OPTIMIZING SUSTAINMENT LOGISTICS FOR A U.S. ARMY INFANTRY BRIGADE COMBAT TEAM WITH INTEGER PROGRAMMING

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ABSTRACT

The U.S. Army has directed the manning and equipping Brigade Support Battalions to fulfill the organic sustainment needs of brigades, as An Army Infantry Brigade Combat Team cannot organically transport all of its assigned assets. We formulated an integer programming model to optimize sustainment outcomes of supported units and analyze risk associated with shortfalls that may arise. We developed a scenario reflecting the steady resupply of an Infantry BCT during combat operations and a system for prioritizing competing resupply needs. Our mathematical modeling framework provides a foundation on which more advanced applications and analysis can be developed in the future.

KEY WORDS

U.S. Army, Infantry Brigade Combat Team, Sustainment Logistics, Integer Programming, Simulation

INTRODUCTION

Brigade Combat Teams (BCTs) represent the Army's primary unit for building and implementing combat power. Prior to 2004, the Army was division-centric, relying on large 15,000 soldier formations to serve as the lowest level unit capable of deploying and sustaining, without outside assistance. General Peter Schoomaker, the Army's Chief of Staff from 2003 to 2007, led the transformation to create brigades of approximately 3,000 soldiers that were self-sufficient. This transformation was designed to allow the Army to deploy more appropriately sized formations, based on the conflict at hand (Garamone, 2004).

Brigades are standardized across the Army, based on the function they are expected to perform. The currently existing BCT formations include Infantry, Armored, and Stryker. Other brigade types that were created during this period of reorganization include combat aviation, fires, sustainment, battlefield surveillance, and maneuver enhancement (United States Army, 2015).

The Army has directed the manning and equipping Brigade Support Battalions (BSB) to fulfill the sustainment needs of the brigade and has identified a transportation shortfall (Van Howe, 2019). We developed a simulation framework with an integrated optimization model for sustainment of an Infantry BCT.

BACKGROUND

An IBCT consists of seven battalions: three infantry battalions, one cavalry (reconnaissance) battalion, one field artillery battalion, one engineer battalion and one brigade support battalion. The BSB is relied upon to support the mobility and endurance of the six other units engaged in combat operations by conducting regular resupply of needed supplies.

The U.S. Armed Forces divide all military supplies into ten classes (Army Regulation AR 710-2 2008), shown below in Table 1. Estimating daily consumption is often a tactical focus of logistics planners and is essential to the conduct of battle. Supplies such as repair parts and construction materials can also be critical to force sustainment. We analyze four categories: Class I (water), Class III (fuel), Class V (ammunition) and a catch-all category known as "all other" which includes Classes II, IV, VI, VII, VIII, and IX.

Table 1–1
Classes of supply

Classes of supply	References
Class 1 – Subsistence, including free health and welfare items.	AR 30–22
Class 2 – Clothing, individual equipment, tentage, tool sets and tool kits, hand-tools, administrative, and housekeeping supplies and equipment (including maps). This includes items of equipment, other than major items, prescribed in authorization/allowance tables and items of supply (not including repair parts.	AR 700–84, CTA 50–900, CTA 50–970
Class 3 – POL, petroleum and solid fuels, including bulk and packaged fuels, lubricating oils and lubricants, petroleum specialty products; solid fuels, coal, and related products.	AR 11–27, AR 700–36, AR 710–2, FM 10–13, FM 10–18, FM 10–68, FM 10–69, FM 10–71, SB 710–2, TM 5–675
Class 4 – Construction materials, to include installed equipment, and all fortification/barrier materials	AR 420–17
Class 5 – Ammunition, of all types (including chemical, radiological, and special weapons), bombs, explosives, mines, fuses, detonators, pyrotechnics, missiles, rockets, propellants, and other associated items.	AR 190–59, AR 190–11, AR 190–13, AR 190–51, AR 700–19, AR 710–2, SB 700–2, SB 708–3, FM 9–38, TM 9–1300–206
Class 6 – Personal demand items (nonmilitary sales items).	AR 700–23
Class 7 – Major items: A final combination of end products which is ready for its intended use: (principal item) for example, launchers, tanks, mobile machine shops, vehicles.	AR 710–1, FM 704–28, SB 700–20, Appropriate authorization documents.
Class 8 – Medical material, including medical peculiar repair parts.	AR 40–61, CTA 8–100
Class 9 – Repair parts and components, including kits, assemblies and subassemblies, reparable and nonreparable, required for maintenance support of all equipment.	AR 710–2, AR 710–1, Appropriate TMs
Class 10 – Material to support nonmilitary programs; such as, agricultural and economic development, not included in classes 1 through 9.	CTA 50–909

