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Decision Support

An application of the multiple knapsack problem: The self-sufficient marine

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ABSTRACT

Self-Sufficiency (SS) is the ability to maintain capability without external support or aid. Operations in austere environments with limited functional infrastructure and logistical support, which are common in humanitarian assistance and disaster relief as well as military operations, must be self-sufficient. In this paper, we explore the challenges of SS in the United States Marine Corps (USMC). Marines engage in a wide variety of expeditionary operations, and must function without logistical support for long stretches of time. They face competing constraints, including the load that a squad can carry, mission requirements, resources required for sustainment, and the extent to which resources can be shared. We extend the knapsack problem in several ways to model a Marine squad's decisions regarding what items to carry and how to distribute them. The Office of Naval Research found the models and the results to be significant as baseline analysis for the resource demands of a self-sufficient squad. Though the data and scenarios are USMC-specific, the challenges of SS can be found in any expeditionary undertakings or operations in austere environments.

1. Introduction

Self-sufficiency (SS) is the ability to maintain operations without external support or aid. Most organizations can rely on local infrastructure and economy for logistical support in their operations, buying fuel and other supplies locally. For operations in environments with limited infrastructure and limited availability of logistical support, which are common in humanitarian assistance and disaster relief (HADR) (Apte, Khawam, Regnier, & Simon, 2015), SS is not merely preferred, but is often necessary for the success of the mission. Similarly, military missions may need to be conducted in regions where there is no logistical support structure. In this paper, we focus on expeditionary missions of the United States Marine Corps (USMC), whose vision statement calls for it to be "focused on executing sustainable expeditionary operations" (USMC, 2009). Though the data and scenarios in this particular application are USMC-specific, the challenges of SS can be found in any expeditionary undertaking or operations in austere environments. The analytical approach and the insights generated are readily generalizable.

Many factors determine SS: resource requirements, size of the operating unit, mission duration, operating environment, and local availability (or unavailability) of resources (Brindel, Fowler, & Meche, 2013). In the USMC, depending on the mission, SS may be required of an individual warfighter, a battalion, or any unit in between. The ability to share resources is a key factor in SS. The availability of supply locally and the timing of availability of organic (USMC-owned) supply chains (Regnier, Simon, Nussbaum, & Whitney, 2015) determine the degree to which resource demands must be met internally and thus the duration and degree of SS required. SS is also dependent on the operating environment, which affects the requirements for both consumable resources such as water and non-consumable resources such as protective equipment.

The USMC is called upon to conduct a diverse range of missions in many very different environments. Conducting expeditionary operations – in the absence of sustainment from outside, is one of their defining roles, and the USMC needs to be prepared to send the right size squad with the right equipment in any mission and environment in which they are needed, maintaining capability for the duration of the mission.

The most fundamental SS question is whether the squad in a given scenario can be successful with the items the Marines in the squad are able to carry. That is, SS can be viewed as meeting a desired threshold – the squad, with its selected loads, is either self-sufficient for a given mission or it is not. A second view is that imperfect SS can be measured as a degree or fraction of full SS. However, the duration of the mission also affects SS. A

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third perspective is that SS is the duration over which the squad can conduct its mission while sustaining itself without external support (Brindel et al., 2013).

SS depends on the squad's load – the items that the squad carries into mission. They need both sustainment items, such as food and water, and mission dependent items, such as combat gear. There may be tradeoffs among items that can substitute for one another. Some items are absolutely required, and other items provide value to the squad but are not strictly necessary. Our model includes each type of item. Each individual Marine has a maximum weight constraint on his or her load. The planning challenge is to select items for the squad's collective load and allocate items among the squad to maximize SS, within the individual weight constraints.

This is both literally and mathematically a knapsack problem; it involves the selection of a set of items to maximize an objective function while satisfying a weight constraint. This application incorporates several different extensions to the traditional knapsack problem. First, it includes multiple knapsacks. The multiple knapsack problem was first developed by Eilon and Christofides (1971) as a cargo loading problem, and can be solved using algorithms presented by Martello and Toth (1981) and Pisinger (1999). Second, in addition to the weight constraints, it includes demand constraints, as used by Cappanera (1999), whose model also includes multiple dimensions of item cost; in the Marine squad problem, only weight is used. Algorithms for solving multidimensional knapsack problems with demand constraints are given by Arntzen, Hvattum, and Lokketangen (2006), Cappanera and Trubian (2005), and Hvattum and Lokketangen (2007). They have been used in capital budgeting by Beaujon, Marin, and McDonald (2001), and in location problems by Cappanera (1999) and Plastria (2001). Third, some of the items under consideration can be transferred between Marines, and others (primarily clothing items) cannot. For non-transferable items that are strictly required, e.g. boots, this amounts simply to setting the decision variables for each Marine's boots equal to 1 and decreasing the weight limits by the weight of the boots. There are a few additional unusual properties of the Marine squad knapsack problem; however, each of these can be treated as a relatively trivial modification. This knapsack problem formulation enables us to explore the implications of various definitions of SS and the tradeoffs and associated insights for several USMC training scenarios. For a more detailed review of extensions to the knapsack problem, see Wilbaut, Hanafi, and Salhi (2008).

