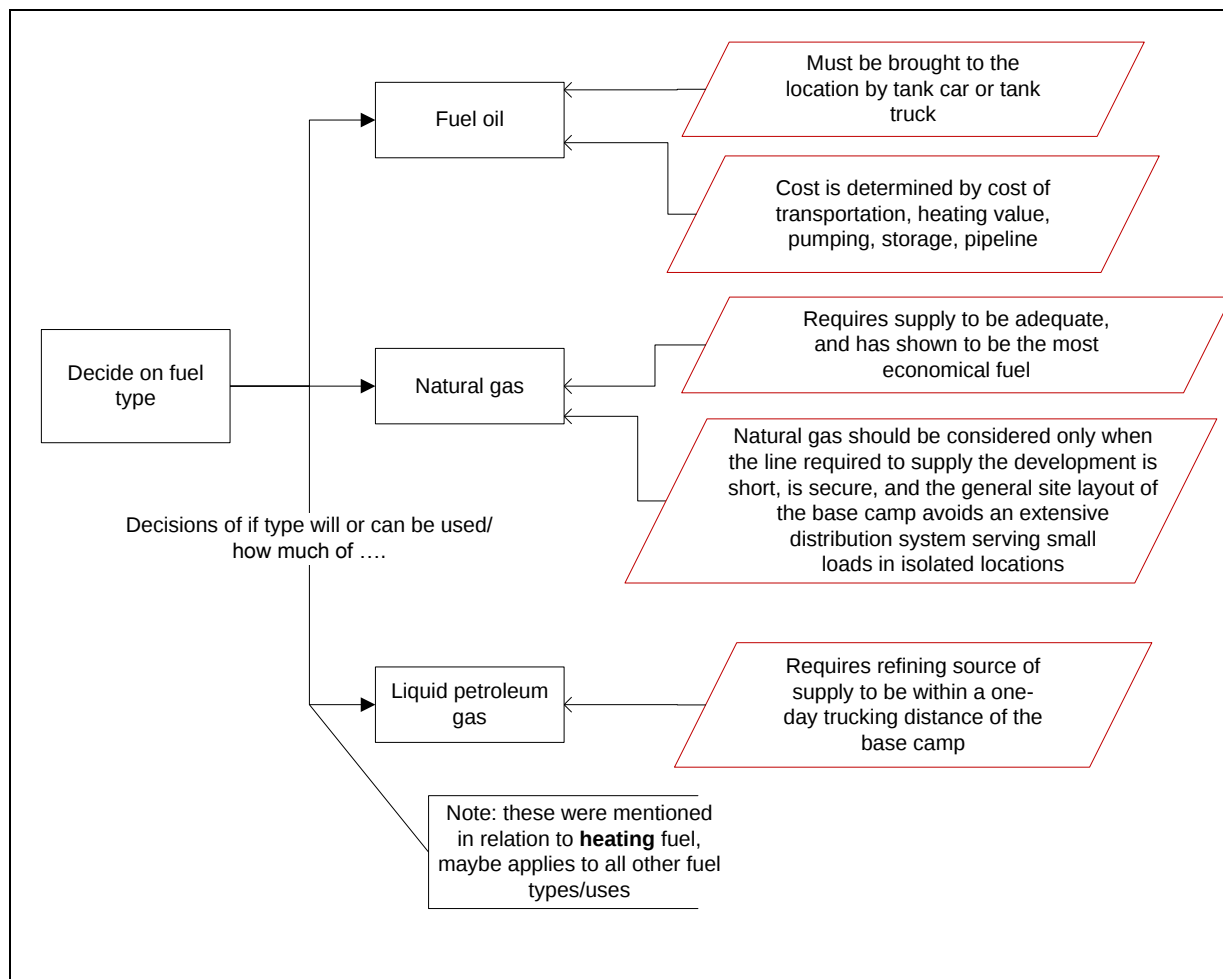
## Fuel Modeling



**Figure 38: Fuel decision hierarchy**

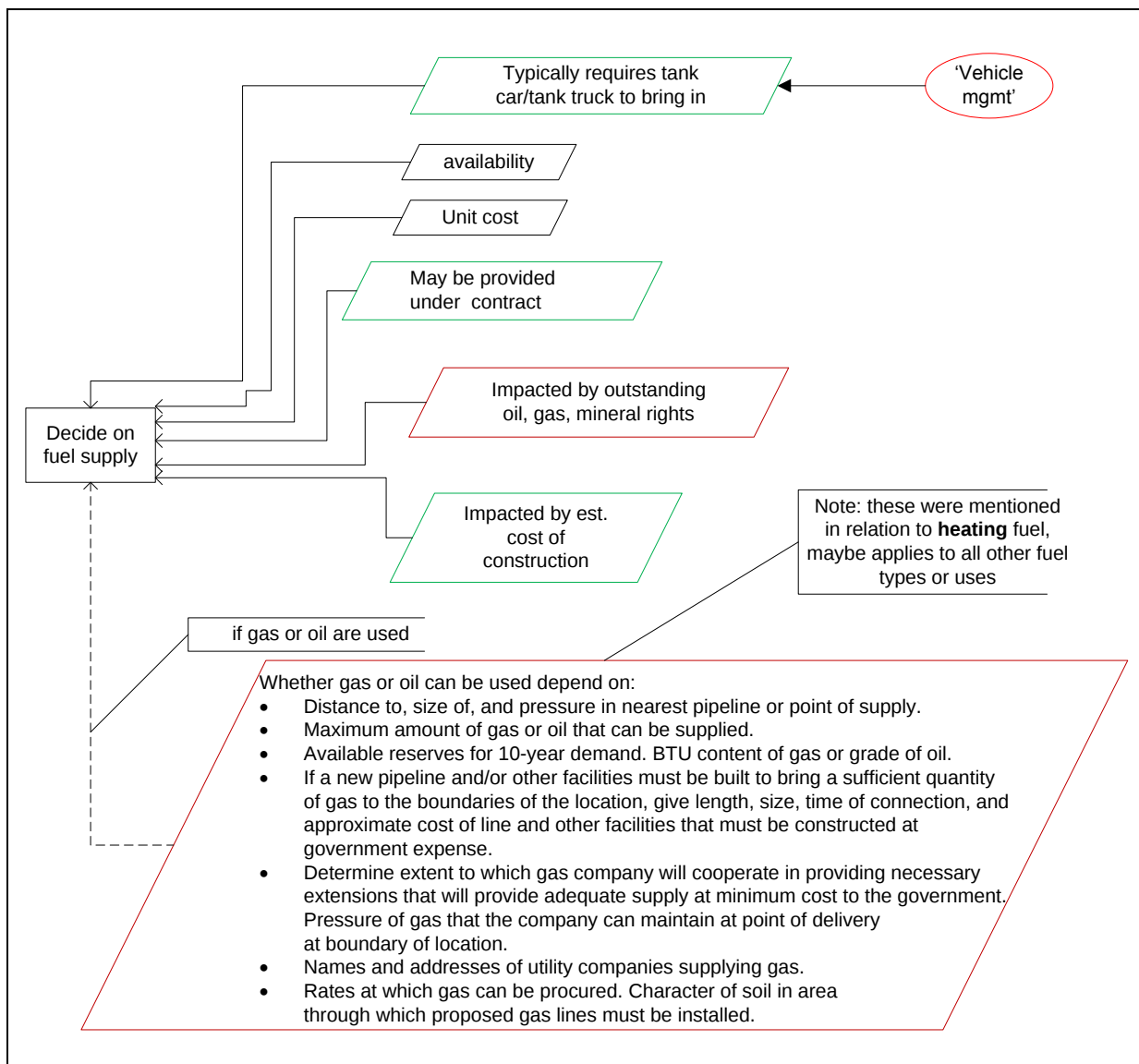
The overall decision – on how to provide fuel (sufficient amount, quality, type...)? is broken down into the sub decisions *decide on fuel type*, *decide on fuel supply*, *decide on fuel use*, *decide on adequate storage*, and *take into account environmental considerations*, as shown in Figure 38. Although environmental considerations were

not explicitly mentioned as a decision point in the reports we decided to group several environmental considerations addressed in the report under that decision node. Note that these sub decisions are not independent of each other. For instance, the type of fuel that will be needed has an impact on the way it will be stored, storage location is impacted by where fuel will be used, and use of fuel depends on the type of fuel available. Thus, although these nodes are separate sub decisions, they can't be traversed completely independently of each other.