Table 1: Ten supply classes from Army Regulation 710-2.

Our primary method for measuring supported unit supply inventories is days of supply (DOS), the number of days that a given quantity of supplies will sustain a supported unit under specific conditions. A DOS is a function of unit size, type, and mission. For example, one DOS of food for a 500-soldier infantry battalion will be higher than one DOS of food needed to sustain a 300-soldier engineer battalion. One DOS of fuel will be much higher for the engineers. DOS gives the commander a common unit to understand the supply readiness of subordinate units. It allows one to quickly grasp the current status of a given unit, without requiring in-depth knowledge of actual quantities of goods needed for readiness in one battalion vs. another. Unless specified for a mission, units deploy with three DOS on hand and expect to be resupplied with one DOS every subsequent day. This provides a cushion for variability of consumption, as well as for the times when resupply is infeasible for one or two days.

SIMULATION FRAMEWORK

Our simulation framework is designed to run a balance sheet of inventory levels of each of our four supply categories at each of our six units. The balance sheet is organized by day with starting balance, consumption, ending inventory, distribution plan and resupply. Each of these is tracked both by supply class and by unit. The framework is depicted below in Figure 1.

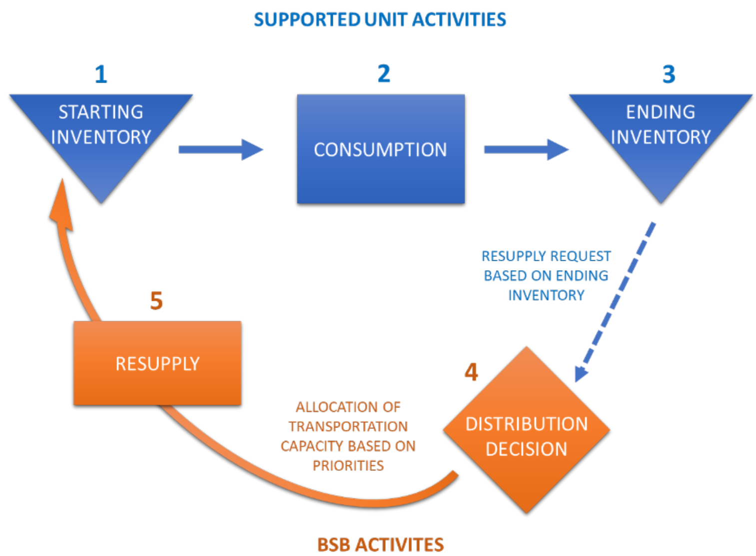

Figure 1: Simulation framework for resupply

We assume that each unit can only hold three days of supply on-hand, so the beginning balance of any category of supply on any day cannot exceed three DOS. Three DOS is also the target amount of supplies a using unit could and would want to carry on-hand. The amount that current inventory is below three DOS reflects the *shortage* of a particular supply for a given unit. We assume that a resupply occurs early enough in the day that those supplies are available to support consumption that day, and therefore included in the day's beginning balance. Our simulation parameters include a minimum, maximum, and average level of consumption for each category of supply.

PRIORITIZING DISTRIBUTION

The central aspect of our simulation is the decision the BSB must make on how best to utilize its distribution assets in order to resupply supported units. When allocating a limited number of transportation assets across competing shortages, a supporting logistics unit would prioritize resupply efforts according to three main *criticality factors* that describe the urgency of the need:

1. Ending inventory level or shortage. When a unit's current inventory stores fall below a certain threshold of supply, maneuver options become increasingly constrained.