One unusual aspect of our analysis is that some of the items can be shared among the squad. For instance, in desert terrain, if one Marine carries sunblock, it is very easy for multiple Marines to use that sunblock with no decrease in the benefit that it provides. A rifle or a pair of boots, on the other hand, cannot be shared in this manner. Sustainment items such as water or rations also cannot be shared this way; their benefit applies only to the individual who consumes them. The extent to which the items can be shared helps to determine the demand constraints; greater sharing is associated with lower demands. The demand constraints also vary as a function of the duration of the mission.

The resulting optimization problems are NP-hard. However, due to the relatively manageable size of the USMC scenarios, we are still able to obtain numerical solutions for these applications of the model. The goal of our work is to examine under the above-described circumstances what items will be carried by the squad in an optimal solution, and how mission, sustainment requirements, and squad size affect the extent to which a squad can conduct its mission while being self-sufficient. The primary purpose of the analysis is to inform baseline operating procedures and higher-level decision making, and not to apply the optimization model to every individual real-world mission for operational purposes.

2. Model

We develop and formulate three different models for the three corresponding interpretations of SS: (1) threshold SS; (2) degree of SS; and (3) duration of SS, using the following notation:

- K Number of Marines in the squad; Marines are indexed as $k = 1, \ldots, K$
- I Number of different types of items the squad may carry, indexed as $i = 1, \ldots, I$
- X_{ik} Decision variable, the (integer) number of item i carried by Marine k
- c_i Weight in pounds (lbs) of item i, each
- w_k Total weight (lbs) that Marine k can carry[1]
- a_i Number of Marines who can use one of item i
- r_i Number of Marines who will be required to use item i to carry out the mission
- t_i An indicator variable specifying whether item i can be transferred among individuals

It should be noted that if item i cannot be shared, then $a_i = 1$; if all of the Marines can share one of item i, then $a_i = K$. Typically, either $a_i = 1$ or $a_i = K$, but it is possible that items can be shared by a few Marines. Intermediate levels of a_i can also be used to model sharing an item that is feasible but difficult or somewhat degrades its effectiveness in practice. In general, for some items, $r_i = K$ for a squad of K Marines, and for some items r_i will depend on the duration of the mission. If a consumable item such as food is defined such that one of the item is a day's rations, then $r_i = K\times$ the number of days the mission will need to be self-sustaining. The number of Marines in the squad who can use item i is expressed as:

$$\sum_{k=1}^{K} a_i X_{ik}, \tag{1}$$

This term is measured in person-days rather than simply number of people; e.g. if it is 24 for food, then a squad of eight Marines has enough food for three days. The purpose of t_i is to ensure that wearable items (typically clothing) are carried and used by the same Marine.

Modeling each Marine's load, rather than the overall squad's load, is important for ensuring that a specified set of items can feasibly be distributed among the squad. When a set of items is split among a group, constraining individual loads is particularly crucial when there are heavy items, or when non-transferable items comprise a large portion of the overall load. In general, however, the overall effectiveness of a solution meeting the constraints will depend only on the combined set of items across the entire squad, not on the individual Marines' loads.

The decision variables are X_{ik} for all i and k: an assignment of a given number of item i to each Marine k. The optimal solution will depend on what exactly is meant by SS. We consider three different cases as described previously, each of which involves a different set of assumptions. The second case requires assessing the value of each item to the squad, while the third case requires distinguishing explicitly between mission items and sustainment items.

2.1. Threshold case

If SS is viewed as meeting a desired threshold, the question is simply whether the squad can carry out a particular mission without additional support or not. In this case, there is a required set of items that must be carried. Preferences and tradeoffs are

[1] This formulation allows different Marines to carry different loads, for example, a given fraction of his or her body weight, though we assume in our numerical analysis that w_k is the same for all k.