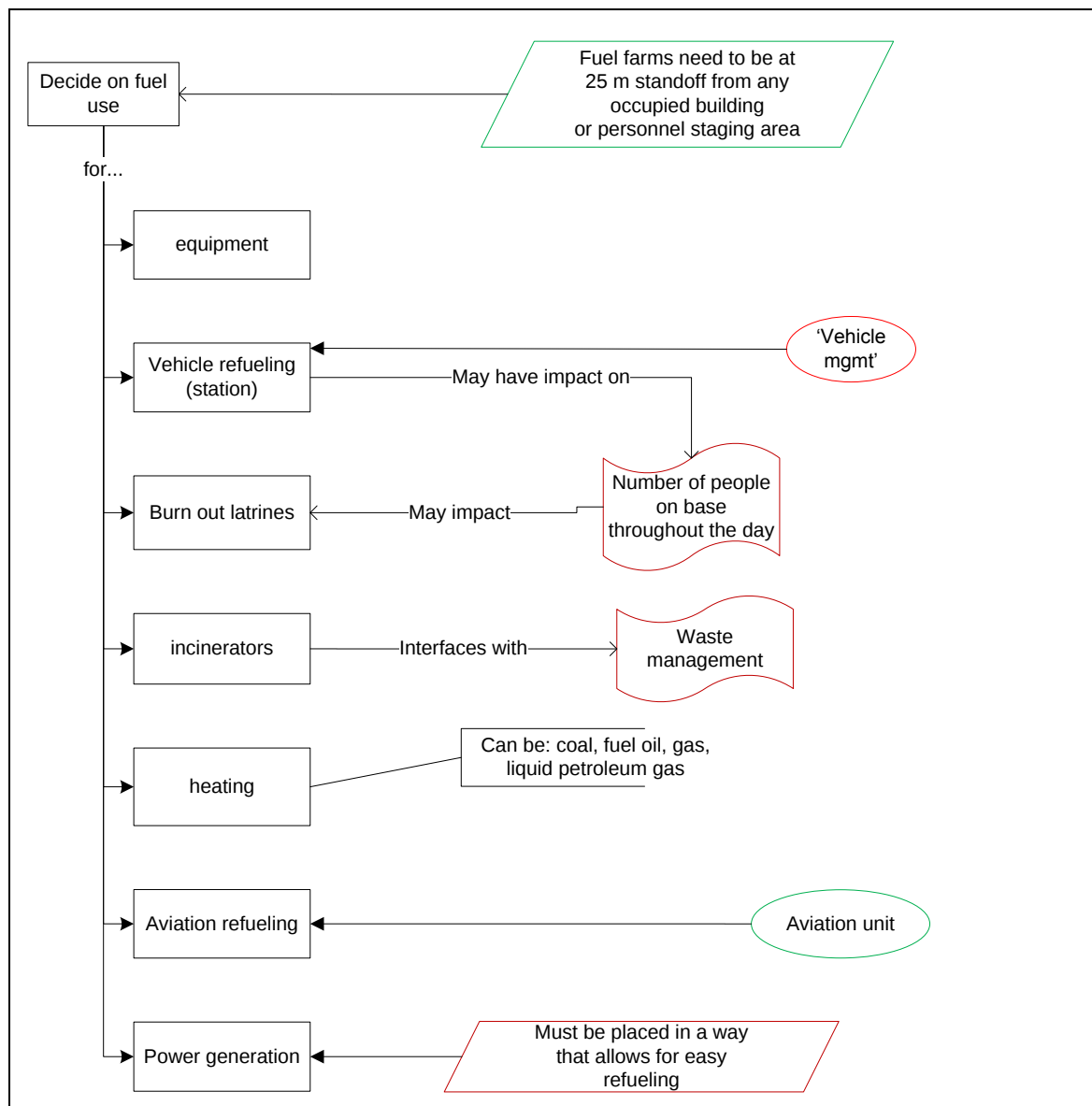
**Figure 39: Fuel Type decision hierarchy**

Figure 39 shows the decision nodes related to the decision of what type of fuel to provide – fuel oil, gas, or liquid petroleum gas. Information on different types of fuel and the parameters that impact fuel types were only mentioned in the Army Corps of Engineers Handbook, and in the context of heating fuel. The parameters are rather complex, however, we could not identify any stakeholders in the document who might be able to provide expert knowledge on whether the constraints are fulfilled.



**Figure 40: Fuel supply decision hierarchy**

Figure 40 shows the decision hierarchy for fuel supply. The only stakeholder identified is vehicle management. On the other hand, a lot of parameters were identified, such as construction costs, or existing rights. A lot of background knowledge would be required to evaluate these parameters, but no stakeholders, who would be able to provide expert knowledge, are listed. For instance, with construction costs as one parameter in the decision of fuel supply, one would expect a construction expert to be involved to estimate those costs.



**Figure 41: Fuel use decision hierarchy**

Figure 41 breaks the decision on how fuel will be used down onto different facilities as identified from the documents. Fuel is used for equipment, vehicles, burn out latrines, incinerators, heating, aviation, and power generation. As a side effect, facilities, such as vehicle refueling may have an impact on the overall number of people on base throughout the day, possibly triggering the need for further decisions in other hierarchies. Our diagrams use the wavy scroll shape to indicate interfaces with other decision nodes, such as *Waste management*. Interfaces with other decision hierarchies identified include burn out latrines and incinerators (interfacing with waste management).

With so many requirements on location one would expect a planner or resource manager to be involved in the decision, or stakeholders of the different facilities, giving

an estimate on needs, or requirements on location. However, the only stakeholder explicitly identified from docs is aviation unit involved in aviation refueling.