2. The relative importance of a supply class. While ammunition may be important to the conduct of combat operations, Class I provides basic life support that supersedes all other supply priorities. Class III is essential to unit mobility and therefore less important than Class I and Class V, that

provides for self-defense. While certain parts or materials might be deemed critical, taken together, the "All Other" class will not be more important that Class, I, III, or V.

3. The relative importance of the unit. In the scenario we have developed, the actions of the infantry units through regular resupply will likely be most important to the overall mission. Therefore enabling them through regular resupply will be a priority. Further, any mission order will designate one unit as the *main effort* in a particular phase of an operation, indicating that the actions of this unit among all others are essential to the accomplishment of the mission. Our main effort is the first infantry unit, whose actions are only slightly more important than the other two infantry battalions. Next, the field artillery and cavalry units are more likely to provide essential support to the infantry battalions and therefore, the combat mission overall. Of the six units, we consider the Engineer battalion the lowest priority during large scale combat operations. While the importance of a unit to the overall mission varies greatly with circumstance and would likely change over the course of an entire operation, we chose to hold these relative priorities constant for the duration. This is reasonable to assume in practice over a relatively short period of time.

We developed a table of prioritization points in order to quantitatively relate these three factors and provide an overall *criticality score* for a specific resupply requirement. We assign these quantitative scores to the replenishment of specific supplies for specific units and utilize them to optimize resupply to best support the overall mission.

OPTIMIZING DISTRIBUTION

We develop an integer programming (IP) model to allocate shipping capacity for our four classes of supplies to our six units, in order to best meet operational priorities.

Original Model Formulation

Indices & Sets

$i \in I$ Class of supply (1, 3, 5, All Other)

$j \in J$ Supported Unit (Infantry 1, Infantry 2, Infantry 3, Artillery, Cavalry, Engineering)

Input Parameters

C Overall transportation Capacity of BSB (number of prime movers)

C_i Distribution capacity for supply class $i \in I$

Calculated Parameters

E_{ij} Ending inventory of class $i \in I$ at unit $j \in J$ (measured in DOS)

W_{ij} Conversion factor for number of vehicles per DOS, for $i \in I, j \in J$

S_{ij} Shortage of class $i \in I$ at unit $j \in J$ (measured in trucks)

P_{ij} Prioritization points for level of supply E_{ij} for $i \in I, j \in J$

Integer Decision Variables

X_{ij} Number of trucks of supply $i \in I$ shipped to unit $j \in J$

Objective Function

$$\text{Maximize } \sum_{i\in I} \sum_{j\in J} X_{ij} P_{ij} \quad (1)$$

Constraints

$\sum_{i\in I}\sum_{j\in J} X_{ij} \leq C$ (total shipping capacity) (2)

$\sum_{j\in J} X_{ij} \leq C_i \quad \forall i \in I$ (shipping capacity by class) (3)

$X_{ij} \leq \lceil S_{ij} \rceil, \quad \forall i \in I, j \in J$ (shipping limit) (4)

$X_{ij} \in \{0,1,2,\cdots\} \quad \forall i \in I, j \in J$ (5)

Our objective function (1) prioritizes shipments based on the current level of supply, by class of supply and unit, seeking to maximize aggregate value. The model allocates transportation capacity subject to four main constraint types. Constraint (2) represents overall number of trucks available for transporting supplies. Constraint (3) ensures that the amount of water, fuel, ammunition and "all other" supplies transported does not exceed their respective available transportation capacities. Constraint (4) ensures that no more than the amount of trucks required to meet demand may be shipped, which is necessary because our objective maximizes prioritization points. Constraint (5) ensures that our decision variables are integers, since distribution assets cannot be divided, due to the specialized shipping requirements of each class of goods.