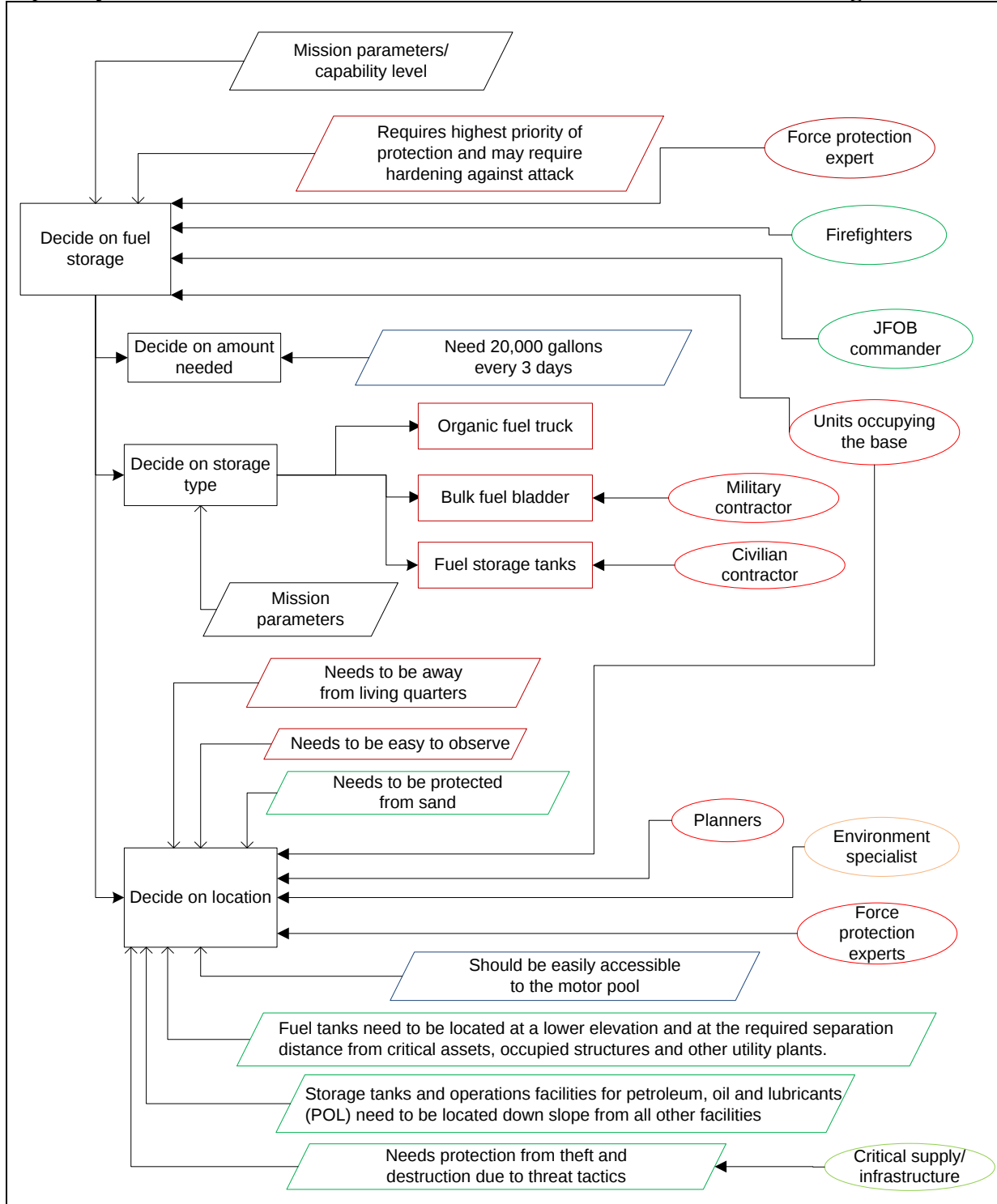
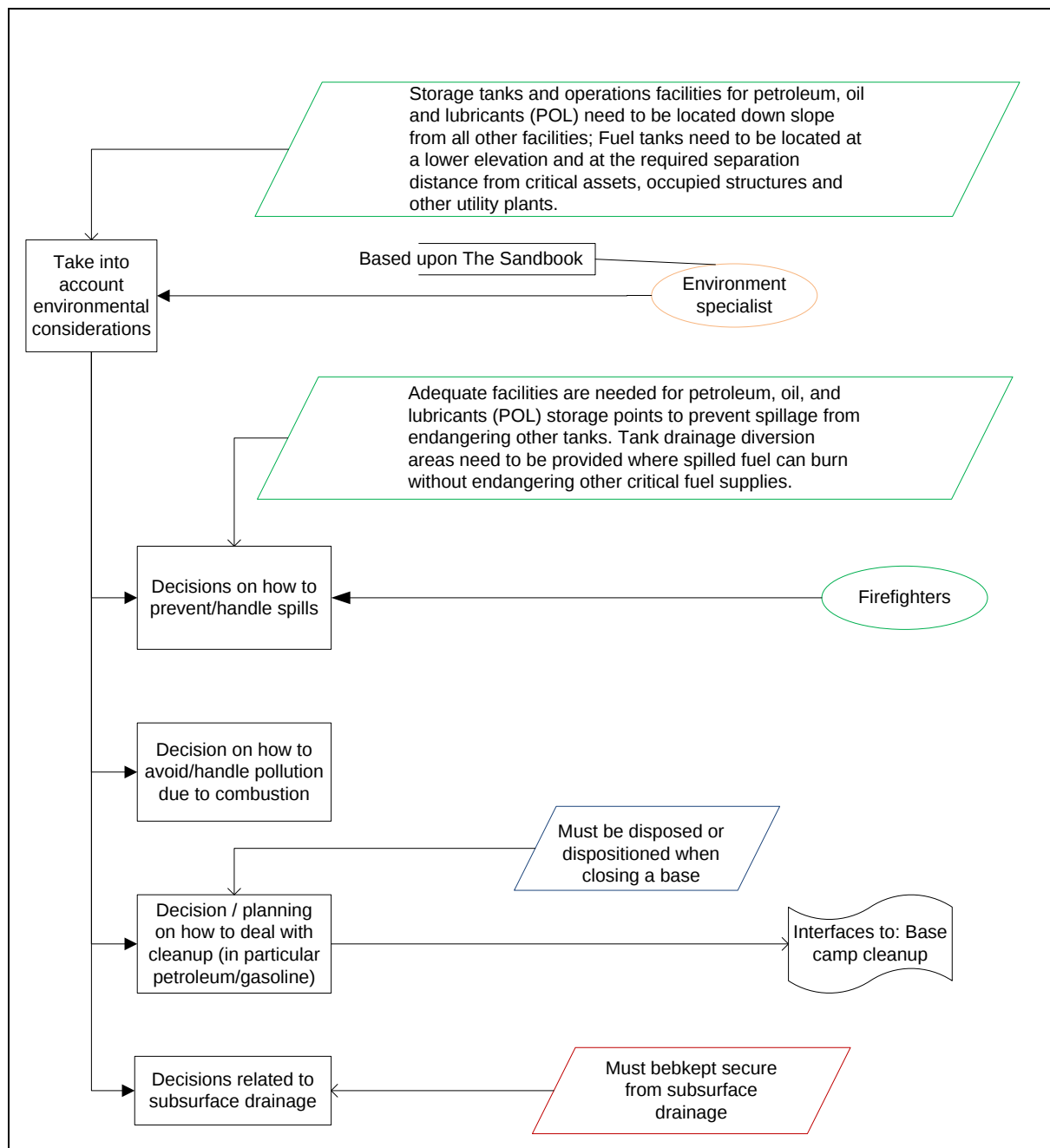


Figure 42: Fuel storage decision hierarchy

Figure 42 shows the decision hierarchy for fuel storage. It is broken down into decisions about amount needed, type of storage, and storage location. The Sandbook mentions environment protection as a part of storage location, but not stakeholder itself; therefore, the stakeholder 'Environment specialist' was added in the diagram (using a yellow oval for a stakeholder extracted from the Sandbook).

The majority of all parameters are related to storage location as taken from all three documents. This matches the stakeholders involved in the decision. For instance, the location 'needs to be protected from theft and destruction...' and involves critical supply/infrastructure as a stakeholder. Most parameters related to storage location affects overall camp layout. This is reflected by involving the planner as a stakeholder in the decision.

A lot of the (decision) parameters – such as 'needs to be away from living quarters', or 'needs to be easy to observe' are vague and therefore difficult to verify.



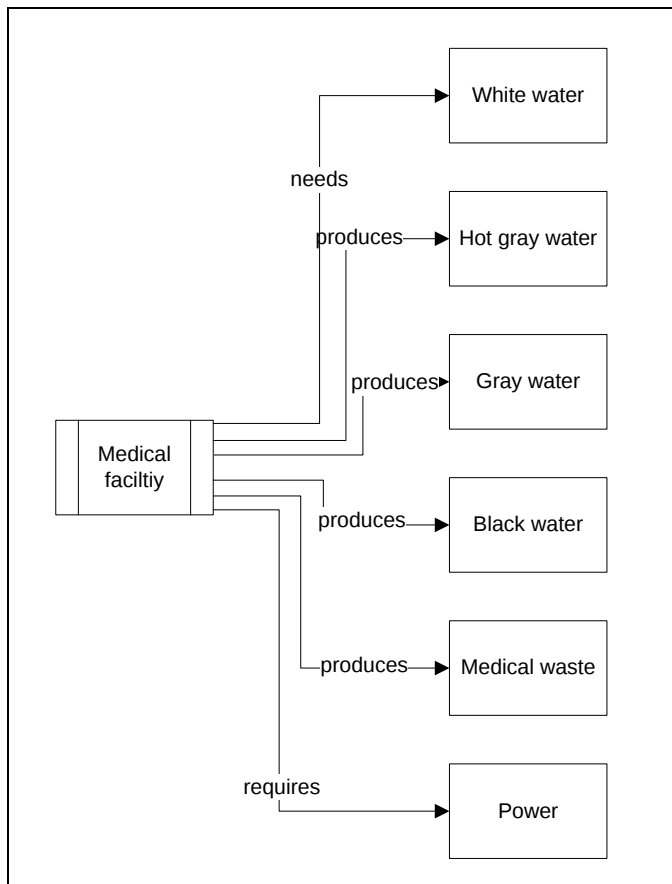
**Figure 43: Fuel environmental considerations decision hierarchy**

Figure 43 summarizes all sub decisions related to environmental considerations, namely, decisions on how to prevent spills, decisions on how to avoid pollution due to combustion, decisions related to clean up, and decisions related to subsurface drainage. The sub decision ‘how to avoid pollution...’ is mentioned, however, no further information in terms of stakeholders or parameters could be found in the documents. Several parameters guiding environmental decisions are related to overall base camp planning, however, no base camp planner is involved in the decision.

One sub decision relates to planning of base camp cleanup, interfacing with the entire decision hierarchy related to base camp cleanup.