Limitations

Ideally, we would want to *minimize* risk, by maximizing the prioritization points reflected in *post-distribution* supply inventories (next day beginning inventory) at each supported unit. However, our integer programing model is not ideally suited to account for these non-linear effects directly. Instead, the model uses *pre-distribution* inventories (current day ending inventory) in order to assess the urgency of need and allow the BSB to prioritize resupply efforts accordingly. As expected, the key limitation of this approach is that optimizing based on prioritization points determined by pre-distribution inventories encourages over-supply. For example, if the highest priority unit has zero days of the most urgently needed supply, the model would maximize prioritization points by sending all vehicles to that location.

Updated Model Formulation

We refined our model to ensure that it does not errantly reward the extra unused capacity in the objective function. To adjust for this issue, we created a second set of binary decision variables and a second set of demand constraints, in which the binary variables are linked to the integer variables and activate when shipments exceed supply. The model then deducts the proportional value of prioritization points within our objective function.

In order to remove the incentive for shipping an underutilized truck for a highly prioritized supply class and unit, we introduce a new set of parameters and binary decision variables:

Binary Decision Variables

Y_{ij} = {1 if a truck is shipped to cover a partial truckload of demand, 0 otherwise}

We can now reformulate our model as

Objective Function

$$\text{Maximize} \sum_{i\in I}\sum_{j\in J}\left(X_{ij} - Y_{ij}\left(\lceil S_{ij} \rceil - S_{ij}\right)\right) P_{ij} \quad (6)$$

Constraints

$\sum_{i\in I}\sum_{j\in J} X_{ij} \leq C$		(total shipping capacity)	(7)
$\sum_{j\in J} X_{ij} \leq C_i$	$\forall i \in I$	(shipping capacity by class)	(8)
$X_{ij} \leq \lceil S_{ij} \rceil,$	$\forall i \in I, j \in J$	(shipping limit)	(9)
$X_{ij} - Y_{ij} \leq \lfloor S_{ij} \rfloor,$	$\forall i \in I, j \in J$	(linking constraint)	(10)
$X_{ij} \in \{0,1,2,\cdots\}$	$\forall i \in I, j \in J$		(11)
$Y_{ij} \in \{0,1\}$	$\forall i \in I, j \in J$		(12)

The updated objective (6) now caps the incentive to ship at the prorated amount of any partial shipment required to fully meet demand. For example, if a unit's shortage was 2100 gallons of water, the BSB would not send more than two Class I platforms (carrying 2000 gallons of water each) to fulfill this need. Allocating any more resources would be result in wasted capacity, no matter how great the initial urgency of the shortage. Whereas objective (1) awarded prioritization points for up to 4000 gallons shipped, objective (6) now only awards prioritization points for the first 2100 gallons shipped.

In order to ensure the binary variables are activated when partial-truck demand utilizes full-trucks for shipments, constraints (10) act as a linking constraint, by rounding down the shortage amount measured in vehicles to less the actual shortage amount allowed in constraints (9). When the shortage is already an integer value, constraints (9) and (10) become redundant.

Constraints (7)-(9), (11) are the same as in the original model. Binary constraints are introduced in (12).

RESULTS

We tested our original and updated models on a multiday simulation run. We achieved reasonable resupply strategies with our original model, but we expect these would become unsatisfactory when simulated over a longer time horizon, or with greater stress placed on transport capacity. The resupply strategies achieved with the updated model were superior. We plan to expand our computational study in future work.

CONCLUSIONS

Our optimization model is intended to inform strategic decisions for the design of supply logistics in advance of a conflict. It can be used to analyze risk and pinpoint opportunities for mitigation. Realistically, not all equipment a unit has will be available for operational use. Both planned and unplanned maintenance will limit the number of vehicles available at a given time. Incorporating this variability in our model through simulation is key to understanding risk. Another area of uncertainty that we will explore in future work is the effect of losses sustained during transportation, due to enemy strikes. While our model is useful for understanding and designing logistics for Army Brigade Combat Teams, once on the ground, the commanders will take into account additional details beyond the scope of our current model.

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