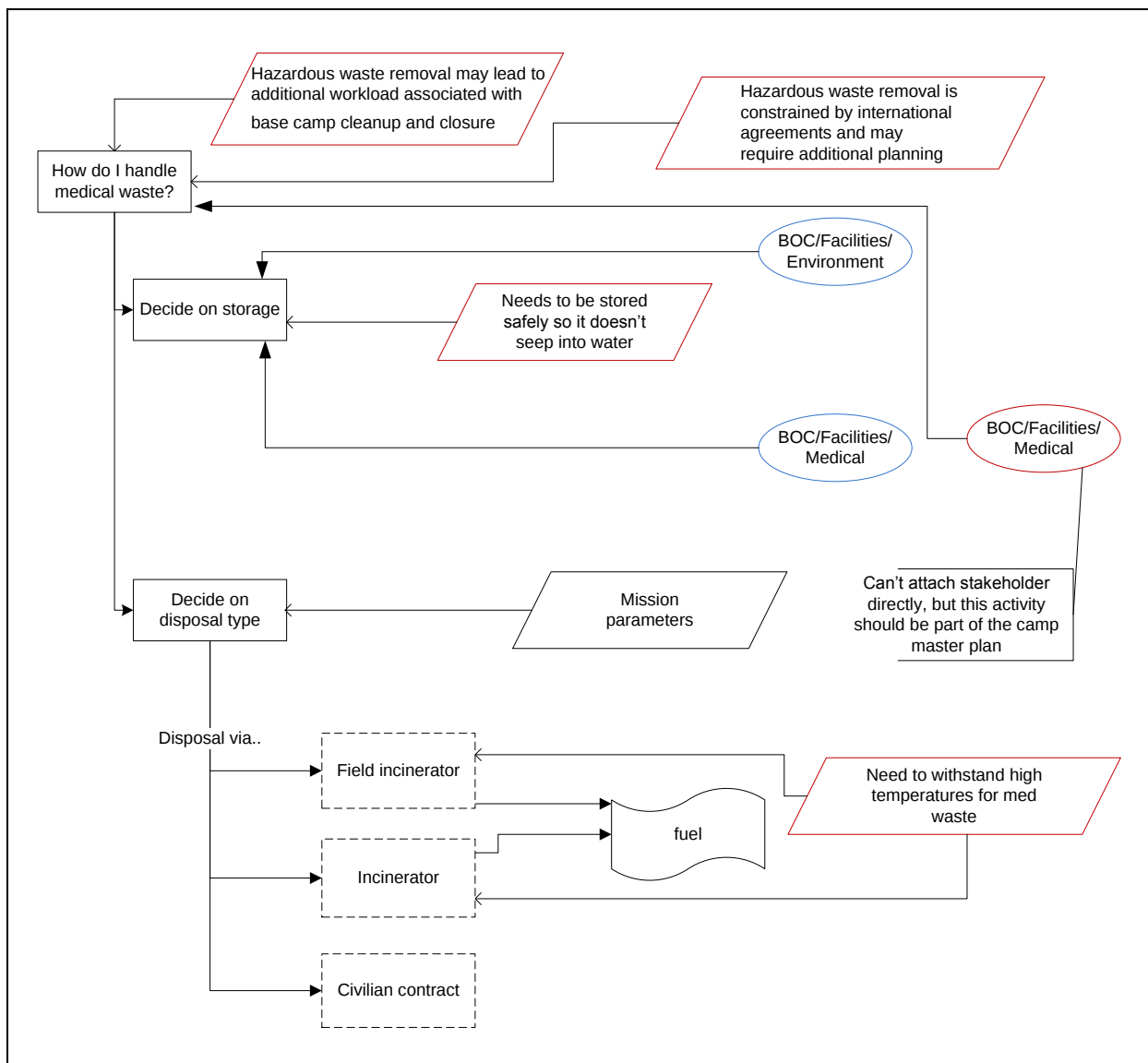
### Medical Facility modeling

To put fuel, white, gray, and black water into a larger context, we modeled a facility that would use or produce all of these entities. We decided on a more complex facility, that would have additional interfaces beyond water and fuel and modeled a medical facility and the resources used and produced.



**Figure 44: A Medical facility key relationships**

In order to show how some of the entities modeled above fit into the bigger picture of a sample facility, Figure 44 shows the key relationships modeled for a medical facility. A medical facility needs white water, e.g., for food/drinking or sterilizing. It produces warm or hot gray water, e.g., from cooling, sterilizing or showers, and black water, from toilets. In addition to those two variations of wastewater, a medical facility produces medical waste and requires power to run.



**Figure 45: Waste Management decision hierarchy**

A key issue for medical facilities is how to handle medical waste.

Figure 45 shows how this decision is broken down into sub decisions and shows the stakeholder involved. Decisions related to medical waste removal can be refined into the decisions related to storage, and disposal type. Medical waste removal in general becomes an issue in camp cleanup and may lead to additional workload.

The only stakeholders found are BOC/Facilities/Medical and BOC/Facilities/Environment in the context of waste storage. Waste disposal is either handled by civilian contractors or through incinerators – interfacing with fuel management (see Figure 41).

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## MODEL EXTRACTION SUMMARY

This section summarizes our findings from developing the models.

**Complex models:** Even such a small excerpt of overall base planning with a very limited scope becomes complex, and already at this high level of detail.

**Consistency of information:** With one exception, we did not encounter inconsistent information across different documents. This was also due to the fact that there was not much overlap between the individual documents.

**Coverage:** On the other hand, we did not discover much overlap between documents. This also raises the question of completeness. We analyzed 3 documents, but it is not clear if this set of documents is sufficient to cover all relevant aspects of water, fuel or medical facilities or are we missing relevant information because it wasn't covered in any of these reports. Would additional documents confirm findings or could an additional document add relevant information not yet covered?

**Stakeholder mapping:** Constraints are not always aligned with stakeholders (e.g., a decision may have a relationship tied to water analysis, but the corresponding stakeholder with technical expertise is not explicitly involved in the decision. In fuel modeling almost every sub decision is related to location and overall camp layout. However, no stakeholder related to that layout planning in relation to fuel could be extracted in relation to fuel. Stakeholders are missing, or if mentioned, are not consistently defined as stakeholders, but sometimes a hybrid between role and position or division.

**Interconnected decision nodes:** It is difficult to completely follow through on the decision hierarchy of one resource without the other as they are tightly coupled interconnected. For instance, white water may require fuel to generate energy to purify water, fuel, on the other hand, can't be planned without taking water (groundwater) into account. The decision for a single entity can't be done independently as there will be further dependencies as you traverse down the decision hierarchy. This can eventually lead to the question where to start as it may lead to a deadlock situation. This may lead to a situation where facilities/resources can't be planned independently of each other, but may have to be planned in parallel. Even sub decisions related to an individual resource or entity (such as whitewater water or fuel supply) can't always be modularized as there are sometimes interrelationships with other sub decisions of that entity.

**Parameters:** It is not always obvious how to determine which parameter to make decision and which one to make performance parameter. A lot of parameters impact one another, and depending on the targeted result, a performance parameter can be switched with its associated parameter (e.g., the set of planned facilities using fuel has an impact on the type of fuel I need to provide, but on the other hand the type of fuel I can provide has an impact on the type of facilities I will be able to run). Depending on the targeted situation and decision to take, both seem to be feasible classifications..

It would be interesting to develop a decision model for energy use, supply, and distribution on a base as such a model would be closely integrated with and builds upon the existing models for fuel and puts it into a wider context, but can be expected to have a lot of interdependencies with other resources, such as water. In addition, this model might help to better understand how to deal with highly interconnected decision nodes.

**Guidance for decision makers:** Our modeling tasks showed that the information needed to make an informed decision is scattered across several documents, making it difficult for decision makers to gather the information needed to make the decision. The resulting decision models are powerful tools to provide an overall picture of the decision hierarchy and provide guidance through the steps of decision-making. A combined and consolidated view of the decision process and the stakeholders involved allows a decision maker to see at one glance, who is impacted by a decision, and who can provide the expertise needed at decision point. The models help a novice base planner ensure that all sub decisions are taken, all relevant stakeholders needed to obtain a complete picture of the problem are considered, and gives an overview of dependencies.

**Understanding through traceable models:** A graphic notation makes the models rather intuitive. Due to the level of abstraction chosen for the models sub decision, their dependencies and stakeholders are understandable and traceable for users and allow them to find additional information in documents.

**Integrate stakeholders into decision process:** Modeling showed that decision making is extremely complex and involves many stakeholders at different levels of the decisions. The models can be used to bring different stakeholders involved in decisions together by painting an overall picture of the decision process and showing how one small (sub) decision fits into the overall process, and what other stakeholders are involved. Furthermore, the models can be used as a basis to extract role-specific views of the decision process to show stakeholders where they play a role in the decision process without overwhelming them with unnecessary information.

**Quality of handbook:** Extracting information from the documents showed that even the combined information from different handbooks is not always sufficient to yield a complete picture of the decision hierarchy. The models developed can be used to support developers or providers of cb planning handbooks to identify information missing in the handbooks and to yield better quality in the documents.

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## TOOL SUPPORT FOR OUR COLLABORATIVE CONCEPTUAL MODELING APPROACH

**Variables**

| Variable              | Description                                                            | Mode of Computation |
|-----------------------|------------------------------------------------------------------------|---------------------|
| Threat_environment    | How severe is the threat environment?                                  | Environment         |
| Power_System          | How much and what kind of power generation should we have?             | Decision            |
| Water_Decision_System | Water decision making system                                           | Decision            |
| Waste_Disposal        | How will we handle waste disposal and how much will we have to handle? | Decision            |
| Base_Population       | How many soldiers and other personnel live on this base?               | Environment         |

**Stakeholders**

Kevin Sullivan  
Lucas

**Relations**

Water\_Decision\_System dictates in part the need for Power\_System

**Social Structure Matrix**

|                   | 1: Lucas | 2: Kevin Sullivan |
|-------------------|----------|-------------------|
| 1: Lucas          |          | x                 |
| 2: Kevin Sullivan | x        |                   |

**Clustering**

SERC\_Model\_Cluster

Name: SERC\_Model\_Cluster

Description:

**Decision Structure Matrix**

Choose clustering: SERC\_Model\_Cluster

Compute DDM

|                          | 1: Waste_Disposal | 2: Power_System | 3: Water_Decision_System |
|--------------------------|-------------------|-----------------|--------------------------|
| 1: Waste_Disposal        |                   |                 |                          |
| 2: Power_System          |                   |                 | x                        |
| 3: Water_Decision_System |                   |                 |                          |

**Figure 46: Screen Shot of CB-Decider, a web-based collaborative modeling environment**

Figure 46 presents a screen shot of a minimalistic CB model linking water, power and waste decision parameters both to each other and to decision makers (here modeled as Kevin Sullivan and Lucas, but in general these would be organizational roles). There is a very simple relation coupling water and power decisions. This coupling is reflected in the computed decision structure matrix, and the inferred need for coordination coupling

between Kevin and Lucas is displayed in the computed "social (organizational) structure matrix."

The tool is designed and implemented as a modern, interactive, and collaborative web application. Its persistence layer is implemented using a scalable, document-oriented, no-SQL database. The business layer is presented as a REST web service. The interactive client software (as in Figure 46) is a rapid prototype that runs as Javascript entirely in the user browser. Updates made through a client to the underlying data are reflected immediately on the screens of all participating collaborators in the style of Google's "Google Doc" collaborative editing system. The underlying computational connectors are Ajax, Comet, Web Sockets.

Our research and development activities in this project included extended use of this technology to build a variety of test models. This experience suggests that at least to start, the most effective use of the tooling is either by a single modeler, or by a group of modelers who work together online with supplementary interactions provided using telephones, Skype, or other ordinary means of interaction. We observed that in our modeling efforts, having to express issues in the terms of our conceptual framework of system parameters, relationships, participants, mappings, and then being able to see the consequences in terms of coupling and coordination diagrams tended to highlight areas of implicit inconsistency, and to drive us to focus on documenting the critical issues in ways that were understandable and that led to a shared vision of the systems issues in play in the CB domain.

This tool and its underlying formalism was also carefully designed to achieve a balance between two competing pressures. On the one hand, it would be nice to have precise and detailed mathematical models of relationships and systems of relationships, so as to be able to compute predictions and properties of CB designs, and of tradeoffs in this space, with precision and rigor. On the other hand, in the early stages of modeling and model reconciliation and integration, we find that what is most important is simply fostering a process of convergence of agreement on what basic terms mean, what parameters and relationships are most important, and what are the technical coupling and organization structure implications that might dictate future courses of action in terms of CB design or organizational refactoring, and what improved forms of modularity in the structure of coupling relationships might greatly reduce the costs of, and provide much improved opportunities for, system adaptation and evolution to changing conditions, or the needs for improved CB performance. Our relationship objects are thus explicitly linked to their corresponding parameter objects, but the semantics of relationships are left informal.

## 4 CONCLUSION AND FUTURE WORK

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The decision processes of contingency base planning and operation are complex. The decision models and supporting methods developed by this research task, based on Army guidance documents and other CB models, are multi-layered, involve numerous

variables, and in many cases have an ill-defined set of stakeholders. For both sub-tasks we have only scratched the surface of discovering the core issues or defining a methodology. Despite limiting ourselves to the example areas (i.e. water management, fuel management, medical facility management, and soldier load for SCU) from CB documentation and key stakeholders, the decision spaces uncovered are complex enough that even experienced CB planners would be hard-pressed to understand the full ramifications of their decisions, especially if given limited planning resources. One goal of this effort was to understand the relationships between stakeholders involved in CB decisions. While the source documents we researched contained some indications of organization at the base camp level, there was little description of the personnel whose duties placed them in charge of the variables involved in a decision. We suspect that this is due to the variable natures of CBs themselves: duties are distributed according to the size of and personnel available on each CB at a particular point in time. Nonetheless, building the systemigrams, SysML, social network of roles that are responsible for variables in a decision (both those variables that serve as input into a decision and those that are impacted downstream by a decision) is beneficial for the decision-maker, who must know who to contact for the latest information.

Originally we had thought that an important aspect of this work would be **identifying and resolving disagreements and conflicting information and defining system boundaries** among the experts. Since contingency bases are complex entities that require expertise from different technical domains, we had expected to find different views of the world (which may be incompatible) and partial views of the overall solution. In actuality, we found very few such disagreements. We expect that this was due to the fact that the different sources we were able to leverage all dealt with different aspects of planning; thus, while they provided coverage over the larger decision-making process they typically were designed for different stakeholders and did not often cover the same parts of that process. The responses to our modeling efforts from members of the Contingency Basing Initiative have been positive. Our hope is to reengage the CB initiative in 2013 after its reorganization in late 2012. The CB Initiative members have suggested that the social network and decision modeling may be of particular use for operational energy distribution (i.e. both power and fuel) decisions among multiple contingency bases within an Area of Operations. More broadly, we believe our rigorous qualitative analysis coupled with the decision space modeling and analysis provide a novel and useful means for understanding and describing the latent decision structures the compose most planning and operation activities.

## APPENDICES

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### APPENDIX A: REFERENCES